STAR 21

TECHNOLOGY FORECAST ASSESSMENTS

STAR 21

STRATEGIC TECHNOLOGIES FOR THE ARMY OF THE TWENTY-FIRST CENTURY

NATIONAL RESEARCH COUNCIL

STAR 21

Strategic Technologies for the Army of the Twenty-First Century

Technology Forecast Assessments

Board on Army Science and Technology
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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These Technology Forecast Assessment reports were prepared by the Science and Technology Subcommittee of the Committee on Strategic Technologies for the Army. The study that produced these reports was conducted under the auspices of the National Research Council and its Board on Army Science and Technology. Appendix A lists all members of the Science and Technology Subcommittee and the other members of the Committee on Strategic Technologies for the Army, along with Army personnel and others who aided the committee in its work. Appendix B provides brief biographical sketches of the authors of the Technology Forecast Assessments.

Preface

The Assistant Secretary of the Army for Research, Development and Acquisition [ASA(RDA)] wrote to the Chairman of the Board on Army Science and Technology in March 1988 to request a study under the auspices of the National Research Council. The study's goal would be to assist the Army in improving its ability to incorporate advanced technologies into its weapons, equipment, and doctrine. The time period to be addressed by the study was specified to extend at least 30 years into the future. The three study objectives stated in the request were to (1) identify the advanced technologies most likely to be important to ground warfare in the next century, (2) suggest strategies for developing the full potential of these technologies, and (3) project implications of the technology changes for force structure and strategy.

The ASA(RDA) expressed the belief that the expert, independent advice provided by such a study would help the Army in selecting those strategic technologies that offer the greatest opportunity for increasing the effectiveness of forces in the field. The study would also assist the Army in designing current research and development (R&D) strategies to ensure that such advanced technologies do become available for future Army applications.

To conduct the study, the National Research Council organized nine science and technology groups and eight systems panels within the Committee on Strategic Technologies for the Army (STAR). These units were subordinated to a Science and Technology Subcommittee and an Integration Subcommittee, respectively. In addition, a Technology Management and Development Planning Subcommittee was set up. These three subcommittees reported directly to the study chairman. An Executive Committee aided the study chairman with policy guidance and served as the principal channel for communication with senior Army leadership.

The majority of the research and drafting work on the auxiliary reports was performed under the project structure described above. The Science and Technology Subcommittee and its nine science and technology groups were responsible for preparing technology forecast assessments (TFAs), which have been joined together to form this volume. Within eight of the TFAs, the technology groups forecast advances likely to occur within specific technologies in time for incorporation in fielded Army systems by 2020. The ninth group's assessment, the Long-Term Forecast of Research, surveys research that will open new vistas for future technology applications beyond the time horizon of the eight other reports. Each of the technology groups retained responsibility for its own report. And although considerable effort was made to harmonize the documents, differences in substance and tone remain.

The study has produced a number of other reports, beyond the TFAs presented here. All are being published under the series title, *STAR 21: Strategic Technologies for the Army of the Twenty-First Century*. The reports prepared by the eight systems panels are being released as stand-alone volumes, as is the report of the Technology Management and Development Planning Subcommittee. A main report, which conjoins and extends the findings of all the subsidiary parts of the study committee, is already in print.

During the study, the ASA(RDA) offered the Army's cooperation to supply the technology users' perspective, provided such involvement did not compromise the independence of the National Research Council's study and review processes. High-level civilians and military officers from the Department of the Army were assigned to support the study committee. The chief scientist of the Army Materiel Command ensured that each STAR study group received support and involvement from Army personnel as desired. This was accomplished by appointing a group of senior Army liaison personnel, drawn largely from Army laboratories and procurement commands. The individual Army liaison personnel assisted the various study panels in gaining access to Army programs and activities as needed.

In addition to the frequent contact provided by the Army liaison personnel, an Army Mission Advisory Group was formed of senior Army and other service personnel, to provide a source of information about projected threats and the future environment. This group, which convened about halfway through the study, provided another means for the STAR participants to interact with Army representatives regarding the progress and appropriate focus of the study.

During the course of the study, over a hundred meetings and workshops, lasting one or two days each, were held by the various subcommittees, panels, and groups, so that members could interact with one another as well as receive briefings from the Army and other organizations as needed. In addition, three major coordination meetings were held, during which representatives of the various subcommittees, panels, and groups presented summaries of their activities for the benefit of other study participants, in an effort to identify significant gaps in coverage.

The National Academy of Sciences, the National Research Council, and the STAR study committee wish to acknowledge their indebtedness to the U.S. Army for its continuous and generous support and encouragement throughout the STAR study. The attention and encouragement of the top managers for Army R&D were of immense benefit. Likewise, the interest of the Army liaison personnel and the help they provided were major factors in making the study possible.

The participants also wish to express their gratitude to the STAR study staff at the National Research Council for their care and devotion to the details of arranging meetings and serving as an information center and

command post while also producing and tracking an endless flow of working papers, report drafts, source materials, and correspondence.

The views, conclusions, and recommendations expressed in this report are entirely those of the STAR study members and should not be construed to represent the views of the Army or the Army liaison personnel.

For the Science and Technology Subcommittee,

Robert R. Everett, *Chairman*
John B. Wachtman, Jr., *Vice Chairman*

Contents

PART VI. ADVANCED MATERIALS

Glossary of Acronyms and Initialisms

ADC	Analog-to-digital converter
AI	Artificial intelligence
AO	Acousto-optical
ARO	Army Research Office
ASA(RDA)	Assistant Secretary of the Army for Research, Development and Acquisition
ASAT	Antisatellite
ASIC	Application-specific integrated circuit
ATC	Automatic target cueing
ATR	Automatic target recognition
BLOS	Beyond line of sight
C^3I	Command, control, communications, and intelligence
CFV	Cavalry fighting vehicle
CIM	Computer-integrated manufacturing
CPB	Charged-particle beam
CTBW	Chemical, toxin, or biological warfare
CW	Continuous wave
CWAR	Continuous-wave acquisition radar
DARPA	Defense Advanced Research Projects Agency
DBMS	Data base management system
DEW	Directed energy weapon
DIAL	Differential-absorption LIDAR
DNA	Deoxyribonucleic acid
DOD	Department of Defense
DRAM	Dynamic random access memory
DSP	Digital signal processing
DU	Depleted uranium
EDA	Electronic design automation
EEG	Electroencephalogram
EFP	Explosively formed projectile
EHF	Extremely high frequency
EKG	Electrocardiogram
EM	Electromagnetic
ERIS	Exo-atmospheric re-entry intercept systems
ETC	Electrothermal-chemical
FEL	Free-electron laser
FET	Field-effect transistor
FFT	Fast Fourier transform
FLIR	Forward-looking infrared radar
FOG-M	Fiber-optic guided missile
FOM	Figure of merit

FPA	Focal-plane array
FWM	Four-wave mixing
GBL	Ground-based laser
GPOS	Billion operations per second
HBT	Heterojunction bipolar transistor
HEMT	High-electron-mobility transistor
HMX	Cyclotetramethylene tetranitramine
HPI	High-power illuminator
HPM	High-power microwave
IFF	Identification of friend or foe
IFRR	Ion-focused recirculating racetrack
IFV	Infantry fighting vehicle
IHPTET	Integrated High-Performance Turbine Engine Technology
IPS	Integrated propulsion system
IRR	Integral rocket-ramjet
IRST	Infrared search and track
JSTARS	Joint Systems Target Acquisition Radar System
KBS	Knowledge-based system
KE	Kinetic energy
LED	Light-emitting diode
LIDAR	Light detection and ranging
LINAC	Linear accelerator
LISP	a computer language often used for artificial intelligence software
LMS	Least mean square
MFLOPS	Megaflop (million floating-point operations per second)
MMC	Metal-matrix composite
MMIC	Monolithic microwave integrated circuit
MOPS	Million operations per second
MOSLM	Magneto-optic spatial light-modulator
MPP	Massively parallel processing (super-computer architecture)
MTI	Moving-target indicator
MUSE	Matrix update systolic experiment
NASA	National Aeronautics and Space Administration
NBC	Nuclear, biological, and chemical
Nd,Cr:GSGG	Gadolinium scandium gallium garnet crystal, doped with neodymium and chromium
NEPE	Nitrate ester plasticized polyethane
NHAM	Nonlinear holographic associative memory
NPB	Neutral particle beam
NRL	Naval Research Laboratory
OEIC	Optoelectronic integrated circuit
ONR	Office of Naval Research

PBT	Permeable-base transistor
PES	Potential energy surface
PLD	Programmable logic device
PM/RS	Powder metallurgy and rapid solidification
PRF	Pulse-repetition frequency
Q, high-Q	Quality, high-quality
QFD	Quality function deployment
R&D	Research and development
RBSN	Reaction-bonded silicon nitride
RDT&E	Research, development, test, and evaluation
RDX	Cyclotrimethylene trinitramine
RF	Radio frequency
RISC	Reduced-instruction-set computing
RNA	Ribonucleic acid
RPV	Remotely piloted vehicle
RS	Rapidly solidifying
SAR	Synthetic-aperture radar
SAW	Surface acoustic wave
SBA	Schottky-barrier charge-coupled imaging array
SBS	Stimulated Brillouin scattering
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SHS	Self-propagating, high-temperature synthesis
SIMNET	Simulation networking
SLAC	Stanford Linear Accelerator Center
SLM	Spatial light modulator
SQUID	Superconducting quantum interference device
SRAM	Static random access memory
SRT	Strategic relocatable target
STAR	Strategic Technologies for the Army
T/R	Transmit/receive
T&D	Transport and diffusion
TEA	Transversely excited amplifier (laser)
TFA	Technology Forecast Assessment
UAV	unmanned air vehicle
UHC	Ultra-high carbon (descriptor for a class of steels)
VHDL	VHSIC design language
VHSIC	Very-high-speed integrated circuit
VLSI	Very-large-scale integration
WSMR	White Sands Missile Range
WST	Wafer-scale technology
YAG	Ytrrium aluminum garnet crystal

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TECHNOLOGY FORECAST ASSESSMENTS

Executive Summary

Science and technology have advanced rapidly in the past 30 years, often in unpredictable directions. There is every reason to expect rapid developments to continue through the next 30 years, along lines that can be foreseen today as well as in completely unforeseen directions. This continuing rapid advance of technology will profoundly alter military operations in the broadest sense.

The assessments presented in this volume summarize foreseeable leading trends in technology pertinent to the U.S. Army. They project the likely impacts of new technology on the Army's operations, equipment, and tactics—and on the Army's potential adversaries. Collectively, the nine technology reports presented here review over a hundred strategic technologies for the Army of the future.

TECHNOLOGICAL ADVANCES WILL PROFOUNDLY ALTER FUTURE LAND WARFARE

Developments in technology in the past 30 years have greatly affected warfare. An army fighting with the weapons of the 1990s would have an overwhelming advantage over an army fighting with the weapons of the Korean conflict. The Persian Gulf war demonstrated again the historical lesson that even a single generation of technological advantage can be a significant force multiplier. Over the course of a single decade, an army that does not continue to assimilate advances in technology and adapt them for its use could easily find itself at a decisive disadvantage. Trends that are evident already and developments whose ultimate success can reasonably be foreseen indicate that revolutionary advances will occur. The Science and Technology Subcommittee of the Strategic Technologies for the Army (STAR) study anticipates at least three major influences on land warfare as a direct result of projected advances in technology.

Advanced electronic and optical sensors will extend precision targeting and the depth of battle to beyond-line-of-sight ranges in excess of 100 km.

Precision targeting, defined as a circular error probability of less than 1 m, is usually limited to line-of-sight ranges of less than 10 km. Visual and infrared optics are typically employed. In the twenty-first century, however, precision targeting can be expected at ranges of more than 10 km, using a combination of standoff weapons, space-based or airborne high-resolution imaging radars, and remotely operated closeup optical sensors. This targeting capability will permit standoff attacks on armored forces, airfields, supply and transport depots, command centers, and other near-in targets. Conversely, even if the U.S. Army fields a potent tactical missile defense system against cruise and ballistic missiles, Army field operations will probably require mobile logistics basing combined with defensive stealth measures and other countermeasures to deny the enemy the capability for long-range, real-time surveillance and standoff attack on U.S. or allied forces.

Advances in biotechnology will permit Army field personnel to operate with greatly reduced logistics, greater combat endurance, and greatly improved personnel protection from both conventional munitions and biochemical agents.

The Subcommittee expects that future advances in biotechnology will make it possible to generate food and water supplies for small, detached units by processing materials available in the field. Adaptive protection suits will provide improved personnel protection. Prevention of illness and treatment of disease and injury will be enhanced by biologically produced materials. As a result of these changes, soldiers will be better protected from the risks of disease and injury that have always accompanied military activity.

Advances in propulsion and ordnance will permit deep attack with greater lethality.

The advent of lightweight, high-strength structural materials and high-temperature propulsion materials, combined with the use of high-energy fuels such as hydrogen cage compounds, will allow far greater operational ranges for both surface and airborne vehicles. These advances will support the much greater depth of operation made possible by the advances in long-range surveillance and targeting. Hypervelocity projectiles will be able to penetrate even advanced armor. Protection against advanced ordnance will depend increasingly on a combination of low-observable (stealth) technologies and the various types of countermeasures capable of destroying, disabling, or evading hostile targeting systems.

DRAMATIC TECHNOLOGY ADVANCES WILL OCCUR IN MANY FIELDS

The STAR Science and Technology Subcommittee was divided into nine groups, called the STAR Technology Groups, to make assessments and forecasts in the diverse technological areas important to land warfare in the next century. Highlights from the groups' reports, which constitute the nine parts of this volume, are summarized below.

Long-Term Forecast of Research

Eleven major trends were identified as likely to draw from and have considerable influence on multiple disciplines:

- *The information explosion* on the battlefield, and in preparation for battle, will continue as intelligent sensors, unmanned systems, computer-based communications, and other information-intensive systems proliferate. Major research results are likely in third-generation data bases, mixed machine--human learning, the theory of representation creation, action-based semantics, and semantics-based information compression.
- *Computer-based simulation and visualization* will give researchers an increasingly powerful addition to traditional theory development and experimentation. Possibilities explored include a broad-spectrum physical modeling language, advanced modeling of nonlinear dynamic systems such as physical signal propagation in inhomogeneous media, and visualization of potential energy surfaces for understanding chemical reactions.
- *Control of nanoscale processes* will give the physicist, chemist, and electronics engineer the ability to create structures and devices whose dimensions are measured in nanometers, or one-trillionth of a meter.
- *Chemical synthesis by design* will allow chemicals to be designed and "engineered" at the molecular level, based on the relation between molecular structure and resulting chemical behavior.
- *A design technology for complex heterogeneous systems* could yield new ways to design complex weapons and information systems. Robustness with respect to variation will be a design objective, but nonlinear behavior in the design process itself may require a technology that focuses on the design process itself, not just the product to be designed.
- *Materials design through computational physics and chemistry* will combine the trends in computer simulation and the use of fundamental relations between structure and function to design new materials with specified properties.
- *The use of hybrid materials* will expand beyond today's structural composites to the emerging field of smart structures that react to environmental stimuli much as an organism might.
- *Advanced manufacturing and processing* will allow mass production of fine-scale materials. Nanoscale devices will be assembled into complex structures through organizing principles learned from biology, such as self-assembly and molecular recognition.
- *Principles of biomolecular structure and function* will be applied in designing new materials.
- *Principles of biological information processing* will be used to design new types of information processing systems and to *biocouple* natural or

engineered biological structures to electronic, mechanical, and photonic components.

- *Environmental protection* will affect how the Army operates and how it deals with release of hazardous materials to the environment.

Computer Science, Robotics, and Artificial Intelligence

Major advances will occur in integrated system development, knowledge representation and special-purpose languages (such as battle management language), network management of diverse kinds of processors, distributed processing over multiple processors on a network, and human–machine interfaces. In these areas the Army must be prepared to invest in research and development (R&D) to meet its requirements that do not have commercial counterparts.

Robotics will be applied to both airborne and ground-based battlefield systems. They may be fully autonomous, supervised by a human operator for nonroutine actions, or under continuous operator control (tele-operated systems). Airborne robot systems will evolve from current sensor-carrying unmanned air vehicles (UAVs) and weapon-bearing missiles such as the cruise missile. Ground-based robots will emerge as "intelligent mines" with advanced sensor capabilities, sensor data processors, and simple weapons capability. They will be designed for specific missions, not as androids with the intelligence, skill, or versatility of a human soldier.

For the following technologies, the Army will be able to monitor and make use of advances originating in the private sector for commercial applications: machine learning and neural networks, data base management systems, ultra-high-performance serial and parallel computing, planning technology, manipulator design and control, knowledge-based systems (expert systems), and systems for processing natural language and speech.

Electronics and Sensors

The three electronics technologies predicted to have the highest impact for Army applications are devices operating at terahertz (10^{12} hertz) speeds, high-speed computer architectures capable of performing 10^{12} operations per second (teraflop computers), and high-resolution imaging radar sensors. Teraflop computing will require a hundred or more processors operating in parallel at terahertz speeds. The high-resolution sensors will require both terahertz devices and teraflop computing capability.

Major advances will continue in thin-layer production methods. The number of bulk semiconducting materials used for special environments will increase and their performance will expand beyond that of current silicon-based technology. At the device level, the emerging technologies include monolithic microwave integrated circuits, superconductive electronics, vacuum micro devices, continued improvement in memory chips, application-specific integrated circuits, wafer-scale technology, microcomputer chips for digital signal processing, and better analog-to-digital converters.

At the subsystem level, data processing applications such as signal processors and target recognizers will be implemented with multiprocessor architectures and neural networks. Smaller, more capable processors will contribute significantly to radar systems, including synthetic-aperture radars, and to networks of acoustic sensor arrays.

Optics, Photonics, and Directed Energy

The Army of the future will need the ability to locate enemy targets at will while denying that capability to the enemy. To accomplish this, a variety of sensors will be used in *smart systems*, including surveillance sensors, smart or autonomous weapon systems, and fire-control systems. In *optical sensor and display technologies*, major advances are forecast for laser radar; multidomain sensors; infrared search, track, range, and identification systems; sensor data fusion (performed in real time at the sensor); focal planes designed for massively parallel data processing; and helmet-mounted or similar "heads-up" display techniques. In *photonics* (the use of light photons to transmit, store, or process information) and *optoelectronics* (the combined use of electronic and photonic devices), the important technologies will include fiber optics, diode lasers, solid-state lasers, optoelectronic integrated circuits, optical neural networks, and acousto-optics for signal processing and high-speed information processing. These technologies will be applied in *sensor fusion* (intelligent combination of information from multiple sensors operating at different wavelengths or signal domains) neural networks, and weapon control.

Directed energy devices generate highly concentrated radiation to be beamed at a small target area. The radiation used may be at optical wavelengths (as in lasers), radio frequencies (e.g., microwave beams), or other regions of the electromagnetic spectrum.

Biotechnology and Biochemistry

The successes of biotechnology to date have been in medicine, agriculture, and bioproduction of specialty natural chemicals. Applications that could be developed and fielded within the STAR time horizon include deployable bioproduction of military supplies, biosensor systems, enhanced immunocompetence [resistance to disease and many chemical, toxin, or biological warfare (CTBW) agents] for personnel, novel materials with design-specified properties, battlefield diagnostic and therapeutic systems, performance-enhancing compounds, and bionic systems.

Gene technologies are methods to modify the genetic material inside cells. As knowledge of specific genes and their interactions increases, the techniques of recombinant DNA, cell fusion, and gene splicing will enable the transfer of multigene complex characteristics into cells and organisms. New substances and organisms with new properties will be produced, such as substances for discrete recognition of a particular organism or substance, compounds that modify biological responses, artificial body fluids and prosthetic materials, new foods, and organisms for decontamination.

Biomolecular engineering will use knowledge of molecular structure to create novel materials with specified properties and functions. *Bioproduction technology* uses living cells to manufacture products in usable quantities. The methods can range from fermentation, which has long been used, to multistage bioreactors. *Targeted delivery systems* are composites of biomolecules that have been structured to deliver an active chemical or biological agent to a specific site in the body before releasing it from the composite. They will be used for drug and vaccine delivery systems, special foods and dietary supplements, decontamination, and regenerating or replacing tissues and organs. *Biocoupling* will link biomolecules or combinations of them to electronic, photonic, or mechanical systems. The discrete-recognition molecules developed through gene technology will have to be biocoupled to such devices to be useful as biosensor systems. *Bionics* is the technology for emulating the functioning of a living system with engineered materials. It will progress from current successes in imitating a specific biological material to eventual creation of complex, cybernetic systems that emulate the neural systems of animal behavior.

Biotechnology offers advantages over more traditional engineering and manufacturing methods for creating extremely complex substances in pure form and for very compact systems engineered at the molecular level. Exploiting the potential of biotechnology for applications specific to the Army will require multidisciplinary research teams with competence in physics, chemistry, biology, medicine, and engineering.

Advanced Materials

In materials technology, three pervasive trends are forecast: (1) use of supercomputers to design materials and to model performance; (2) technology demonstrators to hasten transfer of new materials and methods from laboratory to production; and (3) materials and structures designed to serve multiple purposes, thereby replacing multiple layers of single-purpose materials.

Five materials technologies were identified for special consideration by the Army: affordable resin-matrix composites, reaction-formed structural ceramics, light metal alloys and intermetallics, metal-matrix composites, and energetic materials. These technologies are forecast to substantially alter the state of the art for many Army applications, including armor materials, ballistic protection for the individual soldier, and weight–strength relations for vehicle and propulsion system structural design.

Resin-matrix composites are becoming less expensive because of recent processing breakthroughs. The use of ordered polymers for the matrix yields composites with improved mechanical properties. Further research in molecular engineering of polymers and in matrix composition may yield organic composites with the toughness of metals and stability at high temperatures.

Smart composites have sensing elements embedded in the material. Passive sensors allow the internal properties of the material to be monitored during manufacturing and later during the material's useful life. Active elements can alter properties of the composite.

Reaction-formed ceramics can be preformed to near the final shape of a structure. Techniques for reaction forming are forecast to replace conventional sintering technology, first for specialty components and later for even commonly used, low-cost items. Other ceramic technologies that are advancing include cellular ceramics (with foamlike structures), fiber-reinforced ceramics, and thin-film coatings of diamond or diamondlike materials.

Although some aspects of *metals technology* are considered mature, research into structure–property relations will yield evolutionary improvements even in ferrous metals technology. New aluminum alloys (such as Weldalite) and new processing techniques (such as powder metallurgy for rapidly solidified alloys) have opened up avenues for future exploration. *Metal-matrix composites* are being developed that use either steel or aluminum as the matrix metal. Addition of particulates or whiskers of other metals or ceramics gives these composites the beneficial characteristics of both the matrix and the added material.

Research on *energetic materials* for Army propellants and high explosives is focusing on organic cage molecules. Another promising area of research concerns methods to make explosives less sensitive to fire, shock, impact, and so on, without sacrificing explosive power. Biotechnology may prove important in the production of energetic materials and in the biodegradation of hazardous waste products from their manufacture.

Propulsion, Power, and High-Power Directed Energy

For *rocket propulsion*, gel propellants are the most promising new technology for Army applications, although evolutionary improvements to solid propellants will continue. For propulsion of *air-breathing missiles*, turbine engines and ducted or air-augmented rockets show the most potential. In *manned aircraft propulsion*, gas turbine engine technology is again the most significant technology, for both fixed-wing and rotary-wing aircraft. For UAVs used in surveillance from high altitudes, beamed power from a ground station represents a novel, though still highly speculative, possibility.

For *surface mobility*, primary power production, methods of power transmission, and mechanical subsystems were reviewed. Two general conceptual approaches to vehicle propulsion—the integrated propulsion system and hybrid electric propulsion—received highly favorable assessments. The recommended configuration combines an advanced diesel or gas turbine engine with all-electric or hybrid-electric power distribution.

In *projectile propulsion*, the two technologies with the greatest potential were judged to be chemical propulsion by liquid propellants and electrically energized guns (either electrochemical-thermal or electromagnetic).

Battle-zone electric power includes primary power generation and technologies for energy storage and recovery. For continuous power generation, gas turbine engines offer more potential than the alternatives. Gas turbines for primary power and flywheels for storage would be combined with power conditioning units to supply the pulsed, short-duration power needed by high-power systems such as directed energy weapons. Rechargeable batteries are an alternative to flywheels for energy storage in both stationary and vehicular applications.

In the area of *high-power directed energy*, five technologies were selected for their high potential in Army applications: (1) ionic solid-state laser arrays; (2) coherent diode-laser arrays; (3) phase conjugation for high-energy lasers; (4) high-power millimeter-wave generators; and (5) high-power microwave output from pulsed multiple-beam klystrons.

Advanced Manufacturing

The next generation of progress in manufacturing will focus on the inclusion of information systems with the energy systems and material management systems developed previously. *Intelligent processing systems* use a control system to combine sensor technology with robotics. *Microfabrication*, which manipulates and fabricates materials at a scale measured in microns, will be complemented by *nanofabrication*, which does the same at the scale of individual atoms. *Computer-integrated manufacturing* organizes the single processes or workstations of a production facility into functionally related cells. Cells, in turn, are managed within factory centers responsible for system subassembly and assembly. The application of information systems to management across multiple production facilities is *systems management*.

These methods of manufacturing control by advanced information systems can be combined with specific process technologies, such as those described under "Advanced Materials." Examples include distributed and forward production facilities, rapid response to operational requirements generated in the field, and parts copying from an existing part without the need for plans and specifications.

Environmental and Atmospheric Sciences

The *terrain-related technologies* most important to the Army are a terrain data base that can be queried directly from the field and used to generate hard-copy maps at any scale; terrain sensing; and computerized real-time analysis of changing terrain conditions, which will use both the terrain data base and data from terrain sensors.

Among *weather-related technologies*, the Army will need atmospheric sensors flown into forward battlefield areas, either on UAVs or as ground sensors dropped in place. Satellites will be used for remote sensing by laser and radar imaging. Although the Army can use advances in civilian-oriented weather modeling and forecasting, it is also concerned with modeling and forecasting on smaller scales.

PART I

LONG-TERM FORECAST OF RESEARCH

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Summary of Long-Term Trends

This Long-Term Forecast of Research represents the best assessment by a panel of experts on the directions in which technology of interest to the U.S. Army may progress during the next 30 years or more. Neither specific research results nor the exact technology that will ensue from research are predictable so far in advance. The objectives of this report are to highlight significant trends and illustrate the kinds of technology these trends seem likely to produce.

MAJOR MULTIDISCIPLINARY TRENDS

The forecast panel identified 11 major trends that cut across the traditional boundaries between scientific or technical disciplines.

Trend 1: The Information Explosion. The flow of information in preparation for ground warfare and during battle will continue to increase as intelligent sensors, unmanned systems, computer-based communications, and other information-intensive systems proliferate. Our ability to deal with this information will expand as data bases and their management software progress beyond even object-oriented data bases to *intelligent multimedia data bases* with new modes for indexing and searching stored data and more intelligence in interacting with the human user of the data base. *Mixed machine–human learning* will team the learning capabilities of a person with the rapid data processing and analysis capabilities of a computer.

The current limitations to practical application of artificial intelligence may be overcome if an adequate *theory of representation creation* can be developed and *action-based semantics* can be applied to the Army's battlefield information requirements. The information transmission bottleneck on the electronic battlefield calls for data compression techniques; *semantics-based information compression* would address this problem by assessing the value of information relative to the cost of transmitting or storing it.

Trend 2: Computer-Based Simulation and Visualization. Computer simulation of objects and processes, with graphical display of the computer-generated results, gives researchers a potent addition to the more traditional techniques of theory development and experimental evaluation. Computer simulation clearly depends on progress in computer hardware and mathematical algorithms, but its growth also depends on understanding the basic principles governing the phenomena to be modeled. Long-term progress in integrating computation with science and engineering may require a broad-spectrum *physical modeling language*, rather than special-purpose simulation environments. Computer studies have already played a major role in modeling the behavior of *nonlinear dynamic systems*. This area of applied mathematics presents both limitations and opportunities for computer modeling of processes important for Army technology. For example, computer modeling will make possible detailed studies of how physical signals, including light, radar, or sound, propagate in inhomogeneous media such as the lower atmosphere or forest canopies. In chemical research, the potential energy surface that characterizes a chemical reaction is a multidimensional mathematical function, which can be modeled and visualized for the researcher. But better methods are needed to approximate the relevant properties of complex molecular systems, and models are needed for reactions of particular interest to the Army, such as combustion or detonation reactions at the surface of an explosive.

Trend 3: Control of Nanoscale Processes. As the features of microelectronic devices shrink to sizes measured in nanometers, new phenomena appear that alter how these devices behave. The particle-wave duality of this quantum world affects both physical and chemical behavior. For example, electron transport, which is essential to all electronic devices, becomes quantized at this scale. Neighboring structures no longer behave independently of each other; quantum mechanical phenomena such as quantum interference, tunneling, and ballistic transport occur. These changes limit the miniaturization of conventional semiconductor devices, but they open opportunities for entirely new devices, for example, atom clusters.

Natural biomolecules such as enzymes, or variations bioengineered from them, are likely to provide the first generation of *molecular recognition devices*. These devices will detect a single molecule of a particular chemical species or any of a class of molecules with specified structural similarities. Nanoscale chemistry will also control surface reactions, including surface catalysis, through the design and production of layers having an exact placement of component atoms, ions, and molecules.

These new nanoscale electronic devices will operate at very low voltages and low currents; only a few electrons will suffice to differentiate between the 1 and 0 states of a binary digit. Quantum-based devices subsequently will be incorporated into molecular integrated circuits, and then into monolithic integrated circuits (wafer-scale integration), in which a trillion devices could conceivably be placed on a chip the size of a dime.

Trend 4: Chemical Synthesis by Design. This trend joins with Trends 6 and 9 in an even more general trend. In the future, new materials will be *designed at the molecular level* for specific purposes, by designer-engineers employing fundamental scientific relations between a structure and its functional capabilities. The realm of engineered chemicals will include both surface catalysts and enzyme-like catalytic molecules, whose specificity depends on their three-dimensional conformation. To support research into these structure–function relations, chemists will need to determine—by experiment and by derivation from quantum chemical theory—the three-dimensional structure of complex molecules, including biomolecules. These structure determinations must be both rapid (on the order of hours or days) and at high resolution (on the order of angstroms).

Trend 5: Design Technology for Complex Heterogeneous Systems. If a system has many components and subsystems that vary markedly in physical and operational characteristics but must act as a functionally coherent whole, it can be considered a complex heterogeneous system. Modern combat vehicles, unmanned air vehicles carrying multiple smart sensors, and theater air/missile defense systems are all examples. At present, the design of such systems is largely a process of muddling through to an adequate result rather than proceeding rationally from a testable theory. The mathematics of optimization theory can be improved but probably needs to be supplemented, or even supplanted, by other approaches. New approaches are needed for designing systems with *robustness with respect to variation*, while taking into account the *costs and benefits of marginal design information.*

Statistical approaches that seek *least-sensitive solutions* for a complex design problem hold some promise. But they currently lack a clear theoretical foundation and may not apply if the system's behavior is nonlinear over its operating range. A radical departure would be to *model the design process* itself, rather than attempting to model the system to be designed. Another area worth exploring is the use of *nonlinear modes of control* for systems whose functional dynamic range includes areas of nonlinear response.

Trend 6: Materials Design Through Computational Physics and Chemistry. This trend combines, within the field of materials science, two other trends: the growth of computer simulation (Trend 2) and the design of useful products by application of fundamental relations between structure and function (Trend 4). For materials design, these structure–function relations include interatomic forces, phase stability relations, and the reaction kinetics that determine how complex processes evolve. Possible areas of interest to the Army include lightweight (half the density of steel) ductile intermetallics, new energetic materials superior to current explosives and propellants in energy density and safety, materials harder than diamond, and tough polymers with working ranges extending to 500°C.

Trend 7: Use of Hybrid Materials. Also called composite materials, hybrid materials are especially attractive for Army applications because they can be designed for unique, special requirements. For example, the component phases of a hybrid can be altered, or the formation process can be modified, to improve performance in two or more dissimilar functions. The area of greatest technical novelty is that of *smart structures*. A network of sensors embedded in the structural phase of the composite acts like an animal's sensory nerves. A network of actuators allows properties of the structure to be altered, under the control of a microprocessor that reacts to the sensor signals, analogous to an animal's brain.

Trend 8: Advanced Manufacturing and Processing. The above trends in designing materials, particularly hybrid materials, will be paralleled by trends in manufacturing *fine-scale materials* (at the scale of individual atoms) and *thin-layer structures*. Chemical synthesis methods such as sol-gel processing will be used, as will methods for precisely controlling process energy (e.g., laser processing). As *nanoscale devices* (Trend 3) become available for sensors and actuators in hybrid materials, "smart materials" will be synthesized at a molecular level through the application of principles including *self-assembly* and *molecular recognition*. These principles were first studied in biological systems.

Trend 9: Exploiting Relations Between Biomolecular Structure and Function. The principles that relate the functions of biomolecules and tissue structural components to their molecular structure are now understood well enough to be used in designing materials. Among the potential applications are new personal battle gear made from lighter and stronger fabrics, broad-spectrum vaccines and prophylactic medicines, sensors and diagnostic devices based on molecular recognition properties, and miniature motors and power supplies based on biological energy transduction mechanisms.

Trend 10: Applying Principles of Biological Information Processing. Biological systems receive, store, duplicate, respond to, and transmit information. The knowledge gained about these processing mechanisms will find practical applications in the design of information systems. Capabilities such as pattern recognition and selective abstraction of relevant data may use principles discovered from biological systems. Biological structures, natural or bioengineered, may be *biocoupled* with electromechanical and optoelectronic components. At even higher levels of information processing, a growing understanding of the *biological basis for learning and memory* may provide new models and techniques to improve training and performance for information-intensive tasks.

Trend 11: Environmental Protection. The Army will be affected by the general societal trend toward greater concern over environmental effects of toxic materials or disruptions of ecological balances. In the future, the Army will have increased responsibilities for ameliorating past environmental damage and minimizing new environmental contamination or degradation from its operations. Assessing the full impact of hazardous wastes, for example, will require development and verification of accurate models of the transport and fate of target compounds in soil, air, water, and biota. Better methods to monitor and treat wastes will be required.

DISCIPLINE-SPECIFIC TRENDS

Besides these 11 major multidisciplinary trends in research, a number of narrower trends within specific technological areas will have important consequences for future Army applications. In many cases, these trends weave into the major trends.

In *electronics, optics, and photonics*, the directions for *advanced sensor technology* include conformal sensors and multispectral sensors, with onboard processors for data fusion and for mission-specific processing such as automatic target recognition. Future Army systems will use an integrated mixture of electronic, photonic, and acoustic devices to process both analog and digital output from a range of sensors gathering electromagnetic, acoustic, and magnetic signals. *Active cancellation techniques* will be used to reduce interfering background noise and unmask sources of interest. Extensive *communication networking* will require communication links with very wide bandwidths. Allied with the major trend in fine-structure manufacturing (see Trend 8) will be advances in *micropackaging* and *minifabrication* of components, subassemblies, and entire nanoelectronic systems (Trend 3). Methods for control of optical phenomena will provide faster, smaller, and more powerful architectures for digital data processing as optoelectronic technology expands.

In *aeromechanics*, computer simulations on new supercomputer architectures will allow modeling of rotorcraft vehicles in their operating environment. This greater computing power, combined with advances in computational fluid dynamics, composite structural dynamics, and aeroelasticity, will contribute to the goal of complete *aerostructural simulation* (another example of Trend 2). Propulsion and control technologies will make *hypervelocity projectiles and missiles* possible. More knowledge will be needed of phenomena associated with hypersonic passage through the lower atmosphere, electromagnetic radiative characteristics of hypersonic vehicles, and the impact and penetration by hypervelocity projectiles against anticipated targets. If UAVs become important as brilliant weapons and as means for transporting sensors, the Army will require theoretical and experimental data on *aerodynamics at low Reynolds numbers*.

In *molecular genetics*, information deciphered from both human and nonhuman genes will be of major interest to the Army. The genetic blueprint from nonhuman cells will be used in the bioproduction of artificial products that mimic natural materials and in the design and production of organisms with new or modified properties. Information about the human genome will yield new methods for preventing and treating diseases or the effects of chemical, toxin, and biological warfare (CTBW) agents. Artificial blood, skin, and bone, and perhaps even complex organs such as the liver or kidneys, may be replaced by culturing an individual's own cells.

In *clinical medicine*, new instruments and sensors will be used in diagnostic and therapeutic equipment. The miniaturization of sensors (see Trend 3) and sensor data fusion will allow physicians to measure chemical and physiological events at the cellular and subcellular levels as they happen. Army applications include detecting CTBW agents in the field, monitoring a soldier's physiological condition, and improving the diagnosis and resuscitation of the wounded and sick while they are in transport.

In *atmospheric sciences*, high-resolution *remote sensing* of meteorological conditions will provide the data to initialize and validate *computer models of the atmosphere* on small spatial and temporal scales, for which the Army has special need. The validated computer model can then be used to improve sensor placement. By repeating this cycle, the sensor data-gathering and the computer modeling activities will complement one another. The result should be increased understanding of small-scale weather conditions, including fog and cloud physics, and more accurate representations of turbulence.

In *terrain sciences*, sensor technology and information processing are again important, for both *automated extraction of information from multiple images* and *three-dimensional representation of terrain data*. A key addition to existing terrain data capabilities will be a near-real-time system to analyze and map changes in terrain surface conditions and trafficability. Such a system would use sensor data on rainfall, soil moisture monitors, and computer modeling of soil properties on the basis of hydrologic and atmospheric conditions.

MANAGEMENT OF BASIC RESEARCH

Continued support of Army basic research (funding line 6.1) will be necessary if these research trends are to find fruition in Army-specific applications. Budgetary continuity and stability are crucial to achieving long-term objectives. For this purpose, the Army may find the Office of Naval Research a useful paradigm.

2

Introduction

SCOPE OF THE LONG-TERM FORECAST

Early in the Strategic Technologies for the Army (STAR) study, the Science and Technology Subcommittee divided itself into nine Technology Groups. Eight of these groups were assigned particular fields of technology relevant to Army applications, such as "Electronics and Sensors" or "Advanced Materials." Each group prepared a Technology Forecast Assessment (TFA). The eight area-specific TFAs primarily forecast technology that would be ready for incorporation in Army systems to be fielded by 2020. Because advanced systems require 10 to 20 years to move from concept to a fielded system, the technology must be proven and ready to go within 10 to 20 years.

The ninth Technology Group focused on *basic science* or *basic research*. Many of the research topics examined by this group had applications in technology areas covered by the area-specific TFAs. However, they were typically more speculative projections of novel technological possibilities or revolutionary advances beyond the 10- to 20-year forecast horizon of the eight area-specific TFAs. This TFA evolved into a look at significant trends in research, including speculation on directions those trends might take as scientific inquiry progresses into the twenty-first century.

The discussion for each trend or research topic is divided into three sections. The "Background" provides a factual framework of recent research advances and current problems to be solved. The second section, "Future Directions," ventures beyond what is already known and defensible to evoke possibilities that might be realized. It does not attempt to forecast accurately what technology will result from research in 30 years but rather indicates the potential of a trend or area of research. The third section, "Disciplines Involved and Research Topics," returns to the present. It specifies which disciplines or fields will be required for current research to progress or will be influenced by research results. This section also lists specific topics of relevance to the Army that could be pursued now or in the near term.

CLASSIFYING AREAS OF SCIENTIFIC AND TECHNOLOGICAL PROGRESS

New technologies often—though not always—emerge from the interstices between established fields. Rapidly accumulating advances in one science often spill over into other areas, changing them as well. For both reasons, a classification scheme for long-term scientific and technological progress should aim to locate potential new technology on the map of what is already known, without creating a rigid system that ignores novelty that happens not to fit within its arbitrary definitions.

The Long-Term Forecast of Research was prepared by four focus groups drawn from the members of the STAR Science and Technology Subcommittee. The focus groups followed a traditional classification of scientific disciplines:

- *Physical sciences* include physics, chemistry, electronics, optics, mathematics, and computer science.
- *Engineering sciences* include mechanical and civil engineering, aeronautics, and materials science.
- *Life sciences* include biological sciences, biotechnologies, medical sciences, behavioral sciences, and social sciences.
- *Geosciences* include terrestrial sciences, atmospheric science, and environmental science.

This classification was used to ensure that a broad range of subjects was considered. At the same time, the focus groups were encouraged to develop themes and trends broadly, cutting across traditional disciplinary boundaries as appropriate for the research directions they sought to describe. To encourage interdisciplinary and multidisciplinary thinking, the focus groups were asked to specify the fields relevant to each research effort.

These four broad areas are retained in the report's chapter structure as an initial guide to the research trends. In most instances, however, the disciplinary classification of a trend is less important than the range of disciplines it draws upon or is likely to influence. Indeed, many of the trends intersect one another, and cross-references among the trends are frequent.

THE RESEARCH DYNAMIC OF "TECHNOLOGY PUSH" AND "REQUIREMENT PULL"

The research trends for this long-term forecast, like the shorter-term technology advances forecast in the other TFAs, are sometimes described as driven by opportunities opened by research successes and sometimes as requirements that research will need to fulfill. The former is sometimes called a "technology push," whereas the latter is a "requirement pull."

In the short term, this distinction may be quite important. If the technology has arrived and only awaits good applications, the direction of immediate effort is to envision worthwhile applications, then develop, test, and field them. On the other hand, if the requirement has been posed but the technology is not yet available, research efforts can be directed toward finding successful solutions.

As the length of time for results increases, this clear and practical distinction gives way to a dynamic interaction between prospective research and proposed requirements. When a long-term trend is described in terms of applications that new research would enable, a need for those applications is implied. That need is typically extrapolated from current needs or desires. Similarly, when a trend is described in terms of problems or requirements for which technological solutions are needed, there is implicit reference to the kinds of technology that are likely to work.

In recognition of the importance of this dynamic relation to long-term progress, both "technology push" and "requirement pull" descriptions are used in this report. Both kinds of description may occur for the same trend. (Major Trend 1: The Information Explosion, is a good example.) Over the time required by major trends to mature, both technology push and requirement pull will influence where inquiry leads and what uses arise from the results of that inquiry.

RESEARCH TRENDS IN SCIENCE AND TECHNOLOGY

In many of the rapidly changing fields covered by the Long-Term Forecast of Research, a span of 30 years represents three or more generations of technology. Given the push-pull dynamism between research interests and application requirements described above, forecasts of particular research results or technical achievements are unlikely to be accurate. For this reason, most of the forecasts are presented as *research trends*. The particular results presented for them are important primarily by way of illustrating the trend; the actual results are likely to diverge from these predictions in ways not foreseeable now.

Some of the trends are well defined within an existing field. Others are emerging at the intersection of two areas of research. Still others seem likely to encompass multiple disciplines. As they progress, these multidisciplinary trends will change the landscape of research and technology in several fields. This report identifies 11 such *major trends* and devotes a major section to each. Narrower trends that are likely to remain within one discipline are described in separate sections of research trends for that particular discipline, such as the section on "Research Trends in Electronics," in Chapter 3.

BASIC RESEARCH AND THE ARMY

For the trends considered in this report to fulfill the Army's long-term needs, much basic research will be required. In many areas, the Army will be able to profit from adroit use of research supported through commercial and academic resources. In other areas, Army support for basic research will be essential, whether to provide the initial exploration of an idea or to achieve the transformation from interesting discovery to applicable technology. Through the Army Research Office and other agencies, the Army has sponsored basic research programs in academic and industrial laboratories; these programs have made significant contributions to Army technology. The last chapter of this report discusses ways the Army can continue and perhaps surpass its historical role in furthering significant basic research.

3

Physical Sciences, Mathematics, and Computer Science

MAJOR TREND 1: THE INFORMATION EXPLOSION

Background

The amount of information available on the battlefield and in preparation for the battle continues to increase exponentially. Heavy use of nonhuman sensor systems that are increasingly intelligent will sustain this rate of increase in the value of information reaching human users, while constraining the transmitted volume of (unprocessed) data. This information explosion is at once a consequence of, and a requirement demanding further progress in, three knowledge interfaces:

1. the interface between the world and the information—knowledge representation;
2. the interface between the knowledge and its physical representation—information storage, retrieval, and transmission; and
3. the interface between the knowledge and humans who must understand it in order to use it—the user interface.

These interfaces are discussed to a significant extent in Part II: "Computer Science, Artificial Intelligence, and Robotics." Their treatment here focuses on a set of conceptual trends that were omitted from that TFA because they cross disciplines, are more fundamental than seemed appropriate for an emphasis on applications of technology, or extend further into the future than was contemplated in the scope of Part II. In most cases, these trends are too broad, and still too inchoate, for direct and comprehensive treatment. The research topics cited here to illustrate them are only directed toward partial solutions or limited, exemplifying problems within the following emerging trends:

- theory of representation creation;
- action-based semantic theories;
- mixed machine—human learning and problem solving;
- intelligent, multimedia data bases; and
- semantics-based information economy.

Future Directions

Theory of Representation Creation

A core concern of artificial intelligence (AI) is creating knowledge representations. At the moment, AI appears to have reached an impasse. The major advances of the past 20 years have been in truth-maintenance techniques and uncertainty representation. Some progress has also been made in representing time, causality, and metaknowledge. But AI still lacks an integrating framework that could be applied to solving typical Army problems such as control of an autonomous robot for even narrowly specified missions. AI resembles nuclear physics; continued support of frontier research in AI is important because AI will be fundamental to many of the projected STAR long-term technology trends. To date, however, the bulk of AI effort is applied to tinkering with a few basic representational schemes. But these schemes may be near the limits of their applicability.

A focus on real problems is likely to require new representational technology. Unfortunately, no theory of representation now exists that could guide the construction of such technology or even identify the problems to which various technologies should be applied. Such a theory would delineate, with all the rigor and generality of the best mathematics, the range of application and the limits of existing and possible representations.

An important area of research is in new ways of representing uncertain knowledge or, more generally, degrees of belief. Current lines of research in logics of belief and mathematical theories of belief representation and propagation include "fuzzy logic" systems, Dempster-Shafer probability, and Bayesian probability theories. Various techniques, numerical and nonnumerical, for representing uncertain knowledge need to be explored and enhanced, with the long-term goal of formulating an adequate and tested theory of belief.

Knowledge representations for military use are created ad hoc; the Army depends on trial and error to develop good software. If a rational theory of knowledge representation can be developed, it could contribute to the Army's application of AI technologies in many ways, including

- major advances in all uses for robot systems that are discussed elsewhere in this volume (see Part II: "Computer Science, Artificial Intelligence, and Robotics");
- faster production of more reliable software for complex systems;
- revolutionary advances in intelligent processing applications such as automatic target recognition and fire control, battlefield management software, sensor fusion at the sensor, IFFN (identification of friend, foe, or

neutral), and expert-system diagnostics for fault isolation in complex systems; and

- the mixed human–machine learning partnerships discussed in the previous section.

Action-Based Semantic Theories

Semantics is the science of meaning, of the relations between descriptions and the world described. Although logic and philosophy have had formal semantics for several decades, the basis for prevailing theories is dubious. For instance, in the "possible worlds" semantics often used in AI, a description is said to designate the set of possible worlds in which that description is valid. This definition of course begs the question of what it means for a description to be valid. This theory, and many like it, assumes a one-to-one mapping between things in the world and terms in the description. This mapping, which is called the *reference relation*, is presumed to constitute the fundamental truth relation between the world and the description.

Unfortunately for these reference theories of meaning, the identifiable "things" in the world appear to be largely a consequence of the particular way an agent (the "knower") wants or needs to interact with the world. Consider, for example, an infantry battalion. Does this battalion include the troops under its operational control or only those assigned or attached? If it suffers 50 percent casualties, is it still the same battalion? Does it remain that same battalion if it is merged with another depleted battalion, or is replenished with replacements, or is disbanded but its veterans continue to meet frequently?

Only logicians with a philosophical bent fret seriously over such questions. Nonlogicians are primarily interested in using descriptions to take action in the real world, not in a set of possible worlds. They understand that the world is primarily the location for actions and decisions, not the complement of a description. They can readily acknowledge that the description never captures everything important about the world. Their viewpoint is closer to that of the farmer, the engineer, or the soldier in the field, than to the view of the logician-philosopher.

The Army's battlefield information requirements are, of course, inherently action oriented. It is important to know the range of actions available to one or more acting units (where the units may be individual soldiers, squads, platoons, brigades, etc.) under particular circumstances. The constraints on these actions, whether physical, doctrinal, or operational, must be defined and available for interpreting the situation. And perhaps most important, the crucial inferences to be drawn from information are actions to be taken (i.e., imperative statements), not simply descriptive assertions. On one hand, a rigorous theory of the relation between description and world from an action perspective should help considerably in effective information management, that is, decisions on what information must be stored, transmitted, and so on. On the other hand, the demand for such semantics from the Army could help the AI community break loose from its current self-preoccupation. Once this is done, AI could again become a source of new representation technology useful to the Army.

Mixed Machine–Human Learning and Problem Solving

Programming is an extremely slow and cumbersome mechanism for teaching computers to perform a useful operation. Learning, comparable to the way humans learn, requires an extensive framework of knowledge within which the new information can be assimilated. At the same time, human learning requires accommodation of the knowledge framework to novelty in the new data. Unfortunately, computers have thus far been able to learn (in this human sense) only relatively slowly and only in narrowly defined contexts. The basic problem—almost a paradox—has haunted theories of knowledge and learning since Plato's day: to learn something, you have to almost know it already.

On the other hand, humans are tediously slow and limited in many forms of information acquisition and processing, at which computers excel. For example, it takes considerably longer for a person to become an expert rifleman than it does for a programmable gunsight to execute a newly compiled program for identifying and acquiring a target. Or compare the time a person needs to memorize a long list with the time required for a personal computer to receive, store, format, and display the same list sent to it by electronic mail.

If humans and computers excel at different forms of learning, highly productive technological advances are likely to result from teaming their capabilities rather than trying to make one (the man or the machine) act like the other. Two examples from the computer age illustrate this point. First, the growth rate in computer usage and new applications soared after interactive operating systems, which permit a *dialogue* between computers and users, replaced batch processing as the way most users worked with the computer. Second, computer graphics for data representation and graphics-oriented interfaces for operating systems have similarly catalyzed new ways for humans and machines to work together as a learning team. Given this general principle and its past consequences, what will be the next major breakthroughs in mixed machine–human learning?

Within the next 30 years, it will be technically feasible to provide every person at birth (or upon military enlistment) with a computer to be carried everywhere. Heads-up displays and two-way voice communication will provide a visual and verbal interface between the human and the machine. The computer will also have its own "senses" (e.g., video camera, acoustic and thermal sensors) to supplement the person's perceptual modes. Three key questions must be addressed to expedite machine–human learning: how to expedite (1) the person's learning from the computer; (2) the computer's learning from the person; and (3) the computer and the human learning together from the environment, other persons, and other computers.

One possibility is to use the computer's sensing and data processing capabilities to augment human perception. A heads-up display on a soldier's helmet could indicate where to aim and when to fire a handheld weapon, even when the target is far away or moving rapidly.

Each computer's interactive modes will become uniquely tailored to its human partner. The human will initiate and control much of this tailoring, although some may be performed automatically by transferring information from other machines. Familiar distinctions between actions such as learning, taking and filing notes, transferring data, programming, formulating theories, and making decisions will evolve into other distinctions for the *knowledge work* performed by the machine–human team.

This trend in mixed machine–human learning obviously includes a multitude of research problems and concepts in interface design, but the issues run deeper. Implicit knowledge, rather than detailed manipulation of formal symbols, will increase in importance. For example, engineers and scientists now spend a good deal of time learning to perform the manipulations of differential and integral calculus, but such manipulations are easily performed with a computer. The engineer's key skills, although they are often poorly taught, are the abilities to link a real-world problem to an adequate mathematical representation and to decide which manipulations of that representation are relevant to solving the problem.

Humans will increasingly handle information in the aggregate, with the details handled by the computer. This information probably will be presented in graphical form, to exploit more fully the large fraction of the human brain devoted to visual processing and the visual system's pattern recognition ability. A complex graphic, which may represent thousands of individual data points, will allow the user to shift scales effortlessly, zoom in to focus on key details, then visually step back to view the problem as a whole. Continued research is needed on formulating micro/macro assemblages of data automatically and efficiently, using the computer to free and to stimulate the human intellect.

The Army, perhaps in joint efforts with other services, should actively support research in mixed machine–human learning. The public education system is unlikely to produce enough graduates with the competence to meet the Army's needs. Nor are the steps required to implement these capabilities likely to come from the traditional educational establishment. If the Army can take the lead in developing this new potential, soldiers and commanders of the future are likely to be an order of magnitude more effective than either their predecessors or their enemies.

Problem solving and learning in socially cooperative roles will improve manufacturing and service industries immensely; here the Army should be able to work jointly with the commercial sector or even follow its lead. The Army-unique aspect of mixed machine–human learning and problem solving pertains to adversarial situations, survival situations, and other circumstances unique to soldiers' roles in war. In these areas, the Army will need to lead.

Intelligent, Multimedia Data Bases

Traditional data base methods (including relational data bases) provide an essentially flat, logic-based representation of subject data. These first-generation representations have relatively unintuitive semantics that are static, almost trivial. The representation itself does not convey quantitative relations among subject data, as would be important for a terrain data base. Object-oriented data bases, which can be considered a second generation, divide the subject data into objects. By storing information about those objects, including processing methods for operating on the object data, they can offer a more intuitive semantics and the ability to store a wider range of information. However, the world does not divide into objects nearly so neatly as is often supposed. Terrain maps, for example, provide a mostly continuous representation of the world. The indexing on this kind of information will need to be far more sophisticated and qualitative than is now possible. For instance, a unit commander should be able to call up immediately a list of all threats that could attack that unit within the next hour.

Further, the form in which information can be effectively described and indexed depends profoundly on the person who will use the information. An example from battlefield medicine can illustrate this point. The battlefield of the twenty-first century is likely to have a thinly distributed soldier population, with similarly distributed, but ferocious, pockets of lethal fire. A field-portable medical expert system for this battlefield should present the same life-sustaining diagnostic and treatment information whether it is used by a doctor at a forward field hospital or an infantryman giving first aid to a fellow soldier before the medical corpsman arrives. But that expert system must present its information to the infantryman and the doctor in different ways.

At this point, it is clear that future data bases will use object representations, continuous representations, and a variety of other knowledge representations as appropriate. The semantics of query and report will have to adjust interactively to the user's level of dialogue, just as a human information expert should be able to provide information at the questioner's level of understanding. Quantitative relations, such as spatial and temporal magnitudes, should be built into the mode of representation. The indexing schemes that will support these capabilities are not yet defined, but the opportunity is evident.

Semantics-Based Information Economy

The amount of potentially useful information on the battlefield will continue to increase far faster than the amount of data that can be transmitted through a given band of frequencies. The electromagnetic spectrum cannot be expanded to provide more frequencies, so the transmission of more information with fewer data will become essential.

Conventional approaches to data compression are semantics independent. That is, they work without regard to the meaning of the data being transmitted. Such approaches are probably approaching their theoretical limits. In contrast, the theoretical limits to semantics-based compression are still undetermined. For example, it is extremely expensive, in terms of bandwidth and data, to transmit a video image of a scene containing a camouflaged tank in sufficient detail that the tank can be seen. If the tank has already been recognized, transmitting its identity and grid location is not only economical but, for many purposes, conveys as much useful information. But there is a substantial cost associated with placing the tank-recognition system on site; a more powerful, semantics-based processor (perhaps a human spotter) must be on hand, rather than a semantics-independent video camera.

It should be possible to combine the mathematics of economics and that of information theory to develop a hybrid theory by which to assess and predict the value of information and, therefore, the utility of transmitting or storing it. Of course, the details of the theory's information-value functions will be specific to the situation, but the theory will provide a powerful mechanism for recording assumptions made in that situation, drawing inferences based on an information-value model, and testing outcomes of the model. One potential application of such a theory that would be particularly interesting to the Army would be a *mathematical theory of jamming*, to determine when to attempt communications in a jammed signal environment and what to communicate.

Disciplines Involved and Research Topics

The following scientific and technical disciplines will continue to fuel the information explosion:

- algorithms and data structures
- cognitive science
- communications networks
- intelligent tutoring
- logic
- machine learning

computer architectures
data base design
distributed processing
human–machine interfaces
information theory and data compression algorithms
magnetic storage
optical storage
representation of uncertainty
robotics
sensors
transformation mathematics

Broad topics for research are covered in "Future Directions," above. In addition, the following research topics are of particular importance to the Army:

- targeting—"smart" search techniques and automatic target recognition/identification;
- data representation—object-oriented paradigms, continuous-field and continuous-process paradigms, and mixed object–field paradigms;
- data extraction and manipulation;
- ergonomics and input/output modes for improved human–machine interactions between an operator/supervisor and a remote robot system;
- heterogeneous computing;
- knowledge engineering and real-time expert systems; and
- communications—multimedia (audio/text/graphic), information filing, and language translation.

MAJOR TREND 2: COMPUTER-BASED SIMULATION AND VISUALIZATION

Increasingly, computer simulation of objects and processes is becoming as important to research as experimentation. The objects may be biomolecules, atomic arrangements for designed materials, airframes, or storm clouds. The processes may be chemical reactions, fluid flow, structural deformation, or weather systems. Within 30 years, computer modeling of physical phenomena will have permeated every branch of science and technology. With increasing frequency, mathematical modeling (implemented on computers) precedes physical experimentation because it is faster and less costly. Just as important, the modeling effort often continues in parallel with physical experiments because the model provides information obscured in the experiment.

The importance of computer simulation stems from at least four benefits:

1. Computer simulation and the graphical display of computer-generated results allow the experimental scientist to predict the

outcome of experiments before they are performed, thereby saving valuable time and resources.

2. It allows the experimentalist to interrogate the experimental context on a deeper level than ever before. Although the primary function of experiments in fundamental research has long been to test models, experiments often have been used in the applied work of many sciences as a source of empirical data to which curves may be fitted. The implementation of complex dynamic models on computers means that, for many of these areas, empirical curve-fitting can be replaced by modeling from first principles.

3. In some cases, computer simulation can replace particularly dangerous, difficult, or costly experiments altogether, especially after the model has been successfully demonstrated against physical experiment.

4. In structural or process engineering, alternative designs can be analyzed by computer simulation to determine an optimum configuration. If the configuration developed for testing is first optimized by computer modeling, it is more likely to pass performance tests. This reduces or avoids the need for expensive repeat testing of multiple configurations. An excellent example is in simulations of aeronautical wind-tunnel testing, but the range of potential applications extends to many other fields that have depended on design-and-test cycles.

The computer simulation trend depends on developments in computer hardware and mathematical algorithms. It also depends on understanding the basic governing principles of the phenomena being modeled and the ability to encode those principles in computer software. It depends as well on experimental validation and calibration of the advances in computer-based representation, just as theoretical advances have traditionally been validated through experimentation. Indeed, at the heart of this major research trend is the emergence of computational methods as a third mode of inquiry to accompany and complement the traditional two: theorization and experimentation. In the future, science will progress through complementary work in all three modes.

The applications of computer-based modeling for simulation and visualization are so broad that this trend has been divided into discrete subtopics, each emphasizing a trend in the science of computational modeling itself or in a scientific field where computer-based modeling seems the key to further progress.

- "Physical Modeling Languages" discusses the prospects for fundamental advances in the software technology available for modeling.
- "Applied Mathematics: Nonlinear Dynamic Systems" reviews generally the use of computer modeling to investigate dynamic systems that

show nonlinear behavior: the systems to which the term "chaos" has now been popularly, if somewhat misleadingly, linked.

- "Physics: Wave Propagation in Irregular Media" describes the essential role of modeling in enabling research into a class of physical phenomena of great importance to the Army but not easily studied without the computer's aid.
- "Simulation and Visualization in Chemistry" illustrates how computer modeling has created a new experimental approach to basic research in chemistry.

In addition to its central importance in these four illustrative topics from computer science, mathematics, and the physical sciences, the computer modeling trend is woven into many of the other trends described in this long-term forecast. See, for example, "Materials Design Through Computational Physics and Chemistry" and "Aerostructural Simulation" in Chapter 4 or "Dynamic Atmospheric Modeling" and "Terrain Surface Dynamics" in Chapter 6. Computer-based modeling will also be important in designing complex heterogeneous systems, as described in Trend 5 in this chapter.

Physical Modeling Languages

Background

Modeling languages are steadily becoming more powerful and easier to use but also more specialized. The increased specialization limits the utility of these languages. For example, languages such as Mathematica and Macsyma for manipulating mathematical symbols make it easy to construct, solve, and visualize moderately complex algebraic, matrix, and differential equation systems. However, truly complex physical phenomena often require the use of finite-element methods, which break a continuous structure into tiny volumes (like bricks) and numerically solve the simple but numerous equations governing the behavior of each volume. Such problems are normally set up using a graphical front end to capture the geometry and control the analysis of the structure into "bricks." Symbol manipulation programs do not provide such capabilities, nor do they run fast enough to solve the resulting equations.

There are numerous other examples, ranging from assembly languages, which provide unparalleled control over the computer, through dynamic simulation languages to complex expert-system shells. Each has advantages for a particular set of circumstances, and each imposes constraints. Developers and users of these languages are often unaware of the significance of the constraints.

For example, simulation is often seen as the solution to all problems, but in fact there are many problems that cannot be effectively addressed by simulation, because it predicts system performance for only a single set of input conditions. When a system exhibits chaotic behavior, such a single-point solution may provide no information about the system's behavior when input conditions are very slightly different. Furthermore, it is infeasible to simulate the behavior of a complex system for every possible set of operating conditions, whether or not its behavior is chaotic. The key is to identify the significant operating conditions: those likely to cause problems. Nonlinear systems that show chaotic behavior simply exacerbate this more general problem.

Future Directions

Long-term progress in integrating computation with science and engineering will require a sophisticated fusion of high speed, numerical simulation techniques and symbolic reasoning in a variety of forms. A broad-spectrum physical modeling language would integrate these capabilities and eliminate the constraints that existing specialized languages impose. Both qualitative and quantitative modeling must be expressible through this language, including models that integrate both approaches.

There are three principles that could be used in developing such a language. First, the language should be built from simple sublanguage components. A good example of this principle is Scheme, a drastically simplified dialect of the LISP computer language. The components should be constructed to supply utilities to other components, with a separate and universally available set of interface utilities. The uniformity of software interfaces for the Apple Macintosh computer is a good example. Second, the components should involve a minimum of special tricks, quirks, and restrictions. Third, the language should provide multiple levels of user control. It should start with a level that is easy to use, predictable, and reliable—but less efficient—and then progress to levels with more sophisticated mechanisms. At each level, the language must provide information to the user about both the dangers and the possibilities of alternative approaches to implementing a model.

The task is considerably complicated by the increasing use of parallel and distributed processing. As computer hardware presses toward limitations imposed by nature, the cost of manufacturing a thousand processors of a given speed becomes significantly less than the cost of making one processor that runs a thousand times faster than that speed. But the basic principles of programming a single processor are much better understood, and the languages much less restrictive, than for multiprocessor machines.

The availability of such a language would dramatically accelerate scientific progress in a variety of fields important to the Army.

Disciplines Involved and Research Topics

Computer science, transform mathematics, AI, and applied mathematics generally are likely to be key contributors to the development of broad-spectrum physical modeling languages. In addition, the pressures from the application areas for computer simulation are likely to provide the stimulus and the fertile ground for conceiving and rigorously testing research in this area. Seminal ideas could come from any application area, much as seminal work in nonlinear dynamic systems occurred in weather forecasting. Some of these applications are explored in the following sections on computer-based simulation and modeling.

Applied Mathematics: Nonlinear Dynamic Systems

Background

Computer simulations of phenomena as diverse as fluid flows in the atmosphere or logistics support for a battlefield environment have a limited predictive capability. A clearer picture is emerging of the limits to which one may be able to predict the real outcomes of phenomena from simulations based on specific and precisely established initial conditions, even with extremely accurate computations. The key observation is that in all nonlinear systems—which include most of the interesting real-life systems—an instability or indeterminacy (relative to classical notions of determinate linearity and continuity) causes inherent errors in the specification of the state of the system (when the system state is conceived in classical terms). The effect of the initial error on the system grows exponentially as the system or process evolves over time. A rounding error or a finite-state representation of floating-point numbers in a computer are both subject to this same instability.

Although nonlinearity places clear and quantifiable limits on the prediction of the specific path of such systems, it does not void the statistical predictability of the set of possible paths. This statistical aspect of a nonlinear system's output does not derive from random noise in the system. According to our still-emerging understanding of nonlinearity, it is intrinsic to the deterministic dynamics of these systems. In principle, therefore, better computers and more precise modeling will not allow predictions for these systems to increase indefinitely in accuracy; predictions from models must take into account the inherent stochastic behavior of the model, as well as the system itself. Fortunately, methods exist and can be improved for determining, by observation or computation, the intrinsic limits on the range of system outcomes. These limits characterize the predictability of the system being studied.

Future Directions

The study of nonlinear dynamic systems in diverse applications has two goals: (1) to determine the intrinsic instabilities of the dynamics and (2) to make statistical predictions based on an analysis of the system's behavior. The apparent statistical behavior is governed by quantities that are independent of any particular orbit and thus can be applied to the analysis of all orbits. This new point of view suggests the use of innovative software designs for the analysis of simulations and the determination of predictability. This differs from the viewpoint that expects infinite accuracy to be possible with increasingly powerful and accurate computing capability.

The predictability limits associated with nonlinear system dynamics will become increasingly important to the Army as it seeks to develop, field, and support increasingly complex systems and operations dependent on these systems. Many of these systems and processes are likely to display nonlinear dynamic behavior with respect to performance parameters and results that will affect Army operations on and off the battlefield. Simulations for nonlinear dynamic systems can greatly assist in training and planning, but their inherent limitations should be clearly understood.

Disciplines Involved and Research Topics

Research in nonlinear dynamic behavior continues to be highly interdisciplinary. Computers have been a key tool in this research, but relatively simple machines and software have often been the source of the most fruitful new ideas and techniques. Specifically, much current research in this area focuses on studies of mathematical structures and the qualitative properties of important classes of dynamic systems. Considerable progress has been achieved for systems of low dimensionality.

For systems of infinite dimensionality, however, progress has not been as swift. Examples of such systems are those described by systems of partial differential or stochastic equations. To address the problems raised by these systems, sound analytical and computational procedures are needed. Such procedures are likely to draw on diverse areas of mathematics, including analysis, topology, and geometry.

Physics: Wave Propagation in Irregular Media

Background

Wave propagation can be governed by a variety of physical laws, depending on the nature of the wave being propagated. For example, Maxwellian equations govern electromagnetic waves, Navier-Stokes equations govern acoustic waves, and equations of elasticity govern seismic waves. In most cases, wave propagation in a regular (homogeneous) medium is straightforward. In nature, however, media are often irregular (inhomogeneous), and wave propagation becomes significantly more difficult to model accurately.

Accurate modeling becomes important to Army applications as more subtle wave properties are used to gain information from a signal that propagates as a wave. Active research and development (R&D) in this regard is already occurring for the wave phenomena of radar, acoustics, and lasers. Research into wave propagation in inhomogeneous media can benefit the Army, both in detection and surveillance and in understanding the limitations of systems (such as radar) that depend on wave propagation. For example, our growing understanding of millimeter-wave radar, laser, and acoustic-wave propagation through the atmosphere exposes opportunities and limitations that will guide future R&D on Army systems.

A useful approach to wave propagation in irregular media came in the middle decades of this century, when propagation in layered media was studied (e.g., radio waves in a stratified ionosphere and seismic waves in a stratified earth). During the past 20 years, significant progress has been made in understanding propagation in several types of random media, such as the ocean perturbed by internal gravity waves or the ionosphere perturbed by a variety of waves and plasma instabilities.

Future Directions

Attention is now focusing on more complex media that are both inhomogeneous and anisotropic. A primary motivation for this research is to accomplish remote sensing of a medium by interpreting the fluctuations impressed on a wave as it passes through that medium. Future progress in this field will likely take place in two areas:

- new means of mathematically modeling a medium, such as a forest or soil layer; and

- new methods for calculating how a wave is distorted as it propagates through a medium modeled by these new mathematical techniques.

Because the propagation processes are governed by different properties in different media, the models probably will need to be tailored to a specific medium. Nevertheless, progress should occur in developing mathematical models that can cope with a variety of media. For example, the mathematics of fractal geometry can be used to model many natural media in which variations occur on a wide range of size scales.

Modeling the propagation of waves through complex, irregular media now requires the use of extensive numerical propagation codes that are run on supercomputers. Future development of new physical and mathematical approaches should simplify the modeling process significantly, as well as increase the efficiency of numerical codes. Experimental research is also needed: first, to provide information on media that are not well understood (e.g., acoustic and laser propagation in the atmosphere); and second, to test the theoretical work and provide data to stimulate and challenge the theorists.

Disciplines Involved and Research Topics

Electromagnetic, acoustic, and seismic waves can all be used to gain intelligence and targeting information for Army applications. Laser rangefinders, radar surveillance, and acoustic listening devices are typical systems. Laser propagation in the atmosphere is presently understood well enough that laser beams can be used to make windage corrections for tank gun direction. One area for future Army application lies in understanding the best means (radar, laser, etc.) for imaging tree-covered areas to detect and identify items of Army interest below the tree canopy. An area of current Army research is passive acoustic surveillance for tracking helicopters. Basic research into acoustic-wave propagation in the atmosphere can guide R&D whose purpose is to survey a variety of military targets (e.g., tanks, vehicles, artillery, and aircraft). Seismic listening in the 1- to 5-Hz band may also furnish important information on the location and movement of tanks, vehicles, artillery, and aircraft near the ground.

Basic research in support of these objectives can take three forms. First, experimental work serves to describe empirically the propagation of waves in situations of interest to the Army. This work covers a broad range of situations (e.g., acoustic waves and laser propagation in the atmosphere, or radar waves through a forest). Second, modeling work is needed to describe concisely the important characteristics of a natural medium; chaotic processes or other means of describing multiscale media have a role here. Finally, new physical and mathematical approaches are needed to allow the calculation of wave characteristics, given a useful model of the medium. At present, complex media are usually addressed with numerical propagation codes that require supercomputer processing. New approaches are needed to make the calculation process simpler and more efficient. Eventually, calculations to turn wave observations into useful information could be done quickly by a compact unit at forward locations.

Simulation and Visualization in Chemistry

Background

As noted in the introductory comments on Trend 2, progress in computer modeling of physical phenomena depends on an understanding of the basic principles of the scientific subject area and on computer technology. For simulation and visualization in chemistry, these principles include representations for potentials of mean force, for electrostatic interactions, for quantum mechanical descriptions of bonds and reactions, and for bounded multidimensional systems. In each area, fundamental problems remain in the theoretical physical chemistry and physics that a veridical model must codify. These problems must be solved if the simulations are to achieve their full potential.

These considerations underscore the importance of supporting research into the physical chemistry underlying simulation methods. It is also important to support research that extends the use of simulations toward more complex and important problems. The section below on "Future Directions" describes a few of the areas of chemistry that meet one or both of these conditions for progress in computer-based simulation:

- development of potential energy surfaces (PESs);
- improved treatment of electrostatics;
- real-time simulation of chemical and biochemical processes; and
- molecular dynamics of reactions.

Future Directions

Potential Energy Surfaces. Empirically determined PESs are the heart of current simulations in chemistry. The PES, represented by a multidimensional mathematical function, governs how chemical reactions occur at the molecular level. If the PES is accurate, a great deal of important information such as reaction rates, product channels (alternative pathways), and the temperature dependence of reaction rates can be deduced without further experimentation.

Unfortunately, at this time the PES can only be determined with high accuracy for small molecular systems with three to five atoms. The empirically derived surfaces for more complex systems do not accurately answer the questions of interest to chemists and biochemists. Other PES modeling approaches are needed that are perhaps less precise than the rigorous treatments applicable to small systems but more broadly applicable to large systems, such as those involved in biochemical reactions, solvent effects, and organometallic complexes. One promising methodology in this area is density function analysis.

Even with advances in the theoretical construction of PESs, empirical confirmation of the surfaces calculated from the theoretical models will remain an important task. Some PESs must be determined experimentally to test the theory. Many Department of Defense (DOD) agencies are supporting research in molecular spectroscopy and molecular dynamics, which contributes to developing the information base needed for this experimental verification.

Molecular Reaction Dynamics. Once accurate PESs for molecules have been constructed, computational methods can be used to determine rates of reaction, product channels, and temperature dependencies of reactions, as noted above. At present, classical trajectory methods are used for these computations, but they have limitations. Although computational methods based on quantum mechanical principles would provide more reliable results, they need more extensive computational capability. Less accurate but computationally more tractable models are required to simulate a system as complex as protein dynamics.

For the Army, a critical area for this simulation capability is in the development of energetic materials for propellants and explosives. Combustion and detonation reactions cannot yet be modeled effectively because the elementary chemical interactions in bond making and breaking cannot be simulated adequately to give the simulation results any predictive accuracy. There is no adequate model for combustion or deflagration processes at a solid–gas interface. Although much remains to be done in applying computer simulation to development of energetic materials, there are lines of research in progress that are moving in this direction. For example, research is being funded on the synthesis of nitrogen-containing compounds—the molecular basis of modern explosives—and the molecular dynamics of their chemical reactions.

Real-Time Simulation of Chemical and Biological Processes. Improvements in computing power and in graphical display engines are needed to allow a researcher to observe the simulation of a chemical reaction or other molecular process on a display device at the same time that the underlying computations are being performed. With respect to the human–machine interface, it would also help to have modes of display that allow the scientist to perceive the molecules as solid objects and to translate interactions among atoms into sensory feedback, so the experimenter can "feel" the chemical environment in ways analogous to how the molecule responds to that environment.

Better methods of approximating the relevant properties of complex molecular systems are also needed. No matter how powerful the simulating computer becomes, its resources will be taxed by the need to follow multiple energy minima through dynamic interactions with a "rugged" landscape of potential energy valleys and peaks. It will be necessary to understand which simplifying assumptions can be made without sacrificing accuracy and which cannot be made.

Improved Treatment of Electrostatics. Despite the fact that the Coulomb approximation is only valid in a medium of homogeneous dielectric, nearly all electrostatic calculations in chemistry and biochemistry use this approximation. However, reactions on surfaces, in inclusions, and on enzymes occur at dielectric boundaries. At present the only formally correct way to treat such systems is to solve the generalized Poisson-Boltzmann equation on a grid. This approach is not compatible with real-time computer graphics. Better methods must be found to model these electrostatic interactions for large molecules and on surfaces; especially for surfaces and receptors that act as reaction catalysts, these electrostatic interactions are arguably the most important in chemistry and biology.

Disciplines Involved and Research Topics

The disciplines required for this research include physical chemistry, chemical physics, quantum chemistry, surface and polymer chemistry, inorganic and organometallic chemistry, applications of group theory, and the fields of computer science and perceptual psychology involved in developing more powerful processors, machine–user ergonomics, and new and improved data reduction and display modes. For prospective research topics, see the individual topics above under "Future Directions."

MAJOR TREND 3: CONTROL OF NANOSCALE PROCESSES

Background

In the manufacture of miniature electronic devices, we now shape and control structures whose dimensions are measured in microns (1 μ = 10^{-6} m). As the working scale of devices continues to shrink, we are beginning to fashion structures whose dimensions are measured in nanometers (1 nm = 10^{-9} m). There is more than simply a quantitative change in size involved in moving into this *nanoscale* range. Individual atoms are measured in angstroms (1 angstrom = 10^{-10} m); the lengths of many chemical bonds (the distance between the nuclei of the bonded atoms) are on the order of 1 to 2 angstroms. Hemoglobin, a medium-size protein, has a length of 68 angstroms or 6.8 nm. In this size range, structures and the interactions between them can no longer be reliably described by the principles of classical physics; the very different principles of *quantum mechanics* are much in evidence.

Nanoscale processes operate on a finer time scale as well as a finer spatial scale. Where fast operations previously were measured on a scale of nanoseconds (1 ns = 10^{-9} s), nanoscale processes often occur within times measured in picoseconds (1 ps = 10^{-12} s) or even femtoseconds (1 fs = 10^{-15} s).

The special consideration that must be given to understand and control processes in the nanoscale range has led to the coining of special terminology. Thus, *nanodetection* is the ability to monitor events and structures whose size is in the nanometer range. *Nanoscale fabrication* refers to the construction of functional devices, components, and systems by the placement of individual atoms, molecules, or other structural elements that are in the nanometer size range.

This chapter addresses nanoscale processes of interest to physicists, chemists, and engineers (particularly electronic engineers). The nanoscale region is also the realm of biomolecules, bioengineering, and biocoupling. Long-term trends in these fields are discussed in Chapter 5.

Future Directions

Physics

The current emphasis in microelectronics fabrication is on patterning techniques that use x radiation or electron beams to achieve the necessary levels of precision. This downscaling of geometries for transistor-based integrated circuits is facing a combination of problems related to physical phenomena that first appear at these ultrasmall dimensions.

For example, all electronic devices depend on electron transport, which becomes quantized in nanoscale devices and subject to the constraints on localization represented by the Heisenberg Uncertainty Principle. As a result, individual structures with nanoscale dimensions are expected to interact strongly with neighboring structures; the electron-transport response of one structure will reflect the properties of neighboring structures as well. Among the quantum physical phenomena that affect nanoscale electron transport are tunneling, Coulomb blockade, and ballistic transport.

One approach to control of nanoscale physical phenomena is to begin with atoms and scale upward by creating atom clusters with desired properties. Tunneling microscopy, for instance, has been used successfully to position atoms in an arbitrary arrangement. A second approach is to use biological systems as templates for building nanoscale structures. (See Major Trends 9 and 10 in Chapter 5 for further discussion.) With these two approaches—and others yet to be devised—for controlling nanoscale features, it should become possible to tailor devices that depend on nanoscale phenomena. Rather than being barriers to further miniaturization of the old technology, these new nanoscale phenomena can open the way for an entirely new technology.

As work progresses in controlling nanoscale physical phenomena, the following questions must be resolved:

- Can atom clusters be created at high densities that maintain the desired cluster configuration?
- Can atom clusters be produced in large quantities while their size remains controlled?
- Can clusters be interconnected, or can their interactions be controlled in a way that is analogous to conducting interconnections among transistor devices?
- Can the technology associated with atom clusters be combined with biological templating to create two-dimensional arrays of nanoscale devices?

Chemistry

Nanoscale chemical devices will include single molecules that only interact with a specific reactant molecule, or with a class of reactants with a specifiable structure. The most specific of these *molecular recognition devices* are likely to be natural biomolecules or bioengineered equivalents, where the three-dimensional conformation and charge distribution of the biomolecule at its binding site(s) limit its reactivity to a unique complementary structure. By relaxing the conformational and charge constraints built into the recognition molecule, devices can be produced that react with any of a class of related molecules.

There are ample biological models on which to base molecular recognition devices: enzymes, receptors on cell membranes for small molecules or functional groups of large ones, and receptors for neurotransmitter molecules on nerve cell dendrites. But control of molecular recognition will require more than the ability to structure an appropriate binding site (or find a naturally occurring molecule with the desired binding site). There also must be the means to embed and sustain single receptor molecules in a structural environment that can respond to the recognition event. This response will typically include (1) initiating a signal (information) that will pass to other parts of the system and (2) clearing the binding site so the device is ready for another recognition event.

The *design of catalysts* for specific reactions also will use spatial arrangements of atoms and charge distribution to affect chemical reactions. In catalysis, however, the special chemical environment that is created reduces the reaction energy barrier, which facilitates and accelerates the reaction. The catalyst's structure also may maneuver the molecules of two or more reacting species so they come into proximity in conformations and orientations that are most conducive to reaction. Finally, the catalyst's design must promote release of the reaction products, so the catalyst is ready to repeat its action. Enzyme catalysis provides a natural model for a reaction-specific nanostructure in three dimensions. Noble-metal catalysts and other inorganic and organic catalysts are models for catalysis based on two-dimensional surface interactions, often between a solid-phase catalytic surface and a gaseous or liquid phase that contains the reacting and product species.

In the past, catalyst development was largely a trial-and-error effort. Design of a catalytic structure from first principles requires

1. the ability to model a chemical environment that is favorable in energy and conformation to the desired chemical reaction and
2. the ability to construct that chemical environment.

The first of these requirements will be addressed through the computer modeling technology described in Trend 2, making use of the chemical design principles discussed in Trend 4. The second requirement is where nanoscale fabrication becomes particularly relevant.

Surface interactions associated with *layer growth and reactions other than catalysis* are a third area for nanoscale control of chemical processes. The doping of semiconductor layers and thin-film deposition are techniques already used to control surfaces with distinctive physicochemical properties. Nanoscale fabrication of surfaces will involve layers that are only a molecule thick or that correspond to a unit cell of an ionic lattice. In addition to control of thickness, nanoscale fabrication will allow atoms, ions, and molecules to be placed precisely within these surfaces.

Nanoscale Electronics and Optics

Current trends in electronics include shrinking conventional device structures to the size scale of atoms; increased use of optoelectronic, photonic, and electromagnetic concepts in devices; and the use of artificially structured materials such as quantum-well and superlattice devices. The physical limit for scaling down conventional electronic devices is about 10 angstroms. This limit is likely to be reached early in the twenty-first century. Beyond that point, the future lies with *nanoelectronics* and *mesoscale devices*, which will be based on the particle-wave duality of matter. Because the nature of an electron as a wave packet will become significant, these devices will require both amplitude and phase information to determine properties such as current density. Quantum mechanical phenomena such as quantum interference will become the guiding concepts for developing new devices; the understanding of the interactions among electrons, photons, and phonons must increase if these new devices are to be realized.

Operating voltages for nanoelectronic devices will be very low; for example, digital electronic devices will use from one to several electrons to differentiate between 1 and 0 in an information bit. The operating currents will be very low, and the power requirements to operate the devices will be exceedingly low relative to those of existing devices. The devices will be extremely fast as well; quantum electronic devices that mature within the next 15 to 20 years will allow electronic computing and information processing systems built from them to achieve processing speeds greater than 10^9 operations per second.

The technology for nanoscale electronic devices represents only the first step; integration of quantum-based devices must follow. The field of molecular electronics will become a reality, with complex molecules used as both semiconductor and nonsemiconductor materials to perform electronic operations. If current trends hold, the first applications will be for computer-memory integrated circuits (memory chips). Single-chip capacities will move into the multi-megabyte range. In the area of digital processing, the next step will be more pow _ computers. Another development will probably be *wafer-scale integration* of quantum devices. For a monolithic integrated system, one can envision 10^9 devices on a chip of about 200 mm^2. By 2030, three-dimensional integrated circuits may be available; these are likely to increase the scale of device integration by at least an order of magnitude.

The fundamental physical principles underlying nanoscale electronics will be complemented by new architectures for building and interconnecting components. These architectures are likely to be inherently parallel, implementing such concepts as *cellular automata* and *neural nets.*

Disciplines Involved and Research Topics

The special disciplines involved in researching the control of nanoscale processes include solid-state physics, quantum physics and chemistry, electron microscopy and other short-wavelength imaging techniques, and electronics. Representative research topics of interest to the Army include

- nanoscale miniaturization of electronic components and processing systems for use in brilliant munitions, unmanned air vehicles, and soldier-portable systems;
- early-warning detectors and catalytic neutralizers for chemical and biological warfare agents; and
- applications of neural nets in learning systems.

RESEARCH TRENDS IN ELECTRONICS

Background

Electronics will be profoundly affected by two of the research trends discussed elsewhere in this chapter: Trend 3 ("Control of Nanoscale Processes") and Trend 5 ("Design Technology for Complex Heterogeneous Systems"). In addition, important research trends will occur within electronics itself and in research areas where it combines with optics. Many of these narrower trends are continuations of current R&D efforts, which are discussed in the Electronics and Sensors TFA. They are reviewed here, with special attention to their long-term possibilities, because of their importance to Army applications.

Future Directions

Advanced Sensors and Sensor Data Fusion

In sensor technology, conformal sensors will be an important element in advanced stealth technology. Brilliant weapons that have multispectral sensors with on-board processors for data fusion and automatic target recognition will be developed. These weapons will be launched from standoff platforms to home onto their assigned targets precisely ("zero circular error probability"). Brilliant weapons may use either optoelectronic devices or nearly pure photonic processing. (See next section on "Research Trends in Optical Sensing and Information Processing.")

Perhaps the most significant signpost for the future of signal processing is the breadth of interest and innovation from outside its traditional home in the field of electrical engineering. Physicists, geologists, mathematicians, and many others are now involved. This wide appeal is due primarily to the increasing volume and complexity of data collected in the study of natural phenomena. Over the next several decades, the Army also will be faced with an increasing volume of data collected from more capable versions of current sensors, as well as from entirely new sensors.

The data complexity problem expands even further when observational data from a variety of sensors are considered. Today, for example, Landsat-type, multispectral photography provides less than 10 pieces of information about each 80 m × 80 m pixel. In the next several decades, imaging spectrometers will produce hundreds of spectral bands at significantly higher resolution. Polarimetric and multifrequency synthetic-aperture radar will be collecting data from spacecraft or aircraft. Ground-based sensors will provide acoustic and seismic information. Automated signal interpretation will be needed to separate the small number of highly interesting information "needles" from the data "haystack."

One approach is to think of a large, multisensor data set as a multidimensional image. The interpretation of this image is a subject for basic research. Image interpretation in two dimensions has proved successful in acoustic sonograms, which display acoustic spectral intensity on a plot with time and frequency axes. The recognition and extraction from such images of the acoustic patterns characteristic of helicopters is now becoming a reality. The future need will be to recognize and extract more subtle objects from more complicated, multidimensional images. Work in this area has begun (e.g., *projection-pursuit* methods used in high-energy physics) but will require much further research. The areas of technology pertinent to multidimensional image-processing include signal processing, imaging, and applications of AI to "image understanding."

Future Army systems will use an integrated mixture of electronic, photonic, and acoustic devices to process analog and digital output from electronic, optical, and acoustic sensors. The now-distinct processing paradigms of multiprocessor architectures, neural networks, cellular automata, and optical processors will be blended into these complex integrated systems. The inputs from sensors in multiple domains (e.g., acoustic, magnetic, infrared, radar, and position) will be combined through data fusion techniques to construct a total "vision" of the battlefield. Sensor detector arrays will improve in resolution, operate at multiple wavelengths, and be incorporated into monolithic integrated circuits.

Acoustic Sensors

Acoustic sensors provide a good illustration of future possibilities in electronic sensing. Many processes associated with battlefield action and second-echelon order-of-battle activities generate strong acoustic signals. Examples include artillery, helicopters, tanks, heavy vehicles, and electrical generators. Acoustic signals from these sources can deliver information for targeting and intelligence at distances of tens or even hundreds of kilometers. The advantage of using acoustics to gather targeting and intelligence information is access to non-line-of-sight paths. Diffraction and refraction processes often allow acoustic signals to propagate along non-line-of-sight paths, which are not accessible to laser or microwave radar signals.

The use of acoustic sensors against helicopters is in development; further applications can emerge from the helicopter program. Acoustic sensing can be used by armored vehicles and infantry to detect and identify hostile helicopters. A warning of an approaching helicopter, and the direction of attack, before the helicopter is visible can make defensive action far more effective. The logical next step is to use acoustic sensors to detect and identify tanks, other vehicles, and artillery. Applications for acoustics also can be found in unconventional warfare.

The use of acoustic sensors to locate artillery was a common technique before and during World Wars I and II. However, acoustic location of artillery was abandoned by the Army about 25 years ago. At that time, the data collection and analysis methods available for acoustic signals were deemed too slow, and radars appeared to be superior. Under future battlefield conditions, radar use may be constrained by the need to control electromagnetic emissions.

The next 30 years will see significant improvements in the acoustic sensors to supply data, in signal and data processing techniques to handle the data, and in the hardware to implement these techniques. Arrays of acoustic sensors will be deployed on moving vehicles and in remote locations that provide advantages for observation (e.g., forward deployment toward the enemy). New methods of signal processing will allow detection and interpretation of signals now considered unusable because of interference (e.g., the application of concepts from nonlinear dynamics to signal processing). Modeling of acoustic sources, such as vehicle engines, will increase in sophistication. This will allow a complex, noisy signal to be decomposed into components of known origin, much like decomposing the sound of an orchestra into individual sections or instruments.

The concept of multidomain sensing can be applied to acoustic sensors as well as electromagnetic sensors. In either case the Army's basic research objective in using multiple, advanced sensors effectively is twofold: acquiring basic science to exploit the data, and developing interpretation algorithms useful for Army applications. A basic scientific understanding of both the target and the background environment in situations of Army interest is necessary to plan and implement a successful scheme for interpreting data from multiple, advanced acoustic sensors. Propagation of acoustic signals through the atmosphere and along the vegetation-covered earth is an area where basic research is required.

To meet the second objective, a basic understanding of methods for recognizing the patterns displayed by the target is required. This would also include an understanding of the limitations of the technique. The Army's stake in this work would be in supporting research concerned with "targets": propagation, noisy environments, and pattern recognition. For example, better understanding and characterization of acoustic noise from particular sources will allow identification and provide further information, such as vehicle type and condition.

Source Modeling and Active Cancellation

Another research area is the use of *source modeling* to reduce interference and detect the desired source, much as one listens for a favorite instrument within an orchestra or to an interesting but distant conversation at a noisy cocktail party. An approach to the complexity of sensor signal processing is *active cancellation*. The idea of sampling the signal environment and then altering that environment to cancel unwanted noise by introducing additional signals is not new. To implement this idea, however, two requirements must be met: (1) sensors that work in the frequency range of interest and (2) computational ability that is powerful enough to process the ambient noise and generate *antinoise* as required. The availability of sensors, computing capability, and sources has recently come together to allow practical systems to be produced and sold in the open market (Fisher, 1990).

Developments in active cancellation hold enormous promise for the Army. Research into processing the signal environment has just begun. As new sensors, sources, and improved computational power become available, the domain of application will continue to expand.

Communication Networks

As the preceding discussions of sensor electronics indicate, information collection by unmanned systems will be increasingly important on the battlefield. To reduce the bandwidth required to communicate data from these sensors for processing, dissemination, and storage, sensor arrays with local processing will perform data fusion and information processing prior to transmission. Information collection and dissemination will be supported by communication through *networks of networks*. To support sensor information dissemination, distributed data bases and distributed processing, voice communication, and video data transmission through these networks will require *communications links with very wide bandwidths*. The modes of signal transmission will include satellites, high-frequency radios, and optical fibers. Sophisticated technology for interfacing and interconnecting these links and managing message traffic will keep the underlying complexity transparent to the user.

Network transmission technology will also implement information denial strategies. Friendly communications will be protected with low-probability-of-intercept, antijam, and encryption techniques. Signals warfare against hostile communications will include uncooperative signal interception, identification, and distributed fusion for integrated electronic warfare, including jamming and deception.

Signals from nonlinear systems are intrinsically broadband. All real-world systems are nonlinear when driven hard enough and proper account is taken of the intrinsic physics. Since before World War II, the focus on signal processing techniques tied to narrowband signals (perhaps embedded in broadband noise) has been motivated by mathematical simplicity or necessity, as well as the success achieved in dealing with linear problems. Significant new developments in nonlinear systems made during the 1980s have allowed the classification of nonlinear, broadband, deterministic signals, the associated model building, and the control and prediction that have been familiar in the linear context for 50 years.

As we learn to do with broadband signals what is now routinely done with linear, narrowband time series, an area of major opportunity will be opened for the Army. The ability to exploit the broad spectral regions of a signal opens opportunities for detection, identification, and system control where few or none existed before. Control by feedback on nonlinear systems could allow advantages such as

- quieting troublesome tank, vehicular, or helicopter noise;
- an increase in the parts of the spectrum used for detection and identification of friend or foe; and
- communication in fashions not yet devised or implemented.

Packaging

Even as the complexity of electronic systems increases, important Army applications call for decreases in the size and weight of systems and subsystem assemblies. The electronically equipped soldier of the future must not be overwhelmed by the burden or bulk of his high-technology support systems. Brilliant munitions need lightweight, miniaturized guidance systems to allow delivery of more warhead explosive to the target and more submunitions per launch vehicle. Unmanned airborne or ground vehicles also will place a premium on size and weight.

Many current and future advances in materials and device technology will support this need for smaller, lighter electronics with far more capabilities. Monolithic integrated circuits, including application-specific integrated circuits, wafer-scale technology, and the nanoscale components discussed in Trend 3, also will help. Micropackaging of components and assemblies will require research, as will techniques to increase input and output capacity. In packaging, research is needed in three-dimensional interconnects for monolithic systems. Power sources must be available that do not vitiate the size and weight gains made through device miniaturization. Current prospects for meeting power requirements include solar cells and the use of superconductivity to reduce power loss and waste heat. However, continued long-term research will be needed on how to package devices and power them.

Minifabrication

As monolithic integrated circuits, or chips, achieve progressively higher levels of functionality, the number of chips of a particular type to be produced will decline. To contain system life-cycle costs within budgets, fabrication technology must continue to advance. A promising concept in this direction is minifabrication, which allows low-volume production of specialized integrated circuits at much lower cost than current technology allows.

The equipment required to fabricate new device structures, including nanoscale electronic devices, will employ principles intimately connected with the concepts of the devices themselves. For example, microelectronic and photonic devices will be fabricated with equipment that uses electrons and photons (including x rays). The materials technologies and the fabrication equipment will merge into a fully integrated manufacturing process. Functional specifications at multiple levels—devices, circuits, and systems—will be expressed in automated design languages. The output from the design language will control automated manufacturing processes that produce an electronic component, circuit, or system that performs the specified functions. This trend will combine with the trend toward *in-situ manufacturing*, in which all fabrication steps are performed under high vacuum; the device is not removed from this clean, high-vacuum environment until it is finished. In-situ manufacturing results in higher-quality devices, as well as higher manufacturing yields than older production methods.

Disciplines Involved and Research Topics

In addition to the fields of electrical and electronic engineering, these trends in electronics will make use of solid-state physics, chemical physics, materials science, information science, and applied mathematics. Representative research topics that will support these trends include:

- multidomain sensor/processor networks based on optoelectronic components;
- multifunction, wideband digital radio-frequency communications;
- system design methodologies and languages;
- three-dimensional interconnect techniques for monolithic systems; and
- implementation of minifabrication concepts to lower cost for low-volume production.

RESEARCH TRENDS IN OPTICAL SENSING AND INFORMATION PROCESSING

Background

Two broad areas of research on optical phenomena are *optical sensing* and *photonics*. Optical sensing involves the conversion of electromagnetic radiation into a signal that conveys information about pertinent characteristics of the converted radiation. Photonics is the science and technology for using photons to process, store, or transmit information. Problems in optical sensing relate to the speed and detail with which information can be read from the electromagnetic radiation incident on the sensor. Much progress has been made in simultaneously sensing radiation at several wavelengths (e.g., radio frequency, infrared, and visible) and fusing the information from each of these sensor domains to gain more knowledge about the source of the radiation. In photonics, light is used as the digital signal medium for data, just as electron displacements are used as the signal-conveying medium in electronic data processing.

There are likely to be a number of trends in each of these areas continuing in directions established by past work and opening up new opportunities.

Future Directions

Optical Sensing

Integrated Sensors. Current technology for sensor data fusion converts the incident radiation for each sensor domain into a signal or information stream; these information streams are then fused into a multidomain image of the sensed object. Future multidomain sensors will have this information integrated as part of the radiation conversion operation.

Infrared Focal-Plane Arrays. Current technology for infrared focal-plane arrays uses one type of sensor element, which responds to one set of infrared wavelengths (single-color arrays). Future arrays will have multiple element types, each with its own spectral range (i.e., multispectral arrays).

New infrared sensors and arrays will be based on quantum-well photodetection, using semiconductors more tractable than mercury cadmium telluride (HgCdTe), including gallium arsenide (Corcoran, 1991). These arrays will operate at more convenient temperatures than those based on HgCdTe and will be integrated into monolithic chips (Figure 3-1). This technology will enable front-end focal-plane processing of images, which provides data reduction and fusion at the sensor. As a result, the quantity of data forwarded to system operators and command centers is reduced, while its information value increases.

Signal Processing and Imaging. Current work with feature-extraction algorithms will lead to smarter image-understanding algorithms. For example, automatic target recognition will advance beyond detection to target identification with the goal of no false alarms.

Optics will be used increasingly for the control and processing of microwave and millimeter-wave arrays. Optical signals, distributed to the individual elements of an array through optical fibers, will precisely control the amplitude and phase of the array. Received signals will be processed in the optical domain through wave-front processing techniques. For adaptive antennas, optical control systems will provide multiple-beam and null steering, which will greatly advance the capabilities for radar and communications signals that are jam-resistant, intercept-resistant, and have low probability of intercept. These concepts for adaptive antennas will be incorporated in communications networks (e.g., packet radio networks) to avoid signal collision and interference, thereby increasing the throughput and reliability of the network in the dense signal environment of the electronic battlefield. For

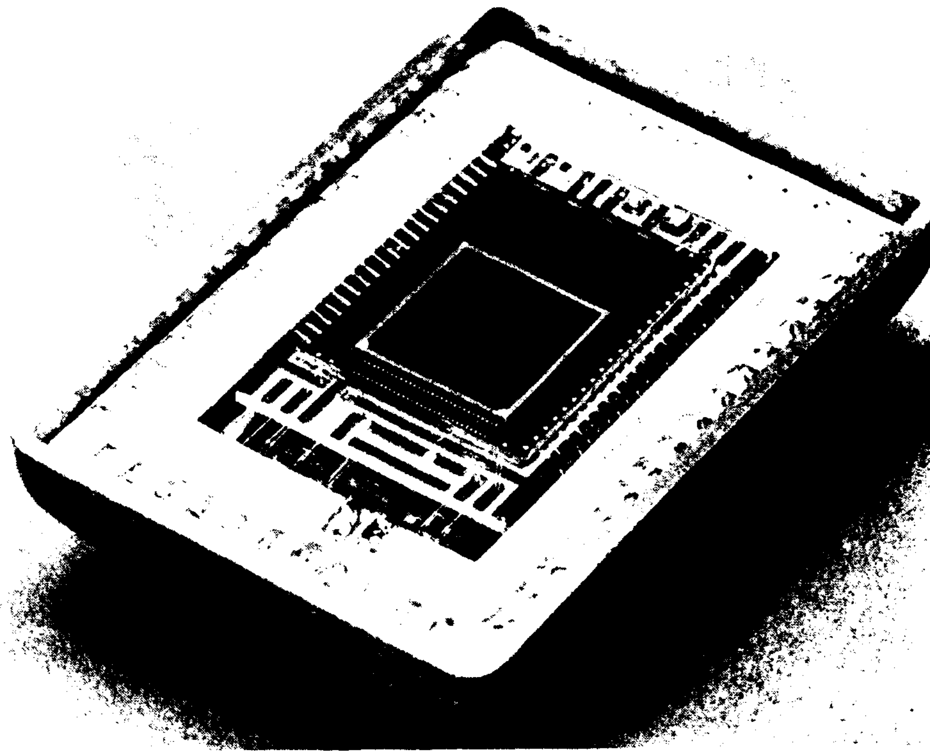

Figure 3-1 An integrated microcircuit (chip) for infrared detection with no special cooling. Future infrared focal-plane arrays will combine better detection, more sophisticated processing, and smaller device size. (Courtesy Texas Instruments Incorporated. Copyright © 1991 Texas Instruments Incorporated.)

example, these techniques can solve the problem of distinguishing near and far signals.

Photonics

The control of optical phenomena for data processing applications will provide faster, smaller, and less expensive ways to perform some functions now performed with electronic circuitry; it also presents entirely new possibilities. In the former category are such things as femtosecond devices (devices with state-switching times of 10^{-15} s or less) and improved clocks based on light frequencies. Diffractive optics and dynamic holography will provide new means of correcting for aberrations in coherent-light systems (lasers) and other applications for adaptive optics. Guided waves and optical switching will expand capacity and performance in communications and signal-processing applications. Photonic implementations of neural net concepts from information science may enable automation of algorithm development; one potential benefit of this automation could be reduced cost of software development for applications where neural nets can be employed.

In the category of new possibilities are control concepts that will use nonlinear media for harmonic generation, phase conjugation, and switching. Near-field effects such as optical and electron tunneling will find uses in microscopy and imaging. Squeezed quantum states of light will be used to reduce system noise.

New architectures for digital data processing will be based on optical interconnections, optical computing, and optical signal processing. Components for ultrafast data processing will rely heavily on integration of nanoscale electronic and optical devices (see Trend 3, above). These optoelectronic interfaces will permit the full utilization of the bandwidths achievable with fiber-optic technology. They also will allow implementation of novel parallel processing functions. In particular, lightwave components will be able to perform memory and data processing functions that now can be performed only by electronic devices. Furthermore, these functions will be performed at processing rates on the order of 10 gigabits per second of combined peak network capacity. (Single-fiber laboratory systems are operating in this range already.)

Optoelectronic interfaces also will allow video-rate data transfer at high definition under battlefield conditions. Video images will be transmittable in real time for subsequent processing, analysis, and decision-making. Command centers will be able to store libraries of images for both hostile and friendly platforms, missiles, and aircraft, permitting the real-time comparisons of target images required for target identification and fire control.

Eventually, optical devices will be introduced directly into microelectronic and nanoelectronic devices, including the monolithic and three-dimensional integrated circuits described in Trend 3. The performance of these devices will be controlled by optical and quantum interference phenomena. Computation will be based on the interactions of electrons with photons. Implementation of these quantum optoelectronic components may achieve the ultimate physical limits of performance, in terms of minimizing device size and maximizing bandwidth.

Combined Sensing and Information Processing Systems

Conventional signal processors are based on digital electronics. Future systems are likely to use analog systems such as optical processors that combine features of integrated sensors (see above) with photonics for data processing. The possibilities in combined sensing and information processing systems are just beginning to be explored through concepts such as the real-time optical pixel processor. The marriage of sensor integration concepts with the pattern recognition and high data-throughput capabilities of optical neural nets will result in "thinking" sensor systems that will handle such difficult situations as occluded targets (e.g., detection and identification despite camouflage or foliage clutter) and multiple high-velocity threats that would overwhelm slower automatic target recognition and fire-control systems.

Disciplines Involved and Research Topics

The disciplines important to research in optics and photonics include physics (including solid-state and chemical physics), information science, materials science, analog and digital signal engineering, and mathematics. Representative research topics include:

- development of uncooled infrared sensor elements;
- infrared imagery and optical processing for automatic target recognition and identification with a low rate of false alarms;
- recognition of occluded targets, using neural nets and other photonics;
- pixel-level optical signal processors;
- image compression to reduce the communications bottleneck associated with image transmission; and
- minifabrication of low-cost focal-plane arrays.

MAJOR TREND 4: CHEMICAL SYNTHESIS BY DESIGN

Background

Two of the major research trends described above will have revolutionary effects on chemistry: "Simulation and Visualization in Chemistry" (Trend 2) and the "Control of Nanoscale Processes" (Trend 3). This section describes the influence on chemistry of a third major trend, which could also be viewed as part of a still larger trend that encompasses materials science and biotechnology. (See Trends 6 and 9.) In the future, new materials will be designed at the molecular level for specific purposes by applying fundamental principles that relate structure to function.

In the chemical synthesis revolution that occurred early in the twentieth century, organic chemists developed methods to synthesize, in large quantity, compounds that were similar or identical to those found in nature. In the chemical revolution that will occur over the next 30 years, large molecules will be designed and manufactured with specified chemical and physical properties. These molecules may be proteins capable of detecting very low concentrations of a chemical or biological agent against almost any background. They may be surface catalysts capable of detoxifying a specific chemical pollutant. They may be enzymes capable of selectively destroying a new, resistant strain of the malarial parasite in the body. They may be materials with special thermal stability or adhesive characteristics. The common element will be that these new molecules will be designed to achieve their respective functions.

Future Directions

In the past, molecules with a desirable function were found by screening natural products, by exhaustive trial and error, or by accident. In less than 50 years, they will be designed and quickly manufactured in response to new needs or new threats. But this capability will first require some successes in learning the principles that relate structure to function. Among these are the chemical principles of heterogeneous and homogeneous catalysis, specific molecular recognition, and protein folding. A complementary area for further research is in methods for rapid, cost-efficient procedures to determine structure at high resolution. If all the needed developments occur, molecular systems that self-assemble from simpler components, and even replicate themselves, will be feasible within 30 years.

Three research areas are discussed below in more detail:

- principles of catalyst function and design;
- mechanisms of molecular recognition; and
- rapid, high-resolution structure determination.

Catalyst Function and Design

The two key functional attributes of a catalyst are specificity and rate acceleration. The research needed to relate these two attributes to atomic and molecular structure will use new techniques to study molecules adsorbed onto surfaces, such as femtosecond (and subfemtosecond) spectroscopy and scattering measurements. Other research areas are time-resolved structure determination of enzyme–substrate complexes, computer modeling of catalytic reactions (see "Simulation and Visualization in Chemistry," under Trend 2), and techniques to identify the rate-determining transition state for important reactions. The objective of this work will be to evolve a set of rules from which the catalytic properties of a structure can be predicted. These rules would become the basis for designing new catalysts. Most of the current work in design of catalysts for specific reactions is aimed at improving existing catalytic processes. A bolder style of research is needed, one that will attempt to design simple enzyme catalysts for oxidation–reduction reactions, metallic and organometallic surface catalysts, and polymers with catalytic properties.

For example, ester hydrolysis reactions often are used in preliminary studies of new organic compounds because they are easy to catalyze. It may be more productive to investigate more difficult reactions that would widen the range of application, such as specific amide hydrolysis or stereoselective hydroxylation and epoxidation.

The style of research that is needed can be illustrated by reference to an area of current interest: development of catalytic antibodies as catalysts-by-design. Although this work is important, and more should be done, there are limitations. First, the rate accelerations achieved so far are modest in comparison with natural enzymes. Second, no new principles have yet emerged. Third, the research done thus far may be missing a significant opportunity by failing to study those antibodies produced in the process that *do not* catalyze the reaction. Typically, fifty or more monoclonal antibodies are generated against an antigen that serves as an analogue for the presumed transition state in the catalytic reaction. Only two or three of these antibodies show any catalytic activity for the reaction, even though all fifty bind the analogue well. Studies of why the other antibodies have no catalytic activity are likely to provide insights into the requirements for efficient catalysis. Another line of research that has been neglected is the development of transition-state analogues for more chemical reactions, particularly oxidation–reduction reactions.

A similar line of reasoning argues for research on why thermophilic catalysts have almost no catalytic activity at temperatures of 20°C or less. Corresponding mesophilic enzymes are fully active. Whatever the thermophilic enzymes lack at this lower temperature range is essential for catalysis and therefore worth exploring.

Molecular Recognition

Molecules designed for specific functions must not only participate in a particular reaction but do so only with the desired reactants. Billions of years ago, nature evolved protein molecules that discriminate absolutely between otherwise similar molecules with phosphate, sulfate, and arsenate functional groups. Knowledge of the principles underlying this molecular recognition will allow chemists to design molecular sensors that can detect exceedingly low levels of a particular molecule, even in a chemical background of similar molecules. Simple molecular recognition systems are being studied already, but none yet have the exquisite sensitivity of their biological counterparts. Along with this current work, there is need for research that focuses on how biomolecules recognize their target substances. Particular research topics in this area are enzyme specificity, receptor specificity, and the mechanisms used by the immune system to develop specificity.

Although this area certainly overlaps with biomolecular engineering and other biotechnologies, it is not constrained to biological systems; its aim should be to discover fundamental chemical principles that will apply to molecules of any type.

Rapid, High-Resolution Determination of Structure

A valuable capability in the future will be to determine the mode of action of a newly encountered chemical or biological agent without exposing human or animal test subjects to it. One approach to predicting how a new agent will act is to determine its structure, then apply the principles relating structure to function (assuming these are known). For this purpose, and also for use in investigating the principles, methods are needed to determine, rapidly and at high resolution, the structures of surfaces, three-dimensional biomolecules such as proteins and nucleic acids, and other complex molecules. Research topics in this area include new ways to crystallize membrane proteins, improved methods of crystal structure determination, and time-resolved techniques for x-ray diffraction and nuclear magnetic resonance. The effect of extreme temperature and pressure on molecular structure is another important area in which little work is now being done.

For simple organic molecules, it is already possible to calculate a structure from a chemical formula and bonding patterns. Work is needed to extend this capability to complex molecules, such as proteins and ribonucleic acids, and inorganic or organometallic systems.

Disciplines Involved and Research Topics

Among the disciplines that will contribute to the design of specialized molecules are chemical kinetics, physical chemistry, chemical physics, biochemistry, physical organic chemistry, molecular biology, and biotechnology. Other areas of chemical research, such as photochemistry, electrochemistry, and synthetic organic chemistry also will have major impacts on this research trend. If a new revolution in chemical synthesis has indeed begun, every area of chemistry will be transformed, and every area will contribute. As described in Trend 2, computer-based tools and the disciplines to develop them will affect progress in this area.

Many prospective research topics were mentioned in the discussion of future trends. A few representative examples are listed below:

- analytical tools, such as femtosecond spectroscopy, to follow catalyst–reactant interactions;
- transition states and catalysis in less-studied organic reactions (e.g., specific amide hydrolysis and stereoselective reactions);
- investigation of properties essential to catalysis by study of "catalysts that fail," such as antibodies to transition-state analogues that *do not* show catalytic activity or catalysts that lose activity in specific regions of temperature or pressure;
- studies in fundamental principles of molecular recognition underlying enzyme specificity, receptor specificity, and the mechanisms by which the immune system creates antigen-specific antibodies;
- rapid techniques to determine three-dimensional structure at the atomic scale; and
- structure prediction for large, complex systems from their chemical formulas and bonding patterns.

MAJOR TREND 5: DESIGN TECHNOLOGY FOR COMPLEX HETEROGENEOUS SYSTEMS

Background

A complex heterogeneous system is constituted from many components and subsystems, which often vary markedly in physical and operational characteristics but must interact as a coherent whole. Successful design of such systems has proved to be far more difficult than the analysis of a system after it exists. Although easily stated, the fundamental difficulty is not readily overcome.

In analysis, the system is given; something is there to take apart, figuratively or literally. In design, the system does not yet exist. The available mathematical tools for design, such as optimization theory, require the designer to first guess at what the system-to-be-designed might be. Then the mathematics can be used to analyze and evaluate that guess. In effect, the system must already exist—at least in terms of the specifications required for the analysis—before the design tools become useful. There are three problems, at least, with this approach.

First, it is slow. The approach implies multiple iterations of design hypothesis and test. The designer must construct each design hypothesis in enough detail to make the analytical tools applicable. The task of constructing and revising the hypothesis is lightened when hypotheses are similar to existing systems or to previous hypotheses that have already been tested. The task becomes more difficult as the designer reaches toward novel design concepts.

Second, the analytical results from one hypothesis may contribute little or nothing to improving the results of the next hypothesis. Consider each design hypothesis as a point in an abstract space of all possible designs for the system. If the system's behavior is nonlinear with respect to one or more dimensions of this space along which hypotheses are being refined, no information may carry over from one test point to another.

The third problem could be called a many-body problem (although it is totally unrelated to the many-body problems of classical dynamics or quantum mechanics). The design of complex heterogeneous systems is, by necessity, the work of many persons. Increasingly, these designers work concurrently, with intermittent phases of integration and design subordination. If the system is designed by a process of successive modifications, as is now done, and if each modifier works in relative isolation from what other modifiers are doing, the cumulative effects of their modifications are not, in the strict sense, designed. In principle—and increasingly in practice—the system may never move toward an optimal design or even toward a functional, though suboptimal, version that can be put into production.

Future Directions

Another approach or multiple approaches must be developed. The mathematics of design now in existence is optimization theory, in which a baseline system is first modeled, then varied to try to improve it, with each variation being analyzed for its performance relative to the baseline on specific assessment criteria. This basic approach has been improved by refinements that attempt to identify key relations or parameters that must hold for any system-solution to be successful. These constraints limit the range of alternatives and options to be tested.

Functional Principles of a Design Technology

Some principles are beginning to emerge as important for the design of complex heterogeneous systems. These principles do not in themselves constitute a design technology; rather, they can be used as criteria to test the functional adequacy of any such technology.

One such principle is to design the components of a system for *robustness with respect to variation*. That is, if the system environment of a component changes, the component continues to behave in the expected way. This robustness helps not only with respect to reliability of the component in operation but also in predictability of its performance from a design perspective.

Our best current approaches to designing for robustness with respect to variation in the operating environment employ isolation, or *modularity*, of components. The challenge is to find other approaches to robustness in addition to isolation through modularity.

Statistical approaches to designing for robustness are one promising area of research. The basic idea is to use a statistical measure of sensitivity to identify the least-sensitive solution from among the possible solutions. For example, Taguchi has applied relatively simple statistical methods to a set of variations, to find the system configuration that is least sensitive to operational variation (Ealey, 1988). But a rigorous mathematical basis has yet to be established for the heuristic approaches in use. In concept, nothing would prevent the adaptation of the principles underlying the Taguchi methods to a more sophisticated statistical implementation.

One caveat here is that statistical measures of sensitivity probably assume linear behavior over the operating range; this possibility is one reason why a rigorous mathematical basis for these measures should be explored. For dynamic systems that are likely to behave nonlinearly, designing for robustness may mean devising methods of locating "islands of stability" in the response space of the system's components and subsystems.

Another functional principle to be incorporated in design technology is the *cost–benefit trade-off for design information*. A balance must be achieved between the marginal value of additional design information and the marginal cost of getting it. When a complex system is analyzed, information is typically gathered only on those aspects important to the analyst. In designing a complex system, ideally one wants only the information necessary to make appropriate design choices. Obvious as this principle may seem, it is difficult to practice, given our present approaches to designing complex systems.

For example, optimization theory does not address this pragmatic cost–benefit balance. The theory assumes that successive trials of approximations to the best result will be made until the optimum solution is well established. However, the *practice* for complex systems has been to run optimization tests on a set of alternatives that is far smaller than the theory calls for.

This problem is further exacerbated when the design process involves multiple designers making independent design decisions. Each designer may optimize components or subsystems on unrelated sets of limited variations, which do not even share boundary conditions. These diverse, independent decisions become an important aspect of the relations between process and outcome, often with disastrous effects for an optimal outcome *in practice*.

Modeling the Design Process

Current modeling methods are applied to the *system* being designed. A further, and complementary, step would be to model the *design process* itself. Complex heterogeneous systems may be particularly amenable to such treatment, for there are likely to be multiple possibilities for a successful system design.

If all the possible outcomes of a design process are arrayed in a "design outcome space," interesting questions can be posed, such as the clustering behavior of successful designs. If the outcome space contains multiple regions of successful system solutions, then a mathematical treatment of the relation between design process and product may be more fruitful than attempts to model the system in isolation from the design process.

Under the classical assumptions of linear variation, the successful solutions to a design process should cluster in a few regions and exhibit smooth gradients toward the locally optimal solution within each region. If, however, the relation between design process and system outcome more closely resembles the chaotic behavior of nonlinear dynamic systems, the classical view of how to optimize system design may be counterproductive. Small differences in the input conditions may result in large differences in the best way to achieve a successful design. These small input differences may include:

- the relative value placed on different factors;
- what environment the system is expected to perform in;
- what the designers want the system to do; or
- what efficiencies or other performance features are assumed for its components.

At present no formal way exists to take these patterns of design behavior into account. Even in practice, they are not taken into account very well. The tendency is to design by habit. Designers reuse their design approaches that have worked well. But if the space of potential good solutions to a design problem is nonlinear, this gradualist approach to design may produce chaotic results. Repeating past approaches in new situations may turn out to be a poor design approach. Similarly, if the current optimization theory is applied within a design process with nonlinear response characteristics, seemingly erratic outcomes may result.

The idea of modeling the design process to achieve a rational system outcome may seem far-fetched at first glance. Yet industrial design technology has come to accept the idea, inherent in the field of concurrent engineering, that the manufacturing process and the manufactured product are interwoven. This concept is particularly apt for the manufacture of complex products such as automobiles, computers, software, and military systems. The possible design technology suggested here assumes that the design process and the design product are similarly interwoven. On this view, a design technology for a complex system will require a formal mathematical structure that exploits rather than ignores the relation between process and product.

Furthermore, although the actual outcome of a system design process remains largely unknown through much of the process, *the process itself exists*. Therefore, characterizing and guiding the process may be a more practical approach to increasing the likelihood of successful systems than attempting to model the outcome.

Linear Control Modes in Systems That Exhibit Nonlinear Behavior

Most complex modern systems are heterogeneous in the sense that they contain a sophisticated information processing subsystem (a computer or at least a microprocessor chip) in addition to their physical subsystems, which may be mechanical, electrical, and in the future, biological. Although the role of the information subsystem is to control the activity of the other subsystems, the modes of control are still largely mechanical, electrical, or chemical analogues of partial differential equations.

These control modes are relied upon not because they are the most efficient but because they are well understood. While the larger system continues to operate within a regime for which the control mechanism's linear response is adequate, the system operates "normally." More precisely, the range of operation must remain within the bounds where the partial differential equation model has solutions that are realizable by the physical control mechanism. However, if the range of possible behavior for a complex heterogeneous system exhibits nonlinear behavior, the controls may, depending on particular circumstances, fail to control the response range of the system. Or, in other circumstances, the controls may unnecessarily constrain the dynamic range of the system.

As our knowledge of nonlinear dynamics increases, that knowledge can, in principle, be programmed into the information subsystem of these complex systems. But the modes of control may also need to show matching, or suitably complementary, nonlinear behavior. Therefore, modes of control that do not fit the classical paradigms will be needed.

As an example, nonlinear systems may nevertheless be well behaved, in the sense that their actual outcomes fall within a bounded region of the possible outcome space. This region is known as the *strange attractor* for the system. While classical control modes work by determining the path along which action proceeds, the strange attractor of a nonlinear system can be used to constrain the response range independent of the path taken to achieve the response.

Disciplines Involved and Research Topics

Disciplines that can contribute to design technology for complex heterogeneous systems include computer science, information science, mathematics (statistics, nonlinear dynamics, and emerging areas such as catastrophe theory), and behavioral science. Pragmatic principles for this design technology could emerge empirically from design efforts in fields as diverse as computer system integration, software development, aeronautics, electronics design, manufacturing engineering for any type of complex system, management of inner-city education, or civil engineering (e.g., urban/suburban infrastructure rebuilding).

Research topics that would contribute to this design technology include:

- alternatives to modularity for robustness of components or subsystems with respect to variation in (1) other elements of the system or (2) elements of the nonsystem environment, particularly for systems or components that display nonlinear dynamic behavior;
- mathematical foundations for statistical measures of sensitivity to system variation (e.g., Taguchi methods);
- theory and techniques for modeling development or process outcomes as a function of designer/design-team behaviors; and
- control mechanisms that support the full dynamic range of nonlinear behavior while preserving system integrity and functionality.

4

Engineering Sciences

MAJOR TREND 6: MATERIALS DESIGN THROUGH COMPUTATIONAL PHYSICS AND CHEMISTRY

Background

Army technology historically has made extensive use of advances in new materials for structural purposes, explosives, and shielding. Underlying the continued evolution of such areas as composites, polymers, and high-energy compounds is the rapidly advancing scientific discipline of computational physicochemistry. This field is directed toward understanding and designing new materials by focusing on the underlying physics and chemistry of those factors that determine the properties of materials and modeling them with the aid of computers.

Over the next several decades, the ability to predict in detail the collective effect of atomic interactions on macroscopic properties of materials will revolutionize the way materials scientists design and tailor advanced materials. A recent publication from the National Materials Advisory Board (NRC, 1988) provides an authoritative and optimistic view of these expected benefits. Supercomputers and the advanced algorithms that run on them will enable scientists to design improved materials and predict their behavior under a variety of environmental and manufacturing conditions. The foundation for these superior computational algorithms will be an improved understanding, through basic research, of atomic forces, phase stability, and other physical and chemical properties. Without a proper grounding in the underlying physics and chemistry of materials, which will require continued basic research, computational techniques will be unable to fill these predictive roles and could even be misleading.

Future Directions

The combination of increasing sophistication in sensors with explosive growth in computational power will make possible a deeper level of understanding of how a given process, either physical or chemical, gives rise to a final material. New insight into processes is already evident in some areas of metal composites, liquid crystal polymers, and chemical synthesis; it should become the norm in the future. This new knowledge offers radically new possibilities for circumventing the trial-and-error process by allowing a more scientifically based predictive methodology that is rationally designed.

The potential for computational physicochemistry can be illustrated from the current state of the art in developing lightweight intermetallic alloys that can replace steel but have half its density. A major obstacle has been that many of the known intermetallics exhibit low ductility. Their noncubic crystal structure does not allow adequate slip and elongation. Alloying agents must be found that will convert these undesirable structures to a more desirable form. Empirical testing of the intermetallic Al_3Ti found that small (approximately 5 percent) additions of copper transform its undesirable DO_{22} crystal structure to a more desirable $L1_2$ structure (Figure 4-1). Subsequently, *a posteriori* electronic structure calculations provided an explanation from first principles of the transformation (Eberhart et al., 1990). From this starting point, it may prove possible in the future to perform calculations for hypothetical alloy systems before they are created and tested empirically. This computational approach could shorten the time it takes to produce custom-designed materials to meet specific Army requirements, such as the need for lighter-weight structures.

The ability to better describe and predict the nature of atomic interactions in solids, gases, and liquids will invariably lead to many advances in materials science and technology. Among these developments, the following may be particularly relevant to the Army:

- improved, lightweight intermetallics to replace steel at one-half its density;
- marked improvement in the ability to predict long-term macroscopic properties, through accurate computer modeling of "lifetime behavior";
- new energetic molecules superior to RDX (cyclotrimethylene trinitramine) or cubanes, for example, in energy density and safety;
- improved superconductor materials; and
- polymers having temperature capabilities in the 500°C range, and thus capable of directly replacing some metals in warm/hot applications.

Disciplines Involved and Research Topics

Computational physicochemistry will be applicable in the fields of ceramics, metallurgy, energetic materials, polymer science and technology, corrosion research, and superconductors. The algorithms themselves will be developed from work in solid-state physics, chemical physics, quantum chemistry, and other areas of basic science. On the theoretical side, condensed-matter physics (for materials) or physical chemistry (polymers,

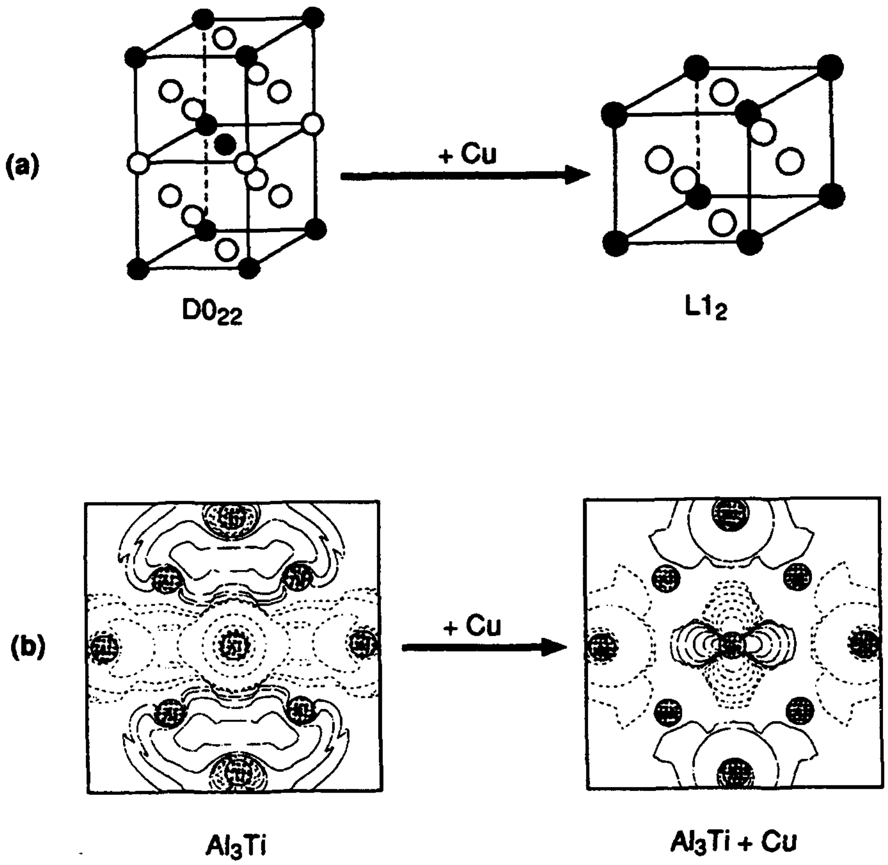

FIGURE 4-1 Structural change (a) to aluminum titanium alloy from addition of copper can be explained from electron density maps (b) derived from fundamental principles. Adapted from Eberhart et al., 1990.

energetic materials) must be coupled to advances in scientific computing and in the general understanding of nonlinear processes.

Among the many potential research areas for computational physics, the following would have long-term implications significant to the Army:

- lightweight (half the density of steel) ductile intermetallics;
- impact-resistant ceramics and ceramic composites;
- new energetic materials superior to RDX or cubanes in energy density and safety;
- materials harder than diamond;
- fracture mechanics at the atomic level;
- advanced nonlinear optical materials;
- improved superconductor materials; and
- polymers with working temperatures extending to 500°C, and thus capable of replacing some metals in warm/hot applications.

Perhaps the most crucial need is for the application of high-resolution measurement techniques, which could reveal the detailed evolution of a system during processing. Only with this type of information can cause and effect for the final product be understood.

MAJOR TREND 7: USE OF HYBRID MATERIALS

Background

Hybrid materials encompass a broad range of composite material forms and uses. There are currently four main categories of hybrid materials:

- selectively reinforced materials;
- thermally managed materials;
- smart structures; and
- ultralightweight composites.

Materials in all four categories possess unique qualities and are potentially applicable for future Army weapon systems and other uses. They can be optimized to meet unique and specific requirements, which makes them especially attractive as candidates for the Army's special needs.

The technology associated with hybrid materials is still in an embryonic stage and remains constrained by a lack of awareness of the potential benefits available from hybrids of dissimilar materials. The existing trends emphasize the use of hybrid materials as structural composites. Although this area of application undoubtedly will grow, their greatest potential lies in other areas, because of the range of unique characteristics they enable.

Future Directions

Hybrid materials can be devised not just to improve one property, such as the high strength-to-weight ratio of fiber-reinforced composites, but to excel in two or more quite different functions. For example, a tank needs both armor and stealth. The conventional approach is to apply a radar-absorbing coating over the armor. If a hybrid material is used instead, a radar-absorbing phase is distributed throughout the thickness of the ceramic armor phase. The result is more effective absorption of the radiation because of the greater distance over which the absorbing material is distributed. Some current or planned ceramic armor materials are hybrids; one or more phases of these hybrids might conceivably be optimized for radar absorption without degrading the hybrid's effectiveness as armor.

Materials with adjustable optical properties can also be achieved with a hybrid design. Prototypes of a window with adjustable color and absorptivity already exist. An ion-conducting layer in the multilayer hybrid permits variable ion migration in response to an electric field applied across the structure. As the ion populations change, the light transmission and absorption at different wavelengths changes, which causes the color of the window to change. In current materials, the color transition is slow (tens of seconds). By improving the design and processing of multilayer materials, the response time can be shortened while the spectral range of the color change is increased. Using this technology, a vehicle might be able to change its electromagnetic signature at will.

In the future, hybrid materials will offer substantial performance enhancement to the emerging area of *smart structures*. Smart structures are characterized by the ability to sense and respond to stimuli in a predetermined manner and in an appropriate time. This ability is achieved through a coherent integration of a hybrid material, consisting of a structural medium in which a network of sensors and actuators are embedded, with computational capabilities and real-time control from a microprocessor (Figure 4-2). The complete smart structure can be thought of as analogous to an animal body. The network of sensors provides a "nervous system" to monitor and communicate with the external stimuli. The network of actuators provides the muscle to change the structure physically. The structural medium of the hybrid provides the skeleton. The microprocessor-based computational capabilities furnish the brains to ensure the optimal performance of the overall system.

The analogy to an animal's nervous system can be used to explain the difference between *smart skins* and *smart structures*. Smart structures use

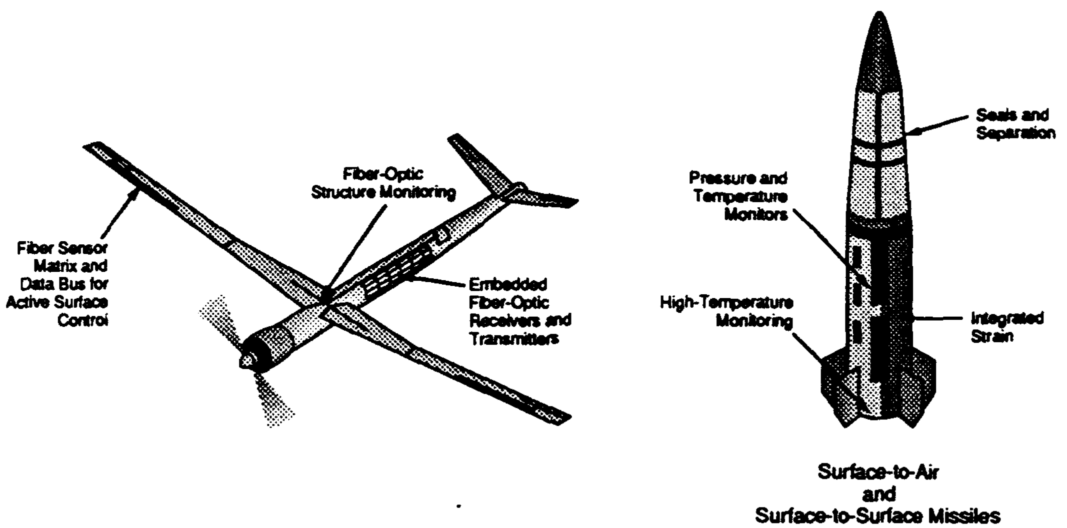

FIGURE 4-2 Concepts for embedded sensors in "smart" materials.

embedded sensors and actuators to monitor and respond to the condition of the material itself, analogous to the role of kinesthetic sensors and skeletal muscle actuators in animal physiology. Smart skins use sensors to detect and interpret a signal (e.g., part of the electromagnetic spectrum or acoustic waves) that contains information about external objects, similar to the role of an animal's distance senses of vision and hearing. Smart skins need not be simply passive sensors; their use in a synthetic-aperture radar system would be analogous to a bat's echo-location system. In Figure 4-2, the conceptual unmanned air vehicle includes both types of smart materials.

Hybrid materials are inherently heterogeneous and tailorable; they can contain embedded sensors and actuators that are small enough to preclude a negative effect on the mechanical properties of the structure while enhancing the overall performance. The variety of combinations allowed by hybrid materials is such that many structural materials will be readily employable as the medium in which sensors and actuators are embedded.

Successful development of smart structures through hybrid materials technology will combine with the trends in nanoscale engineering and molecular design (see Trends 3, 4, 9, and 10) to enable the design and production of the next generation of materials. These *smart materials* will contain embedded sensors, actuators, and processing units integrated in their microstructure. The microstructure will be engineered at a molecular or atomic level using the innovative synthesis and processing techniques based on such principles as self-assembly, molecular recognition, and signal-transduction biomimicry.

Disciplines Involved and Research Topics

Areas of materials science important to progress in hybrid materials will encompass ceramics, metals, polymers, and their composites. Sensor technology for smart structures will use advances in electronics and optics. Prospective areas of research with potential Army applications include:

- ceramic-based materials that are radar-absorbing, for use in stealthy ceramic armor;
- smart skins, in which entire surfaces of an airborne or ground vehicle contain embedded sensors;
- adaptive clothing for countermunition control (to protect soldiers from directed-energy weapons, blast radiation, and chemical agents, as well as the ballistic protection of today's bulletproof vests);
- coatings with adjustable color and emissivity capabilities for chameleon surfaces and other means of signature control over a wide spectral range; and
- electrostrictive materials for active cancellation (e.g., to control vibration and noise in rotorcraft).

MAJOR TREND 8: ADVANCED MANUFACTURING AND PROCESSING

Background

Advances in materials and in processing have a symbiotic relationship. As discussed in previous sections, advanced materials increasingly will involve hybrid materials and fine-scale structures (at scales extending down to individual atoms). The manufacture of these materials presents challenges to processing. At the same time, new and improved processing techniques will enable production of materials that could not be manufactured by present techniques.

This area is, of course, already an active subject of R&D. However, the chemical and structural complexity of new materials typically requires a demanding range of microscale and rapid processing techniques. The challenges and opportunities will keep advanced-materials processing a frontier area for decades to come.

Future Directions

Fine-scale materials have structural features in the submicron to nanometer range. In some areas, such as ceramics, these materials offer major improvements in average properties and in reliability. Examples of properties influenced by fine-scale structures include flux pinning in superconductors; modifications in ferroelectric behavior, electronic transport, and localized states; and superplastic behavior.

Materials with a layered structure offer new ranges of properties (e.g., the supermodulus effect). They also offer the possibility of combining desirable properties not achievable in a single material.

Advanced processing techniques for these materials are in various stages of development. Thin-film deposition techniques continue to advance. Examples include the chemical vapor deposition of multicomponent materials or the innovative techniques that may allow the growth of smooth, large-area diamond films on a copper substrate. Techniques of pulsed electrochemical deposition allow the electrodeposition of alloys that cannot be deposited by conventional, direct-current techniques.

Novel routes for chemical synthesis offer other possibilities for tailoring microstructures, as well as larger-scale structures. The sol-gel approach allows preparation of microprocess materials down to fine scale. Variations on this technique open possibilities for assembling composite materials whose phases have a far finer grain size than existing composites.

Laser processing permits changes in physical state (i.e., melting and solidification) or limited chemical reactions in a processing regime that combines high temperatures with short process times. This regime will permit production of new materials that form only under nonequilibrium conditions.

An exciting possibility is biomimetic processing. Plants and animals use self-regulating natural processes to produce fine-scale and complex structures of amazing variety. In many cases, a hierarchy of structures is produced. The human brain is perhaps the ultimate example of a complex structure produced by a self-regulating chemical process. On a far less ambitious scale, it may be possible to use techniques adapted from biochemistry and biophysics to produce desirable, controlled, fine-scale structures and hierarchies of structures by self-regulated assembly.

Combining several technologies could lead to the development of microstructural materials processing that is "intelligent," or cybernetic, in the sense of being feedback-controlled. Microscale sensors could permit the monitoring of composition and crystal structure locally during processing. To optimize desirable holistic properties derived from microscale structures, computer-aided manufacturing can use highly focused energy sources such as lasers or electron beams to create microstructures in accordance with a computer-generated pattern. The precision and control achievable with these processing techniques can enhance the reliability of operating devices (e.g., microelectronic components and integrated circuits) and structural materials, wherever their reliability depends on strict adherence to complex patterns of microstructure.

Disciplines Involved and Research Topics

Like the closely allied trend in bioengineering, advanced manufacturing will require multidisciplinary teams of experts from across the spectrum of basic science. The disciplines needed to realize these potential advances in manufacturing include those related to the study of the materials (e.g., materials science, solid-state physics, chemical physics, and biophysics) and those related to the processes by which the materials will be produced (for example, optics and laser technology, computer-aided design and manufacturing, artificial intelligence and robotics, biochemistry and molecular biology, chemical–beam and vapor–solid interface reaction kinetics)

The following selection of research areas is merely representative and far from comprehensive:

- in situ processing, including ceramics and intermetallics;
- biomimetrics, including self-assembly and hierarchical assembly;
- nanostructures (see also "Trend 3: Control of Nanoscale Processes"), including Langmuir-Blodgett phenomena and superplasticity;
- intelligent processing, including in-situ diagnostics, processing properties, and interaction and control (see also the discussion of passive/active sensor combinations in smart materials, under "Trend 7: Use of Hybrid Materials"); and
- chemical synthesis of specialty materials, including diamond and boron nitride films, alloys produced by pulsed electrochemical processing, and membranes for chemical separation.

RESEARCH TRENDS IN AEROMECHANICS

This section presents three research trends in aeromechanics that have important implications for the Army's airborne systems and for projectile design. The first trend, "Aerostructural Simulation," is another manifestation of the multidisciplinary trend toward greater reliance on computer simulation and visualization. (See Trend 2 in Chapter 2.) The second, "Advanced

Hypervelocity Weapons," focuses on the effects of the atmosphere on high-velocity projectiles. The significance of the third trend, "Aerodynamics at Low Reynolds Numbers for UAV Development," stems from the forecasts made by several other STAR panels for major opportunities in deployment of unmanned air vehicles (UAVs). [See the Airborne Systems Panel Report (NRC, undated a), Special Technologies and Systems Panel Report (NRC, undated b), and Part II: "Computer Science, Artificial Intelligence, and Robotics" of this volume.]

Aerostructural Simulation

Background

Advances in rotorcraft vehicles require interdisciplinary capabilities in analysis and design from the fields of aerodynamics, structural mechanics, structural dynamics, and materials science for modern composites. To achieve the advances required for future Army air mobility systems, all these aspects of design and analysis must be concurrently and interactively engineered. This ability to simulate the complete rotorcraft configuration in its operating environment is needed to reduce risk, time, and expense in new rotorcraft development.

Future Directions

The simultaneous design analysis of a rotorcraft vehicle and its operating environment will become possible through the use of massively parallel or connective-type computer architectures, numerical solution strategies optimized for these alternative computing architectures, and algorithms that incorporate new knowledge of the dynamics of candidate composite materials. New concepts for rotorcraft components embrace the extensive use of smart structures, which autonomously respond to loading or operating regimes. By providing autonomous monitoring of vehicle "health," as well as vehicle control, these structures will make available new operating regimes and will significantly increase maneuverability.

Advances in computational fluid dynamics, composite structural dynamics, and aeroelasticity will contribute to the goal of complete aerostructural simulation. From these advances, new techniques for vibration control, noise reduction, structural optimization, and flight control will certainly ensue. The analysis and design methodology developed for rotorcraft applications will provide the tools needed for entirely new vehicles that are not feasible with today's technology. Study of the methodology will contribute to the more general problem of designing complex heterogeneous systems.

Thus, aerostructural simulation for future Army rotorcraft is an expression of a number of other trends discussed in this report. It is a particularly important avenue for Army participation in these trends.

Disciplines Involved and Research Topics

The disciplines involved in aerostructural simulation include high-performance scientific computing, alternative computational paradigms, aerodynamics, computational fluid dynamics, structural dynamics, and all the fields underlying advances in smart hybrid materials. Research topics of particular importance to aerostructural simulation include:

- aerodynamic and structural coupling studies for rotorcraft designs; and
- composite materials optimally tailored for aerodynamic loading, vehicle "health" monitoring and load control, and reduction of noise and vibration.

Advanced Hypervelocity Weapons

Background

The trend for Army munitions has always been toward increased velocity, which shortens flight time, increases accuracy, and causes greater energy transfer—for penetration and destruction—from the vehicle (projectile or missile) to the target. Hypervelocity weapons, those whose projectile velocity achieves Mach numbers exceeding 5 or 6, are the platforms of choice to increase the lethality of Army weapons for both tactical and strategic applications. This push toward hypervelocity demands more attention to (1) the survivability of the vehicle during flight through the atmosphere, (2) its mission performance upon reaching the target, and (3) the radiation characteristics (signatures) of potential targets in the hypersonic regime.

A crucial feature of the missions to be performed by hypervelocity tactical projectiles or missiles is that their operating regime generally is entirely within the lower atmosphere. The vehicle is therefore subject to high thermal and friction loads. Because the kill mechanism operates by transfer of kinetic energy, the phenomena of hypervelocity impact and the performance of high-strain-rate materials are important considerations.

Future Directions

A better understanding is needed of the flow physics of projectiles that have a large ratio of length to diameter and are launched from ground level at hypersonic velocities. This knowledge will contribute to the design of missiles with greater stability and accuracy. Improved prediction and control of flight trajectories will increase maneuverability and enlarge the tolerance for evasive maneuver by the target.

Increased knowledge of the phenomena associated with the impact and penetration of hypervelocity projectiles against anticipated targets can improve weapon system lethality and reduce the inventory required to ensure battlefield dominance. Greater understanding of mid-altitude (50–75 km) fluid dynamics and vehicle radiation characteristics at hypersonic velocities may provide unique target signatures, thereby increasing the probability of target kill.

In short, scientific progress in aerodynamics can make significant contributions to missiles and projectiles of the future. These scientific developments are obviously relevant to the design and development of future ground-to-air interceptors and antiarmor rounds.

Disciplines Involved and Research Topics

The underlying sciences are aerodynamics, aerothermodynamics, radiation physics, terminal ballistics, and flight control. Important scientific ingredients for progress in this field include:

- basic research in hypersonic aerodynamics at high Reynolds numbers;
- aerodynamic interference flows;
- thermal degradation of skins and optical windows;
- non-equilibrium flow physics;
- radiation from the plume and from air heated by the bow shock; and
- heat transfer.

Aerodynamics at Low Reynolds Number for UAV Development

Background

The Airborne Systems Panel foresees a large increase in the use of UAVs. The anticipated microminiaturization of sensors and computers and the vulnerability of manned aircraft to small accurate missiles will cause the transfer of many manned aircraft missions to small UAVs. Their size may range from that of small manned aircraft, as in the high-altitude, long-endurance UAV concept, to vehicles the size of a songbird, for low-altitude reconnaissance, intelligence, surveillance, and target acquisition functions.

Either the low air density of the high-altitude mission or the small chords of the wings and tails on the small UAVs will result in airfoil and propeller operation at Reynolds numbers well below the region for which adequate aeronautical data exist. Data on lift, drag, and control at low Reynolds number must be obtained for design of UAV configurations with the best possible performance and maneuverability characteristics.

Future Directions

The research program on low-Reynolds-number aerodynamics that was recently sponsored by the Office of Naval Research has done much to develop valuable understanding of methods and results for this aerodynamics regime. Much remains to be done, however, to develop the data base needed for development of optimum UAV airframes. Even though UAV development is critically dependent on other technologies such as sensor development, data processing, and miniaturized propulsion devices, vehicles with minimum drag and maximum maneuverability are essential. For these vehicle performance characteristics, our understanding of aerodynamics at low Reynolds numbers must be as complete as possible. Propulsion and propeller efficiency also will be affected by low-Reynolds-number aerodynamics.

The required research on low-Reynolds-number aerodynamics falls under the charter of NASA's research functions. The Army should continually monitor research progress in this area. If necessary, it should formally request NASA to acquire (1) a theoretical capability for the computational fluid dynamics required and (2) an experimental data base adequate for the aerodynamic design of air vehicles operating at low Reynolds numbers.

These UAVs will provide a major capability to the Army. The timely provision of the necessary analytical design tools for UAVs is essential.

Disciplines Involved and Research Topics

The disciplines of computational fluid dynamics and aerodynamics will be involved in this research. Wind-tunnel studies will provide experimental validation and testing for the computational models. Representative topics for research include:

- computational and experimental data for Reynolds numbers less than 100,000; and
- the use of this theoretical and experimental data base to model performance and maneuverability, with particular attention to performance constraints such as stall speeds and limits on angle of attack.

5

Life Sciences

MAJOR TREND 9: EXPLOITING RELATIONS BETWEEN BIOMOLECULAR STRUCTURE AND FUNCTION

Background

Understanding the relation between the structure of a biological molecule and its function in the biological system that uses it has always been the province of the molecular biosciences. For decades, the first principles that relate structure to function have been sought by observation, experimentation, and theory. Today, these principles are coming to light with increasing rapidity, as advances in the techniques and instruments of experimental molecular bioscience are combined with advances in computational methods of analyzing data and exploring theoretical posits.

These governing principles can provide entirely new approaches to the design of materials from the molecular level up. They will open up new approaches to the mission-oriented design of structural components, sensors, medical prophylaxis and therapy, and smart (i.e., environment-responsive and self-regulating) systems of all kinds. Because many of these principles enable functions to be performed with molecular-scale structures, the scale of fully functioning components and systems can be decreased significantly. At the same time, the potency and efficiency of biomolecular processes imply that application of their governing principles could greatly enhance performance over current state of the art.

In a sense, the continuing progress of the molecular biosciences will enable tomorrow's materials scientists and process engineers to "go to school on nature" at a molecular level without precedent.

Future Directions

Elucidation of the mechanisms and rules by which biological macromolecules function, fold, and interact with other biological structures to self-assemble into higher-order architectures will provide a fundamental understanding of these processes. Furthermore, this understanding can be applied to designing and producing new classes of advanced materials and structures, which will use these macromolecules—or analogues based on the same principles—as intrinsic components. The ability to understand and predict the complex interaction of forces that govern the structure of a biomolecule and enable its function will allow scientist-engineers to design entirely new complex molecules or adapt existing ones to new purposes.

This ability to design the molecules of new materials and new processes will affect all areas of warfare, from smart weapons and high-performance materials to combat-readiness of soldiers and improved versions of basic consumables such as fuel, lubricants, and potable water.

New battle gear will lighten the soldier's load, as canvas, leather, plastic, and rubber are replaced by lighter and stronger clothing and equipment fabric that is also better-suited to a particular purpose. Soldiers in the field will be able to produce potable water from streams, still-water bodies, or even from the humidity in the air.

Broad-spectrum vaccines and prophylactic medicines will reduce the health risks of rapid deployment into areas with endemic diseases. Molecular-level sensors will detect hazardous chemical or biological molecules in the field at concentrations undetectable by today's best laboratory instruments. In-field diagnostics will indicate proper methods for countering these hazards, based on analysis of the mechanism by which they exert their toxicity.

Biomolecular functions include energy transduction mechanisms. These can be employed in the development of micromotors to power instrumentation and sensors. They can also provide the basis for the micropower supplies needed to sustain the operation of bioelectrical, bio-optical, and biomechanical systems, which will depend on the physicochemical coupling between the biological and nonbiological components of these systems.

Disciplines Involved and Research Topics

In addition to biological sciences (including biophysics, biomedical science, molecular biology, microscopy, and bioengineering), exploitation of the first principles of biological structure–function relations will require expertise in chemistry, physics, computer science, materials science, and mathematics. The range of potential research topics is indicated by the following selection:

- rational design of new materials and processes from the molecular level;
- the influence of surface behavior and chemical environment on complex molecular structure;
- principles of molecular self-organization;
- mechanisms of biomolecular function;
- medical therapeutics on the basis of biomolecular interactions;

- nanoscale biomechanics;
- biomolecular electronics and physicochemical coupling mechanisms;
- biocatalysis and enzymology;
- organization of biosynthetic processes;
- dynamic molecular fine structure in altered milieus; and
- incorporation of biomolecules in lattice matrices.

MAJOR TREND 10: APPLYING THE PRINCIPLES OF BIOLOGICAL INFORMATION PROCESSING

Background

Biological systems—from macromolecules to cells to organs such as the brain—can receive, store, process, duplicate, and transmit information. In many cases, the mechanisms by which this information processing is performed far surpass all man-made machines in capability, miniaturization, accuracy, and adaptability. A rich universe of these information transduction and processing mechanisms exists at the molecular level, the cellular level, and again at the integrated level of the entire organism. The first principles that underlie these novel mechanisms are beginning to be elucidated. Exploitation of these principles can dramatically change the ways we deal with information processing in machines, animals, and humans.

Future Directions

In the next two decades, an enormous amount of knowledge will be gained about basic mechanisms of information processing and memory in biological systems from research in molecular genetics, membrane biophysics, immunology, neuroscience, and behavioral science. This knowledge will apply directly in areas such as classification of military personnel, training and modulation of performance, and the prevention and treatment of battlefield casualties. Less direct but more revolutionary consequences may result when the basic principles, information models, and possibly even bioengineered components, gleaned from these biological information systems, are applied to smart weapons, robotics, and microsystems of all kinds.

On one front, the basic principles learned from fundamental studies of biological information systems will change the ways we process information in computers, optoelectronic devices, and other nonbiological systems. For example, we may be able to close the gap between human and machine performance in such areas as pattern recognition and selective abstraction of highly relevant data from multiple data streams. We also may begin to approach in our processing systems—such as those used for sensor fusion—the animal brain's capability to integrate sensory input (originating as analog signals), carried by neurons, into a perception of self and world (or agent and environment).

The technologies of bioengineering will allow these same principles to be applied in the control and adaptation of biologically derived information processing components. Through biocoupling and the related field of bionics, these components will be incorporated in electromechanical and electro-optical systems. (The technologies for biocoupling and bionics are discussed in detail in Part V: "Biotechnology and Biochemistry." Thus, biological principles and biologically derived components will contribute to the trend toward nanoscale structures and processing, discussed in Chapter 3.

On a different front, techniques will be developed to read and use the information embedded in the biological structures of individual organisms, including humans, about that organism's interactions with its environment and its experience set. The Human Genome Project, which has already begun a comprehensive mapping of the human genome, is just one illustration of efforts already under way to decode the information embedded in biological structures. Better therapies and prophylaxis will result from knowing how to manipulate the immune system's ability to identify and neutralize pathogenic organisms and toxic substances simpler than organisms. This manipulation may even be performed within the human body (ectopic intervention) by enhancing the genome of white blood cells. Limited ectopic intervention is already practiced in special cases, such as bone marrow transplants for radiation victims and therapies for diseases caused by specific genetic defects such as sickle-cell anemia. Transfusions of laboratory-cultured white blood cells have been used to restore limited protective capabilities in human immune systems damaged by chemotherapy. By altering the genome of the cells before transfusing them, researchers are hoping to improve the versatility and potency of the cultured cells, perhaps to the point where this approach becomes effective against diseases such as AIDS and cancer.

On the integrated level, researchers will be probing the biological foundations of learning and memory. Once understood, the principles inherent in these structures and processes can effect quantum leaps in training and in performance improvement methods. The learning capabilities and intelligence of individuals will be increased far beyond the increments achieved thus far through behavior modification techniques, operant conditioning, and other functional metaphors for biological learning processes.

Disciplines Involved and Research Topics

The basic sciences of biology, chemistry, physics, and mathematics, will be required for research into the principles of biological information processing and their exploitation. The concerted efforts of cross-disciplinary individuals and teams will be needed to bring together the capabilities found in such specialty disciplines as:

- behavioral and cognitive science;
- neuroscience;
- immunology and endocrinology;
- molecular biology;
- biophysics and bioengineering;
- artificial intelligence and computer science;
- pharmacology and physiology; and
- psychiatry and psychology.

Representative topics for research, with either direct or indirect relevance to the Army's needs, include:

- multimodal information collection, fusion, and integration in biological systems—for use in sensor fusion technology;
- embedded memory in molecular systems—for nanoscale memory structures;
- high-order integration in neural systems—for alternative computing and processing architectures, such as neural nets;
- information dynamics and parallel processing in biological systems—for application in manmade information processing systems;
- molecular and integrative mechanisms underlying behavior—for personnel classification, training, and therapeutic intervention; also for application to biomimetic systems, robotics, and so on; and
- adaptive principles in immunobiology—for enhanced immunocompetence and other forms of prophylaxis from pathogens or chemical and biological warfare agents.

OTHER RESEARCH TRENDS IN LIFE SCIENCES

The focus group on Life Sciences identified two other research trends that are less broad in scope than the two major trends discussed above. Applications of molecular genetics, an area also referred to as *gene technologies*, will continue the high rate of expansion that began in the 1980s. That decade also saw major new instruments introduced for medical use in diagnosis and in imaging of internal structures and processes.

Applications of Molecular Genetics

Background

The field of genetics is in the early phase of what will become an avalanche of information on gene and protein sequences—the molecular data base of the life sciences. Knowledge of the molecular basis of life is growing exponentially; for example, the entire human genome will be sequenced in a decade. The genomes of many other organisms are being deciphered as well. The first uses of this knowledge will probably be to mimic structures and functions found in nature. Subsequently, the information on basic principles will allow design and production of entirely new molecular arrangements with novel functional and structural properties.

This information from the genome will initially be applied to Army materiel systems; in the longer term, it will be applied to the soldier.

Future Directions

Significant advances will continue in techniques to probe and manipulate the genomes of cells and subcellular entities (e.g., viruses). But the information deciphered from human and nonhuman genomes will have far greater implications of interest to the Army.

Information about nonhuman genes will be used in developing new approaches to materials and processes. First, the genetic blueprint information can be used to mimic unique biological capabilities in artificial products. Second, the principles of structure and function learned from genetic blueprints can be applied to design and synthesis of entirely new materials, composites, and structures (see also Trend 9). Third, gene manipulation techniques can be used to design, produce, and "farm" organisms with new or modified properties.

Information about human genes will enable alterations to individuals' disease resistance and the development of new medical methods for preventing and treating diseases or the effects of chemical and biological agents. Casualties will recover from more serious injuries faster through the use of artificial blood, skin, and bone. Complex organs, such as liver, kidneys, or eyes, may be replaced by culturing new ones from the affected individual's own cells. The information from the human genome also may contribute to improvements in classifying, training, and maintaining the fitness of soldiers, although the precise form of these contributions remains to be fathomed and is subject to various scientific and ethical caveats.

Disciplines Involved and Research Topics

The specialty disciplines required to decipher and apply the information in human and nonhuman genomes include molecular biology, biochemistry, biotechnology, biophysics, microbiology, zoology, biomedical sciences, and bioengineering. Representative areas of research include:

- bioproduction of consumable materiel (food, fuel, specialty chemicals) in forward theaters or where routine resupply is not possible;
- alteration of immune response through changes to the genetic material of immune system cells;
- preventive medicines based on gene modification mechanisms (gene therapy);
- organ culture from self-donated cells, for casualty care;
- personnel assessment, selection, and performance enhancement based on analysis of genetic traits; and
- postsensory coupling (stimulation of the nerve pathways leading from sensory organs to the brain) of machines to their human users.

Physical Instrumentation for Preclinical and Clinical Probes

Background

Parallel advances in the engineering sciences and biological sciences will result in many new instruments, sensors, and machines for use in diagnostic and therapeutic equipment. For example, diagnostic and therapeutic radiology has made great strides and should continue to do so. Sophisticated devices for imaging the brain have dramatically extended clinical neuroscience (e.g., magnetic resonance imaging, positron emission tomography, and magnetoencephalography). Even more recently, the feasibility of *micromachines* has enormous implications for medicine and biological research. The number of clinical diagnostic tests on blood and other tissues will increase, while these tests will become easier to perform and more accurate.

Future Directions

At the level of basic science research, multichannel data processing and integration, together with miniature sensors to monitor chemical processes in real time, may make it possible to measure chemical and physiological events, as they happen, at the cellular and subcellular levels. Mass spectroscopy will be used to characterize large molecules and aggregates. Diffraction techniques may help to determine the structure of partially disordered biological systems.

Bioengineering is likely to produce ambulatory and at-home instruments that can assume a major role in monitoring and managing human deficiencies. For example, diabetic patients may be provided with an *artificial islet of Langerhans* that monitors their blood glucose level and administers insulin from an external supply. Personal information systems will be able to carry a patient's entire medical history at all times, so attending physicians have immediate access to complete diagnostic and therapeutic records for the patient.

In the military environment, these new instruments can be used to detect threat agents (chemical, biological, or nuclear) in the field. They could also improve the diagnosis and resuscitation of the wounded or sick while they are still being transported from the field. Miniaturized instruments carried on the soldier could report in real time on physiological performance and reactions to stress, wounds, fatigue, and other battlefield conditions.

Disciplines Involved and Research Topics

The basic sciences for progress in physical instrumentation include biology, physiology, anatomy, biochemistry, pharmacology, materials science, and engineering. In addition, the following specialty disciplines play a role, depending on the instrumentation involved:

- neuroscience and psychiatry;
- medical sciences;
- radiology and nuclear medicine;
- clinical and experimental pathology;
- bioengineering and physics;
- mathematics and statistics;
- artificial intelligence and computer sciences; and
- electrical engineering and optics.

Areas for research of interest to the Army include:

- instrumentation to monitor the presence of and physiological response to chemical, biological, and nuclear threats;
- sophisticated medical diagnosis and treatment monitors for far-forward use;
- prevention and management of combat stress by enhanced communications between the field and command center (voice, physiological monitoring, geographical location, etc.)

- new instrumental methods for basic research in life sciences, such as physiology and biochemistry;
- monitoring of human performance and life functions under field conditions (e.g., on-line measurement of reaction time, sleep-wake cycles, memory, reasoning, man–machine interface performance, and other physiological, neural, and behavioral parameters); and
- integration of soldier-support systems into the Army organizational structure and hardware.

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Geosciences

MAJOR TREND 11: ENVIRONMENTAL PROTECTION

Background

The focus group for environmental and atmospheric sciences identified one area of research that has the characteristics of a major, multidisciplinary trend: environmental protection. This trend extends beyond the traditional geosciences; for example, work in testing new materials for toxicity and in detecting chemical species in the environment will require research in analytical chemistry and toxicology. Process controls for environmental emissions, especially on mobile Army platforms, will be improved by engineering advances in applying chemical and physical principles. However, the basic theme that informs all environmental research is a perspective on the earth as a complex system of interlocking cycles for the transport of materials and energy.

The discussion here of environmental protection focuses on requirements facing the Army to prevent or ameliorate the environmental damage of its future operations while decontaminating and restoring areas affected by earlier operations that were not environmentally sound. The reasoning here therefore presents these research areas as requirements-led.

The Army, like the Navy and the Air Force, has made a commitment "to clean up and preserve the environment from the consequences of military activity" (Iafrate and Shaw, 1991). Extensive research on environmental problems is already being performed through other federal agencies, including the Environmental Protection Agency, the Department of Energy, the U.S. Geological Survey, and the National Oceanographic and Atmospheric Administration. Even so, the Army has unique environmental problems because of its extensive use of environmentally hazardous materials—including fuels, explosives, solvents, and industrial byproducts—in remote locations. In addition, many of these materials are unique to the Army.

Future Directions

In the future, the Army will be assuming increased responsibilities for protecting the environment. These responsibilities are likely to include repair of damage that occurred in the past, as well as future environmental contamination or degradation. For these purposes, the Army will need to emphasize research in:

- detecting, monitoring, and treating the kinds of hazardous wastes it has generated in the past or may produce in the future;
- accurate models for the environmental transport and fate of hazardous wastes (including the difficult task of assessing the uncertainty of the models);
- analytical methods to assess potential toxic effects of new chemical compounds likely to be used by the Army; and
- means to reduce contaminant exposure and risk by modifying the ways operations are conducted.

Where the Army is responsible for past releases of hazardous wastes into the environment, it must take responsibility for treating these wastes. Candidates for treatment methods include combustion and thermal destruction, biological detoxification and degradation, chemical treatment, separation of hazardous from nonhazardous wastes, and safe containment of nondegradable wastes for long periods of time.

To determine whether wastes are hazardous and the extent to which they are a threat to humans or the ecosystem, exposure levels must be determined. This entails that the wastes can in fact be detected and measured in the environment. The Army may well need to take the lead in developing detection and monitoring technologies, particularly for those wastes it generates uniquely. This effort goes beyond the geosciences in a narrow sense; analytical chemistry, chemical physics, and biochemistry are among the relevant disciplines.

To assess the full environmental impact of Army-generated hazardous wastes, their environmental fate must be determined. For this purpose, accurate models of the transport and fate of the target compounds in all media (soil, water, air, and biota) must be developed and verified. In such models, the degree of uncertainty in the predictions must be assessed, for it is as important as the prediction itself. This uncertainty, which results from the inherent variability of natural processes as well as imprecision in the models, must be quantified.

To avoid or reduce the environmental release of, and subsequent exposures to, substances that are hazardous to health or the environment, those hazards must be identified as early as possible. New procedures for identifying potential hazards of new chemical compounds need to be developed.

These research efforts will lead to better identification and quantification of the effects and costs of environmental contaminants. As these consequences are determined, the Army will need to analyze its operations for ways to minimize negative environmental effects.

Disciplines Involved and Research Topics

The disciplines required for research in environmental protection include chemistry, biology, toxicology, transport and diffusion studies, and computational physics. Important topics of research will include:

- treatment of hazardous wastes;
- detection and measurement of chemical species in matrices and at concentrations representative of their environmental occurrence; and
- computer modeling of release processes, transport and diffusion, degradation mechanisms and breakdown products, toxic effects, and approaches to prevention and remediation of releases.

RESEARCH TRENDS IN ATMOSPHERIC SCIENCES

In atmospheric sciences, two specific research areas were identified: high-resolution remote meteorological sensing and dynamic atmospheric modeling. Each offers potentially high payoffs for the Army. Substantial advances in these areas are likely, because of continued improvements in the supporting technologies of digital computing (rapidly increasing memories and faster computation) and sensor technology (for example, data obtained over a wide area but also at smaller spatial and time scales).

The first area of research, remote sensing, is the first step toward knowledge of the physical processes underlying atmospheric changes at scales of interest to the Army. That knowledge, in turn, is essential for improved forecast capability at these scales. Atmospheric modeling is of prime importance to weather forecasting for Army field operations at scales from the entire theater down to the operational zone of artillery batteries, aircraft and UAVs, and individual combat units.

High-Resolution Remote Meteorological Sensing

Background

In the next 20 years, remote sensing will progress to the extent that high spatial and temporal resolution in the wind field (three field components) and the temperature and humidity fields of the boundary layer will enable the accurate computation of the small-scale atmospheric processes. Highly accurate measurements will be required to initialize the program, understand and develop accurate models, and validate model results.

Future Directions

The numerical codes needed for Army applications will require meteorological sensor data that meet the following standards of accuracy:

- vertical velocity errors less than 10 cm/s;
- horizontal velocity errors less than 20 cm/s;
- temperature errors less than 0.5°C; and
- errors in specific humidity of less than 10 percent of the actual value.

The spatial resolution required is such that a grid spacing of 100 m is feasible. The overall dimensions of the interrogated volume are 5 km × 5 km (horizontal) × 2 km (in altitude). The sheer volume of dimensional data collected by these sensors—with three spatial dimensions and one temporal—will require special techniques for storage and assimilation.

Data gathered by the remote sensors in field experiments can be used to validate computer predictions based on the numeric models. (See next subsection for discussion of the modeling component.) Model results can then be used to derive optimal locations for the sensors in the next round of field experiments. Through this iterative process of model validation and improved sensor placement, the computer models and the field measurements will complement each other in increasingly detailed field experiments. The results will enhance our understanding of atmospheric processes in the boundary layer and our ability to parameterize these processes properly.

Disciplines Involved and Research Topics

The disciplines needed to conduct this research include atmospheric sciences and meteorology, physics, electronics, information processing, and data assimilation. Research topics that will contribute to the larger goal include:

- atmospheric turbulence measurements;
- velocity field mapping;
- temperature field mapping;
- humidity field mapping; and
- measurements of atmospheric aerosols, fogs, and clouds.

Dynamic Atmospheric Modeling

Background

Advanced computational facilities will use numerical codes to analyze, study, and simulate the dynamics of small-scale atmospheric processes. A dense grid of measured values for the canonical meteorological variables will initialize the program and provide the "ground truth" for validating the code. The concepts necessary to quantify meteorological fields (as opposed to point measurements of meteorological variables) on time scales ranging from fractions of a second to tens of minutes remain to be identified and exploited.

The models will emphasize boundary-layer (1–2 km in altitude) dynamics, with special attention paid to the surface layer (10–100 m). The models will extend to a horizontal distance of approximately 5 km—for initial development and verification—and should use a grid spacing of 100 m or less.

Future Directions

Highly complex computer models will be used to guide future field experiments and to study the effects of subgrid parameterization on the development of simpler codes for use in the field.

The computer models will be sufficiently detailed to estimate atmospheric effects on propagation of electromagnetic and acoustic signals and to model transport and dispersion realistically.

Disciplines Involved and Research Topics

The disciplines involved in dynamic atmospheric modeling include meteorology, electronics for remote sensing and data processing, computational physics, atmospheric sciences, computer science, and applied mathematics. Contributory research topics include:

- turbulent processes;
- intermittency;
- subgrid parameterization;
- fog and cloud physics; and
- new sensor concepts.

Weather Modification

Background

As stated in the STAR Environmental and Atmospheric Sciences Technology Forecast (Part IX), "It would be of great value to the Army to acquire even a modest capability to modify the weather. Obvious examples would be clearing fog over a limited region or initiating precipitation." Currently, little progress is being made in this area. However, there is increasing emphasis on understanding and predicting atmospheric conditions on small space and time scales.

Future Directions

In the future, improved knowledge and understanding of the physical processes affecting the weather may eventually provide a limited capability to modify weather effectively, if only locally. This capability would benefit the Army and should be pursued commensurate with our knowledge of atmospheric processes.

Obvious difficulties are our less-than-adequate knowledge of the initiation and growth of water droplets and the effect of fluctuating atmospheric conditions. The Army's research on modeling small-scale weather conditions will necessarily include work on fog and cloud physics and the conditions under which these aerosols form. To support even limited weather modification, atmospheric modeling must include a more accurate representation of turbulence, hence a more accurate description of intermittency.

Disciplines Involved and Research Topics

Scientific disciplines that will contribute to research on weather modification include physics and computer modeling. As prospective research topics, the work described previously for remote sensing of meteorological indicators and dynamic atmospheric modeling will provide the knowledge base that may make local weather modification a usable Army technology.

RESEARCH TRENDS IN TERRAIN SCIENCES

Army activities are directly related to the terrain. The use and control of terrain is, after all, key to success in land combat. Information about the terrain may be divided into three categories:

1. general and relatively fixed terrain characteristics (static topography);
2. semipermanent but slow-changing characteristics, both natural (e.g., vegetation, soil, and natural habitat) and man-made (e.g., roads, structures); and
3. fast-changing terrestrial conditions, which may result from natural conditions (e.g., rain) or deliberate human actions (e.g., enemy actions such as barricade construction).

Remote sensing of terrain and processing of the resulting multiple imagery is essential for current information covering all three categories. To date, remote sensing for terrain imaging has been performed as a two-dimensional representation of the three-dimensional world. Whereas the means of acquiring the *data* for such imagery, using aircraft and satellites, seems adequate (except perhaps for desirable increases in spatial and spectral resolution). Definite constraints exist in the processing of the data into *images*. The angles are sometimes bad or limiting for key aspects of imaging and image interpretation. The quantity of available data, especially for the third category of terrain information, is limited. And compensation for weather and camouflage is difficult with the current technology. To alleviate the image-processing bottleneck and provide terrain information adequate for the second and third categories defined above, considerable advances must be made in one or both of the following research areas:

- introduction of an entirely new sensing approach where the resulting image is directly three-dimensional; and
- automation of the processing of multiple-sensor imagery.

The third category of information requires significant basic research in terrain surface dynamics. Included in such research will be advanced atmospheric sensing and unified hydrologic/atmospheric models for the derivation of soil characteristics. Each of these requirements is addressed below as a separate area for research.

Three-Dimensional Imaging of Terrain

Background

Current remote-sensing systems produce terrain imagery that is a two-dimensional transform of the three-dimensional geography. To recover the third dimension, photogrammetric techniques are then applied to overlapping images. A remote-sensing system that would produce three-dimensional representations directly would constitute a breakthrough. Development of such a system will greatly facilitate the acquisition of terrain data in a form that is more nearly directly usable. Availability of three-dimensional imagery will allow for real-time information exploitation and will be a major step toward an automated terrain exploitation system.

Future Directions

A completely new design theory for terrain sensing will be required to achieve direct three-dimensional imaging. Holographic techniques or some other approach must advance to the point of enabling a remote sensor to record in three or four (spectral) dimensions. At the same time, area coverage and image quality constraints must be met; coverage of ever larger areas at higher resolution will be a continuing demand on the technology.

Success in this endeavor will greatly improve the time lines of many Army missions, including target acquisition, mission planning, in-course and terminal guidance of weapons, and intelligence preparation of the battlefield. Direct sensing of three-dimensional or four-dimensional information about the terrain will open the way to extraction of terrain information and intelligence preparation of the battlefield in near-real time. It can give the soldier in the field a real-time three-dimensional view of the battlefield that is difficult to conceive from a two-dimensional map or display. Data from such a sensor system could be fed directly to image-perspective transformation systems; real-time fly-throughs for mission planning and rehearsal would become an affordable reality.

Disciplines Involved and Research Topics

Research on three-dimensional terrain sensing will involve physics, chemistry, mathematics, computer science, and materials science. Important research topics for this area of inquiry include:

- sensor design;
- massive data storage;
- data processing;
- electromagnetics; and
- multifrequency imaging.

Automated Information Extraction from Multiple Imaging

Background

At present, the extraction of useful information from overlapping terrain images requires intensive human effort. Existing techniques to reconstruct the third dimension from two-dimensional images rely on both a human observer and semiautomatic techniques. Current automation efforts have succeeded in extracting linear features, such as roads, from single images. A significant advance in the state of the art would be an automated capability to acquire directly or reconstruct the original three-dimensional space rigorously from three-dimensional data, then automatically extract terrain features.

Future Directions

Significant reduction can be expected in the effort required to extract information from multiple terrain imagery. Rapid turnaround time from image data acquisition to the production of usable terrain representations will be attained. In addition to the shortened time lines, an automated process offers the potential to increase substantially the reliability of the extracted information, by eliminating error and variability from human interpretation of the data.

Armies in the field have always sought near-real-time information of the terrain on which they intended to operate. It has not been possible to generate this information in less time than the decision-making cycle of enemy operations on the same terrain. Automation of this information extraction process will allow field commanders to have current terrain analysis, mapping, and intelligence data well within the decision-making cycle of the enemy. This superior knowledge of the battlefield could provide a force multiplier, contributing to the probability of operational success.

Disciplines Involved and Research Topics

The scientific disciplines that will be needed to pursue automation of multiple-image terrain information include mathematics, computer science, and engineering. The following research topics are representative of the work needed:

- AI and neural networks for creating representations from data and recognizing patterns for terrain elements;
- pattern recognition techniques and algorithms;
- exploitation of spectral information;
- terrain modeling;
- data structures; and
- geographic information systems.

Terrain Surface Dynamics

Background

The terrain where a battle is being fought is dynamic, sometimes changing significantly within a short time. Such changes may be induced by weather; they also may be engineered by the enemy as passive defenses. In particular, soil conditions and the passability of roads vary dramatically with weather and recent traffic. Nevertheless, given sufficient data on soil type and runoff patterns, as well as recent and forecast weather, it should be possible to make reliable predictions of road conditions and of trafficability off the roads.

Currently, the Army has no real-time system to analyze terrain surface conditions and trafficability. It must rely on data bases of known soil conditions, usually based solely on static data. To generate even a crude prediction of trafficability, weather forecasts and other dynamic information must be overlaid on this static terrain data. This labor-intensive process must be accomplished before an exercise or operation commences.

For example, to avoid extensive property damage in the annual REFORGER exercises in Europe, soil and weather conditions are determined and an elementary map is produced of areas open to the exercise and those which are closed because of poor trafficability (go/no-go distinctions). The mapmakers are encouraged to err on the conservative side. In most operational environments, especially for fast-occurring contingency operations, these favorable circumstances will not pertain. Data on soil conditions may not be available, and the battlefield will be truly dynamic.

Future Directions

Progress toward a system for near-real-time prediction of terrain surface conditions will require development and integration of several contributing technology elements:

- a system for large-area remote sensing of rainfall, capable of providing data at resolutions of less than 1 km;
- a soil-moisture measuring system based on in-place robust sensors;
- capability for remote direct sensing of trafficability, via soil samples taken by robotic systems (for example, unmanned airborne or ground vehicles); and
- a soil property model adequate to incorporate hydrology factors and atmospheric conditions and produce realistic, usable projections of vehicle–terrain interactions.

The data gathered by the first three of these elements could be used in models like that in the fourth element to provide field commanders with assessments of trafficability and mobility. Although it will be easier to accomplish these goals for terrain under friendly control, where hands-on data can be gathered, the long-term effort must aim for reliable assessments of terrain in enemy control or disputed areas.

Disciplines Involved and Research Topics

The disciplines required to model terrain surface dynamics under battle conditions include physics, hydrology, mathematics (particularly for modeling techniques), computer science, soil science (especially the pertinent chemical and biological processes), and atmospheric science (e.g., modeling and measurement of precipitation, evaporation, and freeze-thaw timing). Some of the research topics that can contribute to the required capabilities are

- fundamental structure of drainage basins;
- mechanisms of runoff generation;
- effects of temporal or spatial variations in precipitation on runoff hydrology; and
- physics and dynamic mechanisms of frozen ground and of snow and ice as ground cover and as vehicle traction surfaces.

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Management of Basic Research in the Army

In the Army's budget, most of the research topics suggested in preceding chapters as supporting these long-term trends in science and technology would fall under funding line 6.1, for "basic research" funding. This chapter considers how the Army might best manage its support for research with a long-term payoff.

In future years, as defense budgets shrink, continued support of basic research will be extremely important. Without strong support for basic research, the foundations for the development of future technologies will not be laid. The possibilities for Army-supported research will outstrip the available resources even more in the future than in the present. It will be necessary to leverage the Army's research budget by setting priorities: Which research topics are of the highest potential to the Army? Which are most promising technically? Which will not receive adequate funding outside of the Army?

A paradigm for successful support of basic science by a military service has been the Office of Naval Research (ONR). Over the years, the legislative mandate for ONR funding has partially shielded the Navy's basic research capabilities from the inroads of budgetary instability. Army research might benefit from adopting some aspects of the ONR model. For example, there could be a military two-star as Chief of Army Research, who would report directly to the civilian Assistant Secretary for Research and Development. The Technical Director of the Army Research Office would report to the Chief of Army Research. In principle, the Army could adopt this model without a legislative mandate similar to that under which ONR operates. In the long run, however, such legislation would undoubtedly be preferable.

Another aspect of the Navy structure is the special relationship of the Naval Research Laboratory (NRL) as the flagship of the Navy's laboratory system. In the Department of the Navy, the NRL reports directly to the Chief of Naval Research, who is responsible for its health and well-being. It is worth considering whether a particular Army laboratory or center should be chosen for a special role, like that of NRL, or whether components of various laboratories could be integrated under a single scientific leadership. In any case, actions tailored to fit specific Army requirements may be necessary for the vitality of the basic research enterprise that is essential for future Army needs.

Another key issue for management of basic research is the transfer of technology from the laboratory to the user. The long-term trends described here will only contribute to Army technological superiority when the applications of technological progress are in the hands of the soldier.

The Army's Technology Base Master Plan details the process of moving from basic research through experimental development to advanced technology transfer demonstrations. In general, this process is sound, but in an environment of declining budgets for development and procurement of new major systems and platforms, new means must be sought to ensure that the best technology is fielded rapidly. Technology itself can provide some help; examples from this report include Major Trends 5 ("Design Technology for Complex Heterogeneous Systems") and 8 ("Advanced Manufacturing and Processing"). But innovative management approaches to technology transfer are essential as well. The *STAR 21* main report, particularly Chapters 5 and 7, offers suggestions on improving that transfer, given the Army R&D environment that is likely to prevail well into the next century.

References

Corcoran, E. 1991. Body heat: QWIPs offer a new way to see in the dark. Scientific American 265(4):123.

Ealey, L.A. 1988. Quality by Design: Taguchi Methods and U.S. Industry. ASI press.

Eberhart, M.E., K.S. Kumar, and J.M. MacLaren. 1990. An electronic model for the DO_{22} to $L1_2$ transformation of the Group IV-A trialuminides. Philos. Mag. B 61(6):943-956.

Fisher, L.M. 1990. Adding noise to cut a car's noise. New York Times. 139:C3(N)(col.1), D7(L), January 10.

Iafrate, G.J., and R.W. Shaw. 1991. Shaping the future through basic research. Army Research, Development, and Acquisition Bulletin, March–April: 18–19.

NRC. 1988. The Impact of Supercomputing Capabilities on U.S. Materials Science and Technology. National Materials Advisory Board, National Research Council. Washington, D.C.: National Academy Press.

NRC. Undated a. STAR 21: Strategic Technologies for the Army of the Twenty-First Century. Airborne Systems. Board on Army Science and Technology, National Research Council. Washington, D.C.: National Academy Press.

NRC. Undated b. STAR 21: Strategic Technologies for the Army of the Twenty-First Century. Special Technologies and Systems. Board on Army Science and Technology, National Research Council. Washington, D.C.: National Academy Press.

PART II

COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE, AND ROBOTICS

COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE, AND ROBOTICS TECHNOLOGY GROUP

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Summary of Findings on Computer Science, Artificial Intelligence, and Robotics

Gunpowder and combustion engines, which substitute for human muscle in specialized applications, have already revolutionized warfare. Computers, which also substitute for human thought in specialized applications, can produce an equally significant revolution. The pervasiveness of the computer in future Army applications and technologies is clear:

- Of the 20 prioritized technologies in the draft Defense Critical Technologies Plan, 6 of the top 10 are subfields of computer science.
- All eight STAR systems panels are considering applications that imply significant computer support.
- Each of the other eight STAR technology groups has identified computing as central to progress in one or more of its areas.

The technological pace of computational development is astounding. For comparison, tank guns and armor have improved by about a factor of 10 since World War II. But the performance of computer hardware has been improving by about a factor of 10 every five years. If sustained, this pace of progress will, by 2020, provide watch-sized, $100 computers more powerful than current supercomputers. In 1990, the largest machines have less raw computational power than the brain of an ant; extrapolated power for big machines in 2020 surpasses some estimates of the computational power of the human brain.

Current electronic technology probably cannot support such machines, which may require fundamental and unpredictable breakthroughs in optical or biological computing. Further, it is hard to predict the consequences of "ant-equivalent" machines, which already perform many functions much better than humans; the likely effects of a "human-equivalent" computer are quite beyond our understanding.

This STAR Technology Group has therefore assumed only modest reductions in computer size and cost and only modest increases in power. The Technology Group also has been conservative in anticipating the effects of countermeasures. The projections may seem radical because the Group has tried to state them plainly; the Group emphasizes that the future probably will be stranger than described here.

If the new technologies are applied vigorously, war will change much more between 1990 and 2020 than it did between 1915 and 1945, because the pace of technological change is faster now than it was then. Those who understand the tactical implications of this technological revolution will win, just as Hitler's armies, employing tanks in mass, defeated superior numbers of dispersed French tanks. Accordingly, Chapter 9 portrays the possible impact of these technologies on military operations, sketching the most successful armies for the unpredictable 2020s.

Such rapid change makes it all too easy to believe that "anything is possible." In fact, although the computers of 2020 and the machines they control will be far superior to people at many tasks, they will remain incompetent at many others; their misapplication will result in failures. Chapter 10 therefore discusses fundamental and practical limitations of these technologies.

Most important, Chapter 11 discusses some technology areas in which the Technology Group believes that the Army must take the lead in order to realize the revolutionary military potential of computation. Some of these have been largely overlooked. The discussion has been organized around military issues, to explain why these particular areas are indeed strategic technologies for the Army.

Chapter 12 discusses a variety of technology areas that the Group believes the Army must monitor closely, but in which it should perhaps follow rather than lead. The Technology Group has not covered every computer technology of potential military interest; our selection is necessarily constrained by our own experiences. Rather than producing a bland, "complete," and ultimately meaningless survey, the Group has tried to err on the side of vigorously presenting ideas that may lead to new and useful initiatives. The Group therefore emphasizes that support for a broad range of technologies is needed. Steady, evolutionary progress is as important as new concepts or technical breakthroughs and far more important than this week's passing fad.

KEY FINDINGS

The remainder of this chapter summarizes the key findings of the Technology Group from Chapters 9 through 12 of the report. These findings are in the form of conclusions about current or emerging technology and the Group's forecasts for future technological developments.

Impacts on Future War

Chapter 9 argues that *unmanned systems*, operating mostly under computer control but with human supervision, may become the core weapons of the next century, just as the main battle tank has been the core ground warfare weapon of the twentieth century. Battlefield robots are likely to evolve as increasingly intelligent mines, driven by considerations of cost, logistics burden, and expendability. In addition to stationary systems that are air-dropped or hand-emplaced, there will be airborne and ground-mobile unmanned systems. Designed for mass production and specialized roles, these systems will force development of new tactics and new cycles of measure and countermeasure.

Individual soldiers will experience enhanced effectiveness by using tools that help them navigate, keep them in constant communication, monitor and treat their physical condition, enhance their training, and extend their knowledge with ever-present smart manuals. New computational tools for optimal weapon design and the integration of computer-aided aiming and sensing systems will dramatically improve the effectiveness of manned systems.

Massive data bases, nearly instantaneous communications and analysis, decision aids, and multisensory data displays will provide commanders with unprecedented situational awareness. *Field commanders* will be able to adjust plans and synchronize combat power with revolutionary speed and precision. Machines will perform the data shuffling that now occupies staffs, while the broad experience and incisive judgment of the best commanders will become more valuable than ever.

Logisticians will exploit the same tools but will find their roles merging with those of the tactician and the strategic planner. The timing of system development, and the careful planning of surge production capacity, will sometimes decide battles and wars. Unmanned logistical vehicles will be significant contributors, but the largest change will be in the planning and control of logistics operations.

Strategic planners will rapidly tailor forces, easing force-structuring problems. The military dynamics of unmanned systems will reward surprise and professionalism, decrease casualties among the victors, and allow completely covert attacks. More frequent war, increased danger from surprise, increasingly elusive foes, and high probability of direct attacks on the United States are the likely consequences. Current international trends toward democracy may reverse, as computational technologies shift economic and military power from the masses to technical elites. New computer-based development strategies and the importance of development timing will blur the distinction between peacetime and wartime procurement. Unmanned systems can be produced in great numbers much more quickly and secretly than soldiers can be trained. By exploiting these new technologies and the obsolescence of enemy systems, the swift and total conquest of even fairly substantial nations may become possible.

Fundamental Limitations and Practical Constraints

Decision-makers need to understand the limitations as well as the potentials of computational technology. Misapplications of the technology are common, and they often lead to dramatic failures.

Electronic hardware development sets ultimate but uncertain limits on computational power. However, this Technology Group expects that there will continue to be more computational power than we really understand how to use. Continued improvements in communications systems, power sources, and sensors are also vital. Mechanical system development will accelerate, but this will remain a major limitation on robotic systems.

Computer software fallibility will continue to limit program size and capability. We do not understand most decisions well enough to program them reliably; the world always shows facets the programmer did not anticipate, so large programs always have bugs. Large programs also become increasingly difficult to understand, correct, or replace over time. No complete technical fix is possible, even in theory, although high-level languages (including "automatic programming" systems) will continue to make it easier to frame the problems we do understand.

Vulnerability to countermeasures will remain critical. Computation-intensive systems will be less flexible and adaptable than are humans. Predictability or vulnerability, if exploited by an enemy, can lead to swift defeat.

Communication system overload can also be decisive. While computer power and storage capacity continue to grow geometrically, non-line-of-sight radio communication can be improved only marginally. Satellite and fiber-optic systems can produce continued improvement in capacity but are vulnerable and therefore unreliable. Systems will have to work with both very high and very low communication rates.

Decision-maker overload sets other limits. Computers can manipulate information far more quickly than communication systems can transmit it or humans can understand and integrate it. Even peacetime decisions involve a wider range of interlocking problems than any human can understand; catastrophic mistakes are increasingly likely. Research will help—by providing better abstractions and more visual representations, as well as a better understanding of uncertainty—but the problem will still grow worse.

Educational limitations worsen the issue. The programmer must envision a variety of future events, decide how to represent them in formal computer language, decide what action should be taken when these events occur, and express these decision criteria in computational language. All this must be done carefully enough that unexpected events will not trigger disastrously wrong decisions. The required skills include, first of all, unusual military knowledge, imagination, and judgment; and second, the mastery of a new set of technologies. Such individuals will remain in short supply.

Finally, organizational inertia may produce an army in 2020 that is little different than the army of 1990. The 15-year peacetime procurement cycle is absurdly inadequate when applied to computers, which become obsolete in two or three years. The new systems, like any revolutionary technological development, will disrupt not only existing military structures but also industrial competencies and political attitudes.

Recommended Army Technology Thrusts

The discussion of specific technology areas has been divided into two sections. The last section discusses a broad range of technologies that the Army ought to monitor, but in which the Army probably cannot fiscally afford to take a leading role. That discussion is too diverse to summarize here but has much in common with previous DOD critical technology listings. Support for these technologies is important, but the Technology Group believes that the Army needs to tailor its support carefully, to exploit developments by other services and by the civilian sector, both domestic and overseas.

By contrast, the technologies in which the Technology Group believes that the Army must take the lead can be divided into three areas:

1. system development technologies;
2. integrating technologies; and
3. battlefield robotics.

The magnitude of the system development task can be assessed as the product of (a) the number of systems developed, (b) the volume in which they are produced, (c) the degree to which they are interrelated, (d) the rapidity with which the environment in which they are used changes, and (e) the degree to which they integrate innovative technologies. Clearly, the Army's development problem dwarfs that of any other American organization. Emerging technologies in the civilian sector can help, but they cannot solve the problem. In order to develop the right systems at the right time, reliably and at reasonable cost, the Army will need to go beyond the civilian state of the art.

In particular, the Army will have to learn to structure the simultaneous development of the systems, the civilian surge capacity to produce them in great number without major peacetime investment, and the doctrine to employ their often revolutionary capabilities. This concurrent development of doctrine, systems, and manufacturing processes will require new management processes and a new science of system development. It will also require advanced computational development environments, powerful high-level languages to describe system requirements, computer programs to translate these descriptions into the details, continued development of simulation and optimization, and new theories of mathematical inference about the sets of possibilities produced by variations in production processes and tactical environments.

Once the systems have been deployed, the Army will require integrating technologies in order to coordinate the operations of, perhaps, millions of soldiers and both manned and unmanned systems. No other service deploys forces so numerous, dispersed, diverse, concealed, moving at such varied time scales, and facing so amorphous a threat. Vigorous software development will be needed to integrate the immense information flows involved. In particular, the Technology Group notes the previously unexploited concept of battle control languages: computer languages written to make control of computers seem analogous to the control of manned systems. Advances in knowledge representation will increase the reliability of code by providing new formal structures to describe battle. We must find ways to represent an active and only partially known enemy, our own widespread and only partially predictable forces, and the complex terrain on which we operate. We will need programs running reliably while distributed across thousands of computers that are miles apart and subject to both temporary and permanent disruption.

Managing bottlenecks in the communications network will be one critical task. Another will be to provide the human users of the system with the information they need, without overwhelming them. The year 2020 will see the virtual Tactical Operations Center, with a few pounds of communications and computational equipment linking widely separated commanders and staffs. Map boards will be replaced by projections onto helmet visors. At the same time, we will need to strike at the enemy's computer-dependent systems in a variety of ways, while protecting our own. These technologies will allow the Army to coordinate and focus combat power in minutes rather than hours and to respond to enemy actions long before they become effective.

Last, the Army's need for battlefield robotics is without parallel in other organizations. Robots are incorporated into production lines by reducing the variability of the environment in which the robots work. But the variability of the battlefield is irreducible, to the extent that it is under enemy control; an enemy will quickly exploit the limitations of rigid unmanned systems. For these reasons, the Technology Group believes that military robotics will have limited effect until we can produce microrobot systems that are sufficiently cheap and light to be deployed in very large numbers, compensating with mass for their individual relative vulnerability.

Accordingly, the Technology Group has addressed substantial attention to the problem of *microrobotics*. Battlefield robots will have to integrate a variety of sensory information in order to defeat enemy attempts at deception. Also, autonomous mobility over natural terrains poses problems not faced by other systems. Vigorous development in this area may produce weapon systems and sensor platforms that are orders of magnitude more difficult to detect or hit, easier to deploy, and cheaper to produce than manned systems. By 2020, such systems are likely to far outnumber soldiers on the battlefield, rendering manned movement nearly impossible.

These technologies are synergistic. For example, we will not successfully control the immense numbers of micro-robots foreseen by this Technology Group without battle control languages. None of these technologies is likely to develop adequately without Army support; nor will they succeed without substantial expansion of the base of computationally sophisticated personnel.

SPECIAL NOTE ON UNMANNED SYSTEMS AND THE DECISION TO FIRE

The Technology Group has made no particular effort to distinguish among computer sciences, artificial intelligence (AI), and robotics. The technologies designated by these terms are overlapping and rapidly changing; the concern is instead with the fundamental question, "How can we make computers do useful things for the Army?" However, as the term "robotics" is used here, it does not mean anthropomorphic systems but rather the technology necessary for computers to sense and take direct action in the real world. Further, although manned and unmanned systems are distinguished in some contexts, the distinction is less critical than it might seem. Many decisions in manned systems will be made by computer. Control of manned and unmanned systems will sometimes be by tele-operation (the human spatially separated from the action) and sometimes by program (the human temporally separated from the action).

The members of this Technology Group have frequently been told that the automated decision-making systems it forecasts will not be developed because national leaders will not tolerate fire/no-fire decisions being made without a human in the loop. The Group believes this is wishful thinking. National leaders have tolerated land and sea mines (which make fire/no-fire decisions), harassment and interdiction fires, chemical warfare, and the nuclear bombing of civilian populations. If there is a military advantage in having some decisions made by machines, and the Group believes that there is, then that advantage will be exploited.

9

Impacts on Future Wars

This chapter surveys the potential consequences for land warfare of a range of key technologies in the fields of computer science, AI, and robotics. The rows of Table 9-1 are these key technologies; the columns represent key roles that will be present in the future Army, whatever the circumstances of its particular missions. In the remainder of this chapter, the Technology Group explores how each of these role types could apply the key technologies.

TABLE 9-1 Matrix of Impact Areas and Key Technologies

Key Technologies	Unmanned Systems	Individual Soldiers	Manned Systems	Field Commanders	Logis-ticians	Strategic Planners
Integrated System-Development	X		X		X	
Mathematics of uncertainty				X		
Simulation and optimization		X				
Information Integration						
Battle control languages		X		X	X	
Battlefield robotics	X			X		
Computer warfare	X				X	X
Data base management systems					X	
Distributed processing	X			X	X	X
Human–machine interface	X	X		X		
Knowledge representation	X	X	X	X		X
Network management	X			X	X	
Sensor integration	X		X			

UNMANNED SYSTEMS

The core weapon of twentieth-century land war has been the tank, but the core weapons of the twenty-first century may be unmanned systems, operating mostly under computer control. Mechanically simple, deployed in huge numbers, and integrated with manned systems, these systems will drastically curtail conventional maneuver while making possible new forms of surprise attack. Table 9-2 lists some of the computer-driven contrasts between current and future warfare.

TABLE 9-2 Effects of Computation on Warfare

1990	2020
Armored maneuver	Technical maneuver
Manual staffs and bureaus	Computer-assisted decision-makers
Massive firepower	Omnipresent sensing
Long wars of liberation	Swift conquests
No rational threat to U.S. territory	Diverse threats to U.S. territory

The U.S. Army has employed unmanned weapons for decades in the form of land mines. Mines sense motions; they perform a simple decision logic and then take appropriate action. Originally the logic was carried out mechanically: IF ARMED AND TRIPWIRE TRIGGERED, THEN EXPLODE. From a computer science point of view, they are therefore robots. Other important military robots include cruise missiles and heat-seeking or radar-guided missiles, dating back to the German V-1 rocket. Tele-operated systems include remotely piloted vehicles and wire-guided antitank missiles.

Unmanned systems already have substantial roles in combat. Mines were the second largest tank killer in World War II. And despite the primitive technology available to the enemy, mines were a principal threat to U.S. forces in Viet Nam. But their effectiveness will increase exponentially because of progress along four dimensions (discussed in detail below):

1. the range and variety of their sensors;
2. integrated networks of computers, humans, sensors, and weapons;
3. the range and power of their weapons; and
4. their mobility.

The Technology Group expects these changes to transform unmanned systems from mere barriers and projectiles into decisive components of a battle-winning combined-arms team. In consequence, conventional maneuver will become nearly impossible. New forms of maneuver, however, will sometimes permit remarkably swift victories.

These systems will derive their impact from several characteristics. Because they can be much smaller, lighter, and cheaper than a soldier or manned platform, they can be deployed in large numbers. They can be produced secretly and much more rapidly than soldiers can be trained. They can employ sensors that humans lack and weapons that no human could accurately aim or safely fire. They do not tire or grow afraid, and they can be deployed in places and for tasks where soldiers cannot or should not be sent. The technology to build them exists now; the Technology Group projects only that they will become cheaper, more rugged, and more compact, and that we will understand better how to use the technology.

The results will change the face of warfare. The essential issues are cost, logistics burden, and expendability. Unmanned systems are very cheap compared to humans and, once deployed, require little logistical support unless they are moving (Figure 9-1). Therefore, they can be scattered in great numbers. Since they are also expendable, they can be scattered over enemy territory to a great depth, although air-delivered systems will be less cost-effective than truck-delivered, hand-emplaced, defensive systems.

In consequence, by 2020 no reasonable distinction will be possible between deep forward areas, close combat, and rear echelon areas; combatants may find that the battle area extends over their entire national territory. Airborne systems equipped with powerful radars and infrared sensors will roam the battlefield and the enemy's homeland, forcing him to disperse, protect, and reduce the signatures of all important assets and activities. Stationary systems, air-dropped or hand-emplaced, will provide permanent surveillance of key areas, including not only avenues of approach and helicopter landing zones but also factories, roads, and ports. Small ground vehicles will crawl or leap like grasshoppers, combining mobility and the

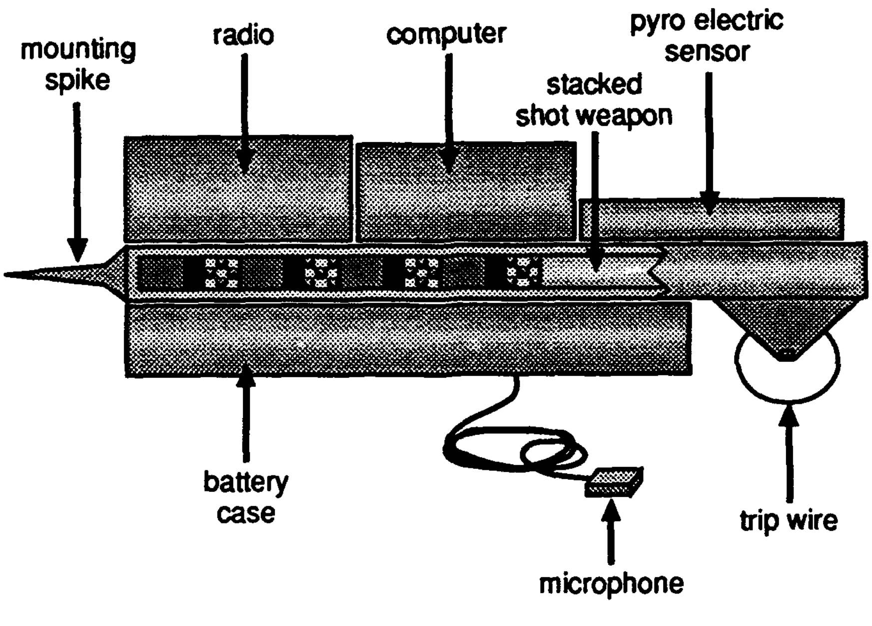

FIGURE 9-1 The $19.95 military robot, a simple system that can hold ground.

advantages of stationary sensors and ground cover. One system now under design offers a speed of 3 miles per hour and a range of 15 miles in a 15-pound package. The information from a variety of sensors—most of them simple and inexpensive trip wires, pyroelectrics, seismic sensors, sonars, and interruptive beams—will be fused to decide where the enemy is; he will then be engaged by indirect, direct, or guided-missile fire, as required.

The human operators of these systems will shift their mode of control according to circumstance, sometimes observing directly, sometimes through cameras, sometimes watching schematic displays. They will guide some weapons themselves, order other weapons to fire, and direct others to fire automatically under specific circumstances. Direct human observation will continue to be needed, to detect countermeasures against robotic sensors. However, the humans will be so dispersed as to be almost immune to indirect fire, and they will rarely reveal their positions by firing themselves. They also will be protected by much larger numbers of unmanned systems. Well-trained soldiers therefore will operate with relative impunity deep inside enemy territory, resupplied by unmanned, stealthy aircraft.

Ground attackers will find these dense networks of sensors, computers, and weapons a nearly complete barrier to maneuver. Machines cannot be frightened by suppressive fire or rumors that the enemy has penetrated to their rear. Clearing the ground of these small systems will be extremely difficult and dangerous. Forces will maneuver freely through their own "obstacles," but these often will become so mixed with the enemy's that neither side can maneuver. The range and adaptability of the systems will allow them to be deployed more quickly than the enemy can maneuver around them, except by air. But, in general, it will prove more effective to air-deploy unmanned systems rather than infantry.

Communication requirements, and the tendency of the user to become disoriented, will remain substantial limitations on "telepresence." Nevertheless, many soldiers will divide their attention among a large number of systems, which will operate autonomously while the soldier's attention is elsewhere. Some of these soldiers may even be located in the continental United States while fighting overseas. The communication systems that make telepresence possible will be major targets. Tele-operation will be particularly important in clearing terrain of microsystems.

Although unmanned systems can prevent physical maneuver, they will remain much more vulnerable than manned systems to astute countermeasures. Thus, they will become ineffective much more quickly. Attackers will attempt to understand enemy systems and prepare countermeasures before war begins. They will produce their own systems secretly, in massive numbers, and initiate war only when the enemy, tiring of heavy expenditures, has allowed his systems to become outdated.

The attackers will attempt to overwhelm and disrupt the enemy by aerial delivery of systems throughout enemy territory, preventing him from deploying his forces and shutting down his economy. They will follow up, if necessary, with armored thrusts to seize key assets and force surrender. Finally, if they cannot force the defender to shut down his own unmanned systems, they will slowly clear the ground. If surprise fails, the networks of the attacker and defender will gradually overlap. Casualties among civilians in these areas will be high, industrial production will be disrupted, and the conflict will sink into stalemate.

Key technologies (described below) for these unmanned systems are battlefield robotics, integrating technologies, and system development technologies.

INDIVIDUAL SOLDIERS

Computation will make good soldiers better. By 2020, every soldier will carry a computer no larger than a deck of cards, controlled by voice or hand motions, that will speak or display graphics by heads-up display on eye armor (see Figure 9-2). The computer will monitor the environment through its own sensors. Soldiers moving in formation will see control measures, friendly

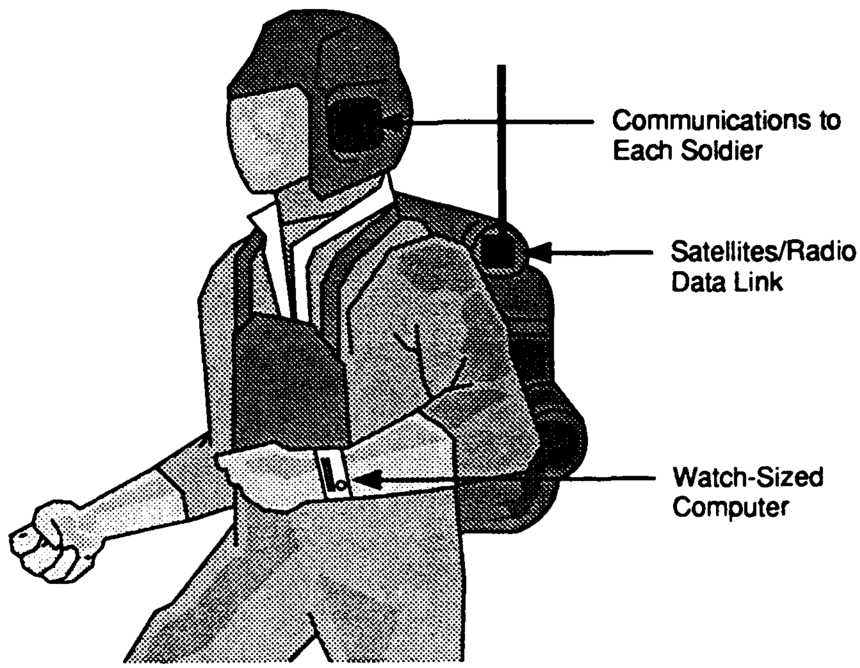

FIGURE 9-2 Soldiers in 2020 will have direct communications and computer links to commanders for enhanced battlefield management.

locations, and mechanically sensed information about the enemy superimposed on the terrain. They will switch at will between natural and computer-enhanced images, for example, in order to "see through" obstacles. Soldiers performing maintenance will see diagrams superimposed on the equipment they repair.

Every soldier will be in continuous contact with command-and-control communications at low data rates through burst-mode cellular radio or direct satellite communications. Periodically, soldiers will access fiber-optic or high-power satellite connections for visual communications and data dumps, which will provide them with instructions, analytical programs, and expert-system support for their next mission. Instant terrain analysis will inform them of dead space, cover, and fields of fire. The individual soldier will never be lost.

The soldier's computer will monitor his or her status through skin conductivity, breath analysis, heart rate, and so on, checking for panic and ensuring alertness. If need be, it will inject medication; self-tightening tourniquets will eliminate fatal blood loss from extremities.

The soldier's individual weapon will help him or her aim by using computer vision and laser ranging. It will actively counter body vibrations, providing every soldier with sniper accuracy and some antiaircraft capability. Each soldier also will be able to call indirect fire, by aiming the weapon, speaking a command, and squeezing the trigger.

A soldier's training will be truly multi-echelon. The personal computer will analyze past performance and the day's training mission to determine the tasks on which the soldier needs to focus; it will display training materials and, either directly or through the soldier's leaders and peers, monitor his or her performance. Simulations will be incorporated into exercises, superimposing enemy, casualties, and the smoky and shattered battlefield onto the view of the terrain.

But the soldier will pay a price for these advantages as the gap between the individual's capability and the complexity of the environment increases. Eighteenth-century drill aimed at producing a human robot; the twenty-first century soldier will command robots on a battlefield of lightning-swift action. Rather than being conditioned to reflexive action, future soldiers will program computers to control the reflexes of their machines.

Rear-area maintenance will take place under conditions of dispersion, danger, and stealth appropriate to a Ranger operation, lest a careless word trigger an acoustic sensor. Human senses will be needed to clear terrain of tiny unmanned weapons and sensors, a horribly stressful task. Courage, discipline, and physical endurance will remain important; imagination, mental flexibility, and broad knowledge will become increasingly important, along with the mental endurance to continue integrating massive amounts of information from a wide variety of sources for long periods of time. The soldiers of 2020 will be better than their counterparts of 1990; they will need to be.

The key technologies for the individual soldier of the future are human–machine interfaces, battle control languages, simulation and modeling, and knowledge representation.

MANNED SYSTEMS

Large, expensive systems will continue to be manned, though crew sizes will be reduced. Optimal design and computer-assisted maintenance will increase utilization and effectiveness. Artillery will be automatically loaded and aimed in response to targeting data. Weapons will respond automatically and instantly to enemy fire and other signatures, according to pre-established plans; firefights may be over in seconds.

Stealth and countermeasures to it will assume critical importance. Many systems will be smaller and designed to use the terrain better, with low bodies and elevatable sensory suites. They will sometimes move in bursts, under the cover of noise and flash, at other times with infinite care, scanning for enemy systems with human and mechanical senses. Fire, smoke, radar chaff, blinding beams from laser and microwave energy, and noise-making devices will be used continuously to confuse or detect enemy sensor systems. While effective ranges will be extended almost indefinitely, signature reduction requirements may push some systems toward shorter ranges. Some projectiles may be propelled by compressed air or carbon dioxide, eliminating heat signatures.

Manned systems will rarely exchange direct fire. Instead they will use tele-operated projectiles (such as FOG-M) against high-value, hard targets and indirect fire against softer ones. Guns often will be used at close range in low-velocity, near-line-of-site modes, producing fire accurate and swift enough to hit moving targets just "over the hill." Manned aerial platforms will face increasing threats, as well as competition from unmanned aircraft.

The key technologies for manned systems are knowledge representation, sensor integration, and system design technology.

FIELD COMMANDERS

In 2020, commanders will integrate unprecedented numbers and varieties of systems. They will need, and have, real-time visual representations of forces and war-fighting variables (space, time, distance, resupply) at selectable levels of resolution. This ability to organize the presentation of large amounts of information, matched to commanders' information processing and assessment strengths, will provide them with an unprecedented ability to synchronize combat power (see Figure 9-3).

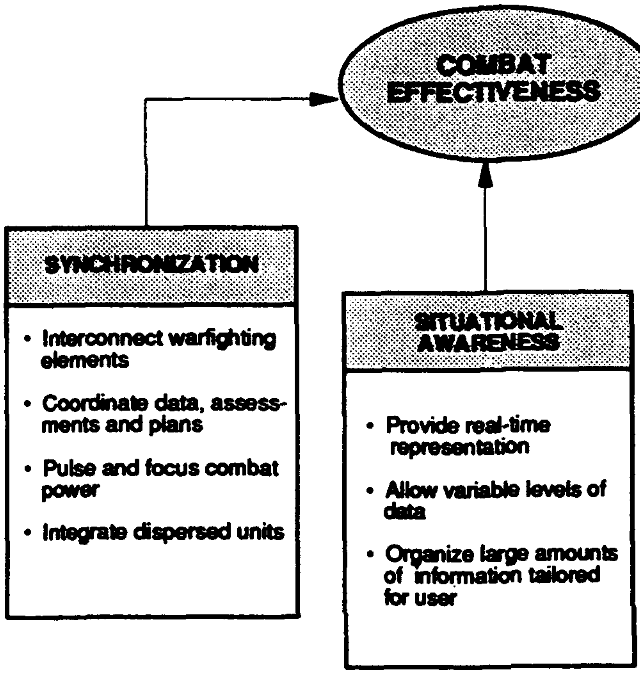

FIGURE 9-3 Significant technology thrusts based on computer science, artificial intelligence, and robotics will enhance combat effectiveness.

Commanders will focus combat power from widely dispersed force elements: some in close contact with the enemy, some located as much as thousands of miles away. Force element "ownership" will change rapidly and frequently, creating tensions with the psychological needs of soldiers and the volume and integration of information. Orders will be prepared and implemented by computers and humans in combination, with great speed.

For the first time in modern war, commanders at every level will know where all their forces are, all the time. On demand, they will be able to monitor their troops' logistical status and physiological indicators of their degree of exhaustion and fear. Commanders will be tempted to curtail subordinate initiative.

Unimaginative enemies will find their order of battle and maneuvers anticipated. Decoys and feinting maneuvers will trick them into committing forces too early and in the wrong places. Deception will become an essential part of all maneuver; no substantial forces will move anywhere undetected. Weapon systems will be reprogrammed in battle, in response to countermeasures and new threats. Skillful commanders will recognize and decisively exploit weaknesses in enemy sensing or programming, thereby achieving victories even against heavy odds with minimal friendly casualties.

The size of headquarters will decrease, as paper records and grease-painted maps are replaced by electronic storage and display; humans will make decisions, not record and transmit information. Commanders can be separated physically from their staffs without losing information, using "smart helmet" information displays and shared interactive computational environments. They will need to carefully control their own information flows, looking for the key information in the mass of data and avoiding being overwhelmed.

Widely dispersed unmanned weapons will make it difficult for commanders to move around the battlefield, yet communications, remote sensing, and displays will make it possible to control battle from thousands of miles away. As in World War I, the physical and emotional remoteness of the battle controllers from the battle fighters may lead to disastrous decisions, high casualties, and low morale.

In 2020 more than ever before, good commanders will be priceless, and bad ones disastrous. Fortunately, commander quality can be improved. Training exercises mixing live troops and fires with simulated ones, opposed by an aggressive enemy, will provide unprecedented training realism. Continuous physiological data collection will identify panic. Performance will be assessed on the basis of direct, objective, and fairly complete information, collected directly from the ubiquitous sensors and personal computers.

The key technologies for field commanders are battle control language, the mathematics of uncertainty, knowledge representation, network management, battlefield robotics, human–machine interface, and distributed processing.

LOGISTICIANS

Logisticians, like commanders, will benefit from the new ability to gather and display information. Many of their calculations (e.g., time and distance or supply requirements) will be automated. Keeping track of material will be much easier, though the quantities and variety of material to be tracked will increase dramatically.

Field handling of material will be reduced to a minimum. Rapid communications and computerized priority tracking will allow shipments directly from the rear. Computers will assist in damage assessment, provide real-time status of fighting capability, enhance onsite diagnosis, guide repairs, assist in system reconfiguration, and control parts substitution.

Materiel often will be transported by unmanned air vehicles (UAVs), or mobile ground vehicles. Unmanned logistical ground vehicles will be closely based on civilian designs to reduce costs, whereas UAVs will resemble ultralight aircraft. Wastage will be high, and logistical support generally austere. Required indirect fire tonnages will drop, as massed targets are replaced by dispersed networks.

Weapon systems, optimized using new design technologies, will show greater lethality, reliability, and flexibility. As factories for civilian products become more flexible, careful design will permit military and civilian items to be produced on the same equipment, allowing unprecedented surge capability.

In consequence, the traditional boundaries will blur among logistics, intelligence, procurement, research and development (R&D), tactics, and strategy. Consider the following hypothetical but technically feasible scenario. An attacker might identify a key weakness in the sensory capability of an opposing defender's backbone systems. In secret, the attacker may plan and produce unmanned systems that exploit these weaknesses, employing plants designed for dual use and highly flexible manufacturing. With systems produced in secret over time, or within a period of a few days or weeks to preclude effective response, the initial attack could be overwhelming. So the clever logistical exploitation of a tactical insight gained through good intelligence may deliver a strategic victory.

The key technologies for logisticians are integrated system-development technologies, battle control language, network management, distributed processing, computer warfare, and data base management systems.

STRATEGIC PLANNERS

The strategic planners of 2020 will face a bewildering variety of threats. For several reasons, war will become more common and threatening, and the boundary between war and peace will blur. The Persian Gulf war illustrated how casualty considerations have become a major factor in modern strategic planning and in the acceptance by the U.S. public of contingency operations.

First, war will become more acceptable to the peoples of advanced nations, including the United States. Human casualties will decline for armies that successfully employ unmanned systems, although defeated forces and civilians may suffer horrifying losses. The victor's few casualties will be highly trained professionals. As the ability to control friendly forces increases, and as skill becomes more important than commitment, mercenaries may reappear as significant military components. Americans have already demonstrated that they will support short wars involving casualties comparable to the highway toll on a bad Labor Day weekend.

Second, the rewards of aggression will be higher. Computers become obsolete in two or three years; hence, it will be difficult and expensive to maintain a computer-based army at a high state of readiness. Conversely, it will be possible to expand a computer-based army rapidly and secretly. A potential aggressor can hope, by astute timing and the careful use of countermeasures, to overwhelm his victim quickly and at minimal cost. As the pace of technological change continues to accelerate, the possibility of technological surprise will increase, even from foes who appear at some time to be technologically behind the United States.

Third, war may cease to be the province of nation-states, which often can be deterred by the threat of retaliation. Unmanned systems can render large or small pieces of terrain almost inaccessible to government police, tax collectors, and military patrols, at little risk and reasonable cost to those who emplace them. Drug lords; ideological, religious, and ethnic factions; or even corporations (seeking, for example, freedom from pollution laws) may replace governments as the primary controllers for large areas. These rulers will stay carefully hidden, immune to retaliation.

Fourth, threats to the United States are likely to increase. Soon, small nations and even large companies or drug cartels will be able to launch attacks using unmanned aircraft that are armed with chemical and biological weapons and guided from commercially available terrain data bases. It may often be impossible to determine who launched the attack; preemption will be an attractive option. The temptation to close down the coca fields by setting unmanned systems to guard them will increase. Even pollution may one day be regarded as a reasonable cause for war, as the most dangerous waste-producing activities move into the least-regulated nations and the potential for low-risk strikes increases.

Fifth, technological imperatives may be producing subtle changes in world societies, creating the potential for conflicts between liberty and progress on one hand and democracy and equality on the other. These conflicts may foment new kinds of threats to U.S. interests.

The military, production, information, and motivational technologies of the industrial age (the seventeenth through the twentieth centuries) have reinforced democracy and democratic institutions. These technologies rely on and empower the individuals who compose the bulk of modern societies. For example, the mass armies of the industrial age have been built primarily on the citizen-rifleman; a few month's training, coupled with determination to defend his cultural values could make this citizen-soldier the rough equal of the best armed and trained professional. Similarly, mass production systems are built around the assembly line, whose productivity depends on the joint abilities and mutual good will of large numbers of semiskilled workers. Mass communications supply the same information to anyone who can afford a newspaper, radio, or television. Modern authoritarian governments, communist and fascist alike, have sought control largely through ideological commitment generated and sustained through mass propaganda. In the century now ending, the principal threat to U.S. interests has been from authoritarian regimes that promised their people either a postindustrial millennium or rapid transition from a hierarchical preindustrial culture to a mass industrial society of equal means for all.

It is less clear that mass equality of means is compatible with twenty-first century technology. The military, production, information, and control technologies of the computer age rely on and empower elites defined by their superior abilities and skills, a meritocracy or, in the original sense of the work, an aristocracy. In a war fought largely with unmanned systems, the abilities of a few designers, commanders, and highly skilled professional soldiers may outweigh the mass army of citizen-soldiers. Perhaps the remarkably low casualties suffered by the technically superior U.S. and allied forces in the Persian Gulf war against a supposedly "battle-hardened" Iraqi army provides a first instance of the new pattern. Automated factories already in operation depend on just a few highly skilled maintenance and supervisory personnel. Compared with the newspaper broadside or the broadcast, information stored and transmitted by computer can be private; it is also too voluminous for any but the brightest and hardest working to comprehend and use to advantage. Corporate raiders have earned phenomenal returns in part by exploiting the computer's power to sift financial data. The most successful economies of the late twentieth century, those of the Pacific rim, provide substantial economic liberty and superb educations for their elites, but they have not provided democracy in the sense of mass participation in multiparty political systems.

In the most extreme possibility, computers could conceivably be directly used to control people, with a tiny system permanently attached around neck or ankle. The computer would track their whereabouts, listen to their conversations, and check their emotions. Perhaps it also could condition their emotions, injecting euphoric drugs at the sight of The Leader's face on television, or depressives in response to anger directed at the boss (sensed by his own computer). We cannot predict the effects of such a slavery, particularly if imposed at an early age.

These nightmare scenarios underscore two points for strategic planning. First, the technology of the computer age does not necessarily make the world permanently safe for democracy and traditional American values. Second, planners should think about being proactive in preparing for threats mounted with the aid of advanced computer technology. Waiting until an attack occurs to start preparing to defend democracy could be even more costly than delayed reaction has been in the past.

The strategic planners of 2020 therefore will face direct threats to U.S. citizens at home, as well as to allies and sources of raw materials. It may become necessary to eliminate potential threats before they become dangerous. Planners may be required to use military forces to supplement police forces, for example, in clearing urban areas of unmanned weapons emplaced by gangs. Planners will need to develop new systems much more rapidly than at present or face obsolescence. Yet they must manage their production with great care to avoid bankrupting the economy.

Computers, data bases, and software programs will themselves be targets. Potential enemies will seek to tap the massive information stores, gathering intelligence. They also will act aggressively, subverting programmers to plant hidden errors and dormant viruses in large programs, capable of destroying systems at critical junctures. However, strategic planners also will receive massive assistance from computers. Data bases will be maintained on all threats. Programs will watch for the signs that a threat is increasing and advise on countering it.

Units will be swiftly reconfigured, trained, and equipped, enabling them to adapt to a wide variety of battlefields. The right units and the right equipment will, in general, be sent to the right place. Military planning will be tightly integrated with civilian production, research, and development, with much hardware and software being converted to military use with minimal adaptation.

The key technologies for strategic planners are knowledge representation, distributed processing, and computer warfare.

10

Fundamental Limitations and Practical Constraints

HARDWARE

Device-level or transistor-level miniaturization will fairly soon reach limits set by quantum mechanical effects and manufacturability. However, computers are still mostly packaging, connections, and interface systems. Increased production yields, three-dimensional stacking, and improved interfaces will make possible much smaller machines even with conventional technology. Optical or biological computing may completely leapfrog these limitations.

Communications will remain an important limitation. Non-line-of-sight radio can carry only small amounts of information, and line-of-sight and fiber-optic systems are vulnerable to enemy action. Direct satellite communications offer high bandwidth and fairly low vulnerability but at considerable cost.

Mechanical hardware and electronic sensors will improve steadily, but they will continue to be less flexible than similar human capabilities. Their power will continue to reside in the ability to tailor them for specific tasks at which they far exceed human capabilities.

In summary, hardware improvements are likely to continue to be rapid, at least for some time to come. The real limitation will lie less in the computers themselves than in our ability to understand how to use them.

SOFTWARE

Software development and maintenance are already difficult. Large-scale development failures are common, and large successful programs often must be maintained long after obsolescence because they cannot be replaced safely. Computer languages multiply; compatibility problems plague every field. Recognized computer software development and maintenance represents 8 percent of the DOD budget, or about $25 billion, and is growing rapidly. Of that, 85 percent is for labor-intensive rework, maintenance, and updating of software originally developed for previous generations of hardware.

These problems will be worse in 2020, despite continuing advances in software technology. The Army can achieve fully trusted software only by slowing development so far as to give potential adversaries a decisive advantage. Decision-makers need to understand why this is so. There are six fundamental reasons:

1. Even "buggy" (i.e., algorithmically imperfect) programs can be enormously useful. Indeed, the heuristic or expert-systems approach to programming can be viewed as the deliberate acceptance of buggy algorithms that usually work. We cannot restrict ourselves to problems for which we can guarantee correct solutions.

2. Programming requires us to imagine possible future situations, represent them in a precise formal language, and decide what should be done when the situations arise. But decision-makers miss key factors even when events are directly before them, still more so when the events are only imagined. When we contract for a program, we cannot be certain that the programmers will understand the problem well enough to represent it accurately, or make the right decision, years and miles from the events themselves.

3. The Technology Group foresees millions of computers running thousands of programs, all interlinked. Many of these programs will be huge, not so much written as evolved by thousands of people over the space of decades. Old programs do not wear out, and they can be improved more easily than old machines. The improvements correct some errors deliberately and others more or less accidentally, but they also introduce new errors and usually increase program complexity. As the program becomes harder to understand, it becomes harder to replace, since complete replacement is certain to introduce new bugs. Some of these programs will have been written by enemy agents; the enemy will exploit the predictability of the rest.

4. Special-purpose languages (for example, spreadsheets, hypertext, and expert-system shells) offer such enormous advantages that they will continue to evolve. As the problems they attack become more complex and diverse, so will the languages; compatibility and standardization must be striven for but will never be achieved.

5. Learning systems are helpful but no panacea. First, such programs must be tailored to the material to be learned, a task involving great skill and considerable luck. Second, the results of mechanical learning are often impossible for humans to understand and therefore to trust or modify. These problems apply especially strongly to neural nets.

6. High-level languages, including the specifications languages used in "automatic programming" and "verification" systems, can help by making the problem statement more intelligible. However, mathematical verification cannot in principle be fully automated, and in practice is possible only for relatively small programs. Further, verification can show only that the program is consistent with a set of specifications, not that the specifications are consistent with the real world. Finally, while high-level languages require less attention to detail than do low-level languages, the more complex problems they can address often require the programmer to have more mathematical sophistication and domain knowledge. They also move the programmer further from the problem, sometimes encouraging mistakes.

Even in 2020, computer systems probably will remain more predictable and less adaptable than humans. Thus, even if software works correctly under the planned conditions, the enemy may be able to exploit its characteristics. This can lead to swift and total defeat. Ways must be found to produce software that is as robust as possible. More important, we must provide battle commanders with the ability to modify quickly the behavior of their systems, in order to adapt to new threats.

Rapid hardware development will continue. In some ways this makes the software development task easier, because hardware speed can sometimes be substituted for software sophistication. However, user expectations tend to rise in parallel with hardware capabilities; the software to exploit those capabilities develops more slowly. Worse, increases in hardware speed may require new, parallel architectures that appear much harder to program than the serial architectures that are currently standard.

The Technology Group expects software development technology to continue (see Figure 10-1), but also expects software development to be a controlling item in most substantial Army development processes. The major implication of these predictions is that the single greatest challenge the Army will face may be to provide human resources that can efficiently exploit the capabilities of its computers. By experience and training, the Army's senior technologists are hardware oriented; the pace of change coupled with the critical importance of software to military performance will create a severe mismatch between available and required skills. Addressing this mismatch is likely to require a massive and continuing educational effort in advanced software skills.

HUMAN LIMITATIONS

Computers can manipulate information more quickly than communication systems can transmit it and far more quickly than humans can understand and integrate it. In battle, users who are overloaded with information may break down or make catastrophic mistakes. One implication of this difference between computer and human information processing for robotics applications is that tele-operated robot systems, although useful in specialized roles, are unlikely to have the impact of autonomous systems.

In peacetime, our ability to adapt to change sets a principal limit on the speed with which we can adopt computational technology. Educational limitations worsen the issue. The programmer must envision a wide variety of future events, decide how to represent them in a formal computer language, decide what action should be taken when these events occur, and express these decision criteria in computational language. All these actions must be performed carefully enough that unexpected events will not trigger severely wrong decisions. This requires, first of all, unusual military knowledge,

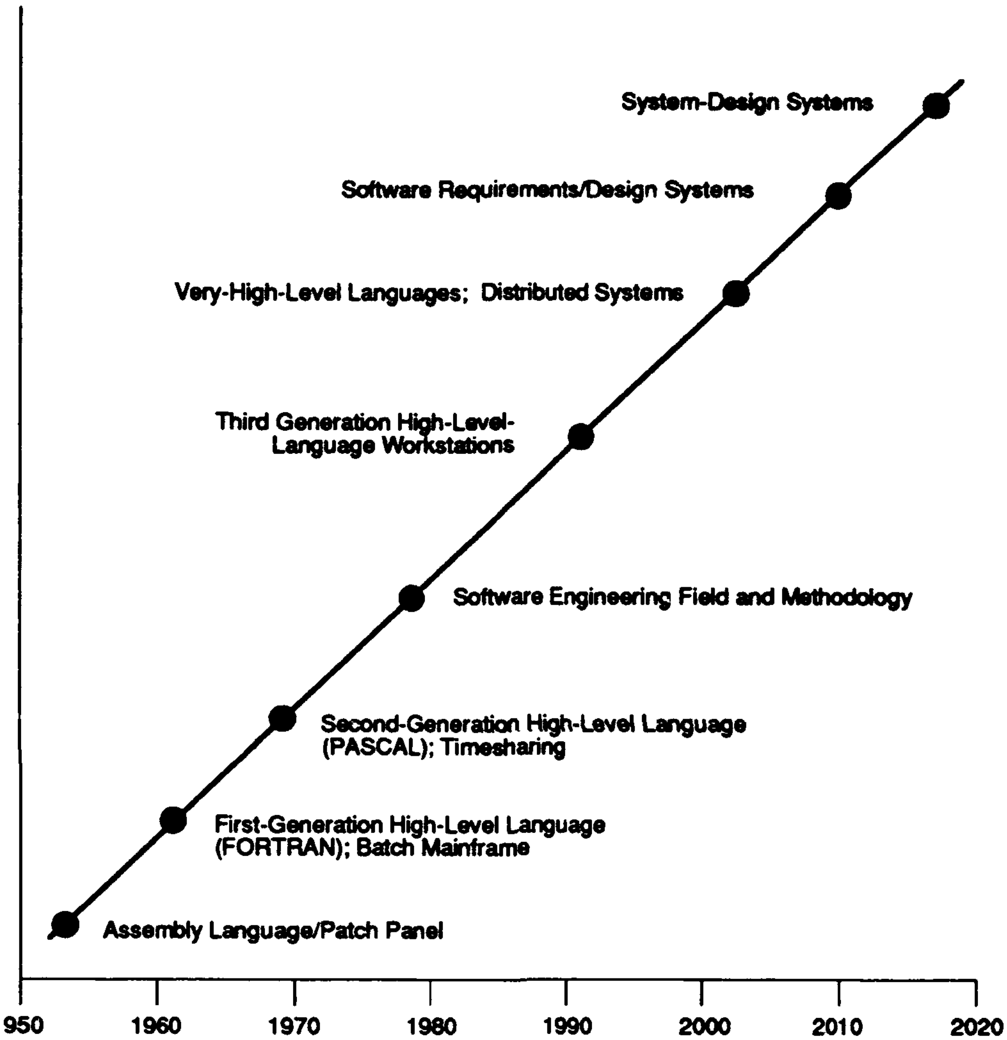

FIGURE 10-1 Software development advances will feature high-level languages and increasing ease and reliability of programming.

imagination, and judgment. Second, it requires the command of a new set of technologies. Such individuals will remain in very short supply, even if we start now to try to produce them.

Finally, organizational inertia may produce an army in 2020 little different from the army of 1990. The 15-year peacetime procurement cycle is absurdly inadequate when applied to computers, which become obsolete in two years. The new systems, like any revolutionary technical development, will disrupt existing military structures and industrial competencies. Especially when adopted too soon, they will be expensive and often will not work. When they do work, they will remain vulnerable to enemy countermeasures. They cannot be trusted blindly or simply substituted for humans; they require understanding on their own terms. They are surrounded by cycles of exaggerated expectation and disillusionment. In general, they will not be welcomed.

Still, the underlying technologies are changing faster and faster. We ignore them at our peril. In addition to continuing to support a broad range of research, the Army needs to focus attention on some key technologies. These key technologies for Army attention are discussed in the next chapter. But one must not lose sight of the final major implication of this discussion of constraints and limits. Computer technologies cannot be considered in isolation; their development must be integrated into the development of the Army and its personnel as a whole. Accomplishing this integration at the speed required by technical developments will be an extremely difficult task. Succeeding will provide U.S. forces with the kind of technological edge that can be a sustained force multiplier well into the next century.

11

Recommended Army Technology Thrusts

The following sections discuss three broad technology areas in which the Technology Group believes that the Army should assume a leading role. The introduction to each area describes its Army-unique aspects and the impact that success would have on the Army. The remainder of the section then discusses in more detail the component technologies in that area.

INTEGRATED SYSTEM-DEVELOPMENT TECHNOLOGIES

The topics discussed here are generally referred to under such titles as software engineering, electronic system development, mechanical design, design for manufacture, and total quality management. If each area is considered independently, the Army can probably afford for the most part to trail civilian practice. However, where these technologies relate to one another and, more importantly, where they relate to tactics and training, the Army will need to take the lead. The cost of failure to do so will be enormous; it will be counted in ballooning software costs, cancelled programs, and defeat on the battlefield. What is needed is a variety of approaches that cut across the arbitrary boundaries between these fields.

The Army's Development Challenge

An emerging confluence of technologies is revolutionizing the way in which complex systems are specified, designed, and procured. These include low-cost, high-performance workstations, simulation and optimization technologies, languages for describing designs and environments at multiple levels of abstraction, and new understandings of the development process. The Army currently trails civilian industry in these areas. But because of the unique character of its system development needs, it cannot simply adopt the best from industry or its sister services. Rather, it needs to play a leading role in developing these technologies.

The Army's development challenge is unique in the following ways. First, the number of different systems that must be managed—and the complexity of their interconnections—is greater than for any other organization, civilian or military. Second, the ground battlefield is more varied and changes more rapidly than any other battlefield or any civilian market. Third, the battlefield changes in response to the development process; new systems trigger responses that dramatically reduce their effectiveness. (For example, consider the dynamics between the current generation of antitank missiles and reactive armor.) Few other system developers are forced to operate in so complex and unpredictable an environment.

Fourth, there is the potential qualitative difference in cost of failure. If a civilian systems development effort misses a target date for production release by a few months, the cost may be in millions of dollars. If a critical Army system misses field release by a few months, the cost may be in lives, perhaps even in battles lost. A modern army that cannot develop faster than its opponents may find itself out-developed into defeat.

Fifth, the new design and automation technologies tear down the walls between planning, specification, design, and manufacture. Victory in battle may depend on the rapid development and production of an automated weapon system precisely tailored to exploit a specific enemy vulnerability. The development teams will need to be small, sharing intelligence about the enemy and their expertise in tactics, software, and electronic and mechanical hardware. They can pool their knowledge of, and access to, civilian production lines to achieve development times measured in weeks rather than years. Development will become a form of maneuver, whose aim is to establish and exploit breakthroughs and gain advantage from an enemy's weaknesses.

The widespread introduction of computation on the battlefield will exacerbate these problems. The current process from basic research to fielding produces computer systems that are obsolete before the first unit is in the field. System development needs to be much more rapid. Mechanical hardware must be designed for use through multiple cycles of electronic, software, and doctrinal change. The two-year computer obsolescence cycle and the vulnerability of unmanned systems to countermeasures will make it impossibly expensive to maintain constant superiority over every potential threat. Instead, systems will have to be designed to meet potential threats, then fielded only as those threats materialize.

If this process is successful, by 2020 the development process will be an agile offensive weapon. Processes and computational tools will simultaneously develop complete systems, including platforms, sensors, weapons, computer hardware and software, training, and doctrine. Systems will be robust: effective and reliable despite variations in tactics, enemy, other systems, and weather. Developers will model the effectiveness of alternative systems at varying levels of detail, deepening the model as the system design develops, and making rational decisions among tactical, manufacturing, and development cost issues. Military needs will be specified irrespective of the division of systems between hardware or software or platform. Design trade-offs at the system level will interact automatically with those lower levels that are specific to platform issues (e.g., weight, speed, size), sensors, weapons, and computers.

The discussion now turns to the technologies that will allow this transformation. Throughout, the Technology Group has attempted to address the complete system.

Development Environments

Good development environments, with convenient representations and flexible tools for debugging and performance monitoring, have contributed heavily to improvements in software engineering productivity. Comparable environments are beginning to emerge in the digital design domain. In mechanical design, however, computational representations of geometry are too low-level to have positive effects on overall productivity. A variety of feature-based design efforts are attempting to combine information about geometry with information about intent, though generally still at a fairly low level of abstraction. At this level, several initiatives of the Defense Advanced Research Projects Agency (DARPA) are expected to produce new computational techniques for sharing common data bases among the development team. This will be much more important for the Army than for most civilian organizations, because of the geographic dispersion of the Army's development efforts. The physical co-location normal for concurrent engineering teams is often impossible for military systems.

No one at this time seems to be considering a complete *system-development environment* (Figure 11-1). Such an environment probably requires a substantially better understanding of the nature of the design processes, as well as new software architectures to handle the variety and volume of computation required. However, we are confident that such environments will ultimately emerge, dramatically speeding the system design process.

Design Languages and Compilers

Viewed as a computational rather than a structuring technique, the idea of abstract representations for designs leads naturally to the idea of high-level languages in which to describe the design. A compiler would translate the design language descriptions into more detailed descriptions. There are two fundamental issues connected with this idea: (1) Is the high-level language description correctly translated into an acceptable implementation? (2) Does it accurately reflect what the designer wanted in the first place?

The first problem has been addressed most successfully in software engineering, where run-time efficiency losses in compiler-generated machine code are normally unimportant compared with the enormous gains in programming efficiency. Instead, general-purpose high-level languages are bounded largely by the second problem, leading to the development of a variety of specialized languages that make it easier for the designer to express his intent for particular domains. Extremely high level specification languages for automatic programming have been demonstrated for very narrow applications, but major and unpredictable breakthroughs may be required to

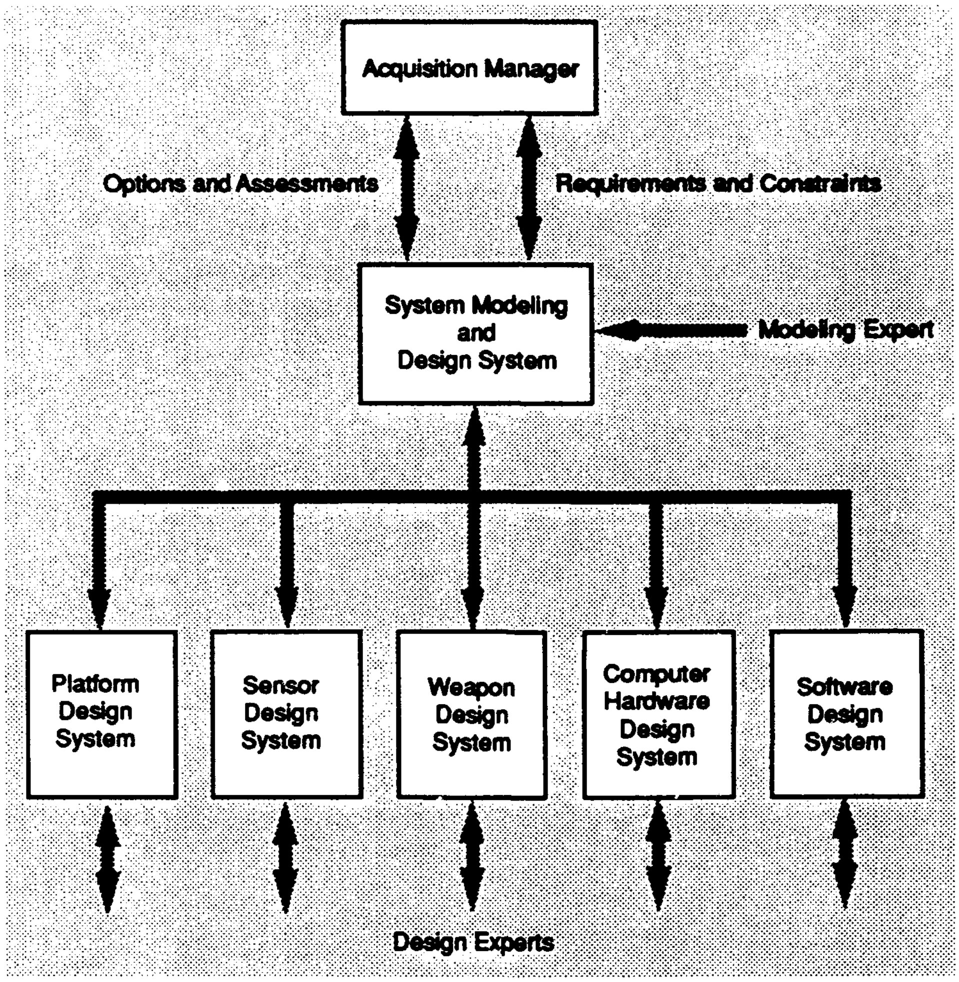

FIGURE 11-1 Future development environments will integrate computer-aided system design from multiple sources.

achieve general-purpose automatic programming. The Technology Group expects that software design in 2020 will remain a difficult problem, but that very-high-level languages will have shifted most software development out of the hands of programmers and into those of experts on the problem the software is intended to solve.

Over the past five years, in a program supported primarily by DARPA, considerable progress has been made in automating the design of very-large-scale integrated (VLSI) circuits, in part through the use of "silicon compilers." Today it is possible to proceed from design specifications to hardware implementation using computer-assisted design (CAD) software, workstations, networks, and silicon foundries that accept circuit designs and yield physical circuits embodied in silicon. By 2020, the Army can expect adequate infrastructure as well as design tools, languages, and improved foundry engineering to deploy such technology to forward maintenance depot sites. It will be possible to program and produce application-specific integrated circuits (ASICs) and special-purpose microprocessors for special weapon, signal processor, or communication tasks with turnaround times of one day. The Army needs to maintain both an active electronics CAD program and continuing research in methods to identify and exploit ASICs with production runs as small as one chip.

In mechanical design, both the mechanical components and the interactions between them are more complex than in electronic design. Optimization with respect to manufacturability tends to be more important and complex than in either software or electronic hardware design. System structure can rarely be as "clean" and logical as in digital hardware. Hence, mechanical design compilers lag substantially behind their counterparts in electronic design. *Parametric design* systems tie geometry to equations, enabling the easy design of families of components. *Expert systems* can automatically generate designs for narrow classes of objects. Special-purpose, very-high-level programming languages, tuned specifically to mechanical design, are available for the construction of these systems. More general mechanical design compilers and languages are just beginning to appear. By 2020, we project that all routine mechanical design tasks will be done automatically, allowing the rapid exploration of many alternatives, and the very rapid design of new military systems.

Problem-Solving Strategies

Real-world problems are all examples of *heuristic construction*, or the creation of a complex solution by incrementally piecing subsolutions together. By contrast, early expert systems relied entirely on *heuristic classification*; their problem-solving strategies took advantage of a limited number of possible solutions to the problem.

The AI field is now developing problem-solving strategies that work for design problems in which there are huge numbers of possible solutions, so heuristics are needed to construct reasonable candidate solutions. Further progress in all of the following areas will make these techniques applicable to much wider classes of design problems:

- *Conceptual modeling of the application domain*. The model may include static and dynamic properties; it may emphasize the use of high-level abstract concepts similar to those used by humans. These features also permit interactive design, because the machine and human can interact at a level of abstraction that is natural for the human.
- *Abstraction hierarchies*. Abstract concepts need to be tied down to, and computable from, lower-level details.
- *Representations for intermediate, partial design information that captures dependencies among design goals, constraints, and decisions*. These representations must deal with abstraction hierarchies, alternative designs, and goal structures. They must also support incremental redesign and design modifications.
- *Problem-solving strategies operable at high and low levels of abstraction*. Such strategies must adapt to work with the dominant constraints and must exploit domain-specific heuristics.

Simulation and Optimization

Simulation systems take design descriptions (usually low-level) and computationally predict and display their performance under a set of circumstances. Simulation and visualization tools allow the user to anticipate the consequences of decisions by playing out the results. For example, these tools can allow a researcher to "walk" among the molecules of a new material or a designer to "drive" a vehicle that has not yet been built. High-level simulation languages, merging with object-oriented programming techniques, will continue to make simulations easier to construct. By 2020, little effort should be required beyond that needed to formulate the design (or the operational plan) itself. High-resolution simulations, calculated directly from first-principle nonlinear equations and physical relationships, will replace dependence on linearized models. The capacity for such high-resolution, high-realism simulations will be particularly valuable to the researcher and the designer.

Real-time, interactive simulations of complex systems and operational environments will be achieved by networking thousands of dispersed individual simulations, simultaneously processing information at various levels of abstraction and detail. SIMNET (Simulation Network), originally developed by DARPA, is a significant step toward this goal. Simulations combined with computer image generators will synthesize virtual environments, allowing the user to examine and interact with ideas at scales ranging from atomic to cosmic.

Simulations at high levels of abstraction will continue to be used to predict the effects of proposed systems or doctrinal changes. These must be treated with care; they move the point at which human judgment is applied away from the top-level decision and down to numerous lower-level assumptions. Although the low-level assumptions are individually easier to generate, they may be too numerous and interconnected to be verified completely.

Optimization programs (often "wrapped around" simulations) systematically vary the design parameters, then simulate or analyze the resulting designs, looking for the best. They are therefore generally slower than compilers, but they can often achieve good designs even when reliable design rules are absent. For example, turbines are now optimized by programs that systematically vary their operational parameters while evaluating the results through analytical programs.

However, simulation procedures do require that a design be formulated before it can be simulated. In addition, there are no general-purpose, completely reliable, and reasonably fast methods for optimization. As always, the form in which the design problem is represented can control its solution. This makes some creative solutions impossible and leads to bad solutions when the problem has been poorly stated. Mixed systems, involving logical operations and nonlinear algebraic or differential equations, are difficult to optimize. Unfortunately, this is precisely the class of system in which the Army is most interested.

In 2020, large networks of fast machines will perform very large optimizations with reasonable speed. Heuristic and learning systems will help guide the optimization process. Stochastic effects will be modeled. Simulation and optimization will be integrated with compilers and set-based inference mechanisms to create design environments in which a human works in parallel with multiple machines. The machines will monitor and extend human decisions as best they can, warning of problems, filling in details, and presenting the results in terms understandable to their human partners.

The Mathematics of Uncertainty

The Technology Group has placed this topic under system development, but the technologies discussed have important applications in battle control as well.

Centuries of physics tell us how to deal with single objects under particular conditions. For three reasons, the system developers must unfortunately reason about sets of objects under sets of conditions. First, manufacturing processes are not perfect, so the actual objects produced differ from the ideal that the designer may have had in mind. Second, no one can predict precisely the environments in which the objects are to be used. Third, each developer cannot know exactly what decisions will be made by other developers, or even by himself at a later time; he can make a confident decision only if he can be sure it will be correct regardless of other, later decisions.

The fact of variation has traditionally been ignored except in the last phases of the development process, where tolerance stackup may be acknowledged. For the most part, developers have performed their calculations on the basis of ideal cases, relying on factors of safety and military standards to compensate for variation.

The result is often expensive overdesign at most points and failure at others. Even when this approach can be used successfully by humans, it is poorly suited to automation. Computers cannot intuitively make allowances for variation or identify the points at which the ideal solution is likely to break down.

A range of methods have been proposed for dealing with the problem of variations:

- *Probabilistic reasoning* is the oldest and most firmly grounded of these, with a history of use in development that extends back at least to World War II. However, many sources of variation are not in fact probabilistic (e.g., decisions yet unmade); game theory can shed some light on these. Formal probabilistic reasoning often requires unavailable knowledge of conditional probabilities. Nor is it often obvious how to use probabilistic methods in development.
- *Taguchi methods* are a recent introduction from Japan to the United States (Taguchi, 1986). They have achieved a substantial following because they clearly identify mechanisms for tying probabilistic issues to development questions. They use reasonable approximations to deal with the problems of limited knowledge, which can bedevil formal probability theory. Their precise scientific standing is still hotly debated, but they are widely accepted in industry.
- *Dempster-Shafer probabilistic methods* have grown out of military-funded AI research (Shafer, 1976). They attempt to provide a formally based inference mechanism that does not require detailed knowledge of conditional probabilities. They do not seem to have been used in development as yet.
- *Interval arithmetic* has been used to reason nonprobabilistically about tolerances and about the accuracy of numeric software. The labeled interval calculus is an extension that has achieved some success in automating mechanical system design.

By 2020, researchers should understand the connections between these formalisms and be able to assess when each should be used. The Army needs to be deeply involved in this research, because the battlefield is a source of deliberately antagonistic variation unlike that faced by civilian equipment developers. The anticipated results include equipment at much lower cost, which is developed more quickly but can function reliably in a variety of environments despite aggressive countermeasures.

TECHNOLOGIES FOR INTEGRATING INFORMATION

Introduction: The 10-Million-Computer Battlefield

The battlefield of 2020 will see literally millions of computer systems and components, interlocked in complex grids and networks, serving myriads of tasks. These machines will range from tiny microprocessors embedded in weapons, to complex networked communications microcomputers embedded in helmets and sensors, to sophisticated mobile command-and-control centers scattered across the battlefield. All of the systems will be interlinked through a wide range of communications media using complicated switching and interoperation protocols.

The machines will be ubiquitous, critical, and essential. A whole new form of warfare will evolve based on the use of these systems and on methods to attack, deceive, and neutralize them. Battle results will depend on their performance and reliability. Strategy, doctrine, effectiveness, and results will all hang on the ability of the force to exploit computer systems.

In this section, the Technology Group discusses a variety of technologies needed to integrate the resulting profusion of information. These technologies are somewhat abstract and hard to grasp, but they are essential to victory. They will not be developed far enough or intensely enough by any organization other than the Army, because no other organization must coordinate the same number of computers, processing comparably vague information. For example, a large company may own tens of thousands of tools, each controlled by a computer or microprocessor, operating in a factory environment that has been deliberately (if not always successfully) designed to enable the entire system to work. The company's competitive environment may change on a scale of months, as new products are introduced and consumer tastes shift. By contrast, the Army may employ tens of millions of smart sensors and intelligent mines in an environment that an enemy deliberately makes as hostile as possible to the system's operation and that is subject to change in minutes.

Knowledge Representation

In 2020, more than ever, victory in battle will depend on the manipulation of knowledge, on Wellington's "knowing what is on the far side of the hill from what one can see on this side." Computers perhaps a million times more powerful than those now available will assist in this manipulation; the question is, "Will we know how to tell them what to do?" In part, the answer is, "Only if we know how to represent our knowledge."

Modern science and technology are the product of a series of developments in knowledge representation. Arabic numerals made multiplication and division, as well as logistical planning, practical. Descartes' discovery of the link between algebra and geometry made possible the calculus—and indirect fire. Boole's formulation of simple logic as an algebra of ones and zeros made possible the computer itself. In our time the search for new mathematical representations is driven by the computer. And because the needed mathematics often does not exist, the search for new mathematical representations is proceeding at a much higher rate than ever before.

An example will illustrate the state of the art. Suppose we seek to know based on interception of radar signals, where the enemy has placed his air defense batteries. He may have more than one kind of radar associated with each kind of battery. According to traditional Bayesian probability theory, a *posterior probability* for the location of the batteries can be calculated from a combination of *conditional probabilities* and *prior probabilities*. The conditional probabilities might include the probabilities for (1) certain mixes of radars, given specified kinds of batteries; (2) certain kinds of batteries, given specified kinds of terrain and targets; and (3) certain placements, given certain terrain and targets. The prior probabilities needed would be those of the terrains and targets in question. Once these conditional and prior probabilities are known, the radar intercepts would allow us to calculate the probability of finding each kind of battery. But, in fact, we rarely know these things in sufficient detail. This problem has led to the development of a new theory, Dempster-Shafer probability, which allows us to make the best possible computations in the face of our partial ignorance (Shafer, 1976). This is a more or less solved problem.

On the other hand, suppose we are trying to determine an attacker's course of action, based on sensor readings and front-line reports. Here, the enemy is moving. We cannot know for certain whether two reports refer to the same enemy unit; lacking this, we cannot even be sure how to index the information. We must reason about uncertain intervals of time, without being sure even what the subjects of our reasoning are. There is no satisfactory current representation for this kind of problem.

As this example suggests, knowledge representation is closely linked with the development of new mathematics in a general sense. Most of our current mathematics arose from efforts to represent physical phenomena; it has remained limited by the relative simplicity of the phenomena that could be studied and the simplicity of the symbolic manipulations possible with pencil and paper. Chaos theory and the theory of algorithms are just two examples of new mathematics arising more or less directly from work with computers. Also, there is new work in design and planning that is shifting the emphasis from the traditional focus on functions to mappings and the study of ternary relations. As a consequence of computation, logic has undergone a transformation in importance and scope. These current directions in mathematical representation of knowledge will expand and new ones will join them as human minds continue to interact with computers.

No one can predict what knowledge representation technologies will be available in 2020. Indeed, the term likely will be obsolete; as the dependence of science on computation grows, knowledge representation may be seen as synonymous with science. But it is very clear that we will not have reliable programs for predicting enemy actions, or even the results of our actions, unless we have mathematical tools for reasoning about time, about terrain, about sets of possible futures, and about an amorphous and uncertain enemy. No other organization will fund the development of these tools; in this area, the Army must fund basic research.

Battle Control Languages

Current top-down programming methodology requires a full understanding of the problem and a formulation of the solution before writing any code. But the programs of 2020 will coordinate millions of computers and humans in the face of an intelligently innovating enemy. Complexity, chaotic change, and the obscuring fog of war will preclude the understanding required by current programming methods. Bugs and conceptual errors will require commanders and privates alike to reprogram computers under fire, because weapons, soldiers, and computers will be so intermixed that shooting, commanding, and programming will be inseparable. In the Falklands war, antiaircraft missile systems were in fact reprogrammed under fire. Despite all simplifying efforts, soldiers will live (and die) under information and skill overload.

To fight on the 2020 battlefield, the Army will need to develop new, Army-specific, very-high-level computer languages. Just as the spreadsheet so closely mirrors business calculations that most users don't realize they are programming at all, these *battle control languages* will take control of the computational battlefield away from technicians and give it to commanders. They will be based on the following six concepts:

1. *Create high-level computer languages that make programming look like thinking about battle.* Statements in these languages will look like

operations orders, unit TOEs (tables of organization and equipment), and map graphics. Soldiers will understand what they are telling the computer to do, because the language interpreters will be based on the concepts and formats that the soldiers actually use.

2. *Use limited, simplified languages where possible.* For example, the uniformity and simplicity of rules can sometimes make complex expert systems predictable and understandable.

3. *Develop mathematical models for battle.* Programs always implement some mathematics. They are powerful when the mathematics is clearly understood and accurately represents the domain. The complexity of battle will require the development of new mathematics, such as new forms of knowledge representation drawing on chaos theory, map theory, or new logic systems.

4. *Experiment and improve constantly.* Battle control programs, like all large programs, will contain bugs. The early theories will be wrong. Theories and code must be tested and improved early, often, and in the field.

5. *Build in local robustness.* For example, a "move unit" instruction should not allow a user or program to move a tank unit through the middle of a deep lake. Systems also must be fault-and-noise tolerant; they must, for instance, be able to ignore a single piece of bad data and must degrade gracefully when overloaded or pushed beyond their capacity. Layered architectures, distributed representations, and carefully defined interfaces and objects are all mechanisms for ensuring that a program module will behave as well as possible, even when other modules fail.

6. *Build compatibility or commonality on good theories.* Logistics and operations must share representations of units, lest information transmitted between units at the speed of light require retyping between desks. However, those representations must be valid and not merely directed from above.

Battle control languages will let commanders control, read, and summarize nearly instantaneous data flows about unit status and logistics. Continuous simulations and watchdog programs, running in the background, will provide "what-if" advice. The commander and his staff will easily modify these to reflect immediate experience and the peculiarities of the unit, enemy, and terrain. Historical data will be collected automatically and analyzed continuously.

Broad mission orders will automatically generate implementing instructions; many of these will be directly executed by automata. Intelligence will be correlated and communicated in seconds, and operation orders prepared and transmitted in minutes, reducing an attacker's planning advantage.

Network Management

Sophisticated data processing and communications systems supporting the Army in the field and throughout the logistics chain, as well as in command locations, will depend on complex computer networks. The networks of 2020 will carry voice and data at very high data rates. Network connections will be available anywhere in the field, either via digital radio links or through hard-wired connections. Many different networks will be interfaced or "gatewayed" together, and access will be largely transparent and ubiquitous to Army users. Such networks exist today; in fact, some of these features have been available for 15 years. However, the rate at which technology is being infused into the battlefield sector suggests that the current unsolved problems of network management will continue to plague the actual deployment of these technologies in 2020.

Problems arise when different networks with different access schemes and protocols are required to communicate with other networks or to pass traffic through to additional networks. Addressing problems will multiply geometrically as different networks are interfaced. Delay and reliability, throughput, redundancy, priorities, and so on, all remain largely unsolved problems. Today a practical solution is possible for a bounded problem, but no large general-purpose solution exists for large, high-bandwidth, and multimedia interconnected networks.

In considering most Army applications in the year 2020, be they C^3I problems, battlefield control languages, sensor networks, air support, airlift, or fire control, it is clear that these systems will have multiple interfaces with other systems. Research is needed on protocols, network performance, and network management. The Army also can play an important role in this technology development because the nature of the battlefield requires a more robust and multimedia approach to the network management problem. The Army has an especially useful role to play in offering prototype and experimental environments for the 2020 deployment of this technology.

Distributed Processing

The Army will distribute its computation across thousands and ultimately millions of machines. Distributed processing can be characterized by the level at which a new application must interact with the distributed complex:

- application;
- object data base, messages;
- operating system, network protocols; or
- hardware (processors, links, sensors, effectors).

Today the level of distributed processing is typically the operating system or the protocol. By 2020, it should have advanced to the application level. Interaction at the application level will accomplish distributed sensor fusion, situation assessment, operations planning, and other decision-making, based on sophisticated models of space, time, network topology, delays, rumor propagation, sensor status and performance, and weapon status and performance. To support this advance, the Technology Group foresees (1) massively distributed worldwide networks down to each soldier, (2) dynamic real-time protocols as part of distributed operating systems, and (3) distributed object data base management systems that support all data accesses and communications by applications.

The Army faces some distributed processing issues that are uncommon (though probably found in special circumstances) in the civilian context. The following three examples indicate the range of factors that set the Army's distributed processing requirements apart from the norm of civilian systems.

- *Time scales and prioritization.* The speed with which processes must be handled will continually vary, depending on enemy action and the desire of commanders for data. No rigid, preplanned prioritization scheme can be expected to work. Our computer systems must give commanders control over their data.
- *Massive damage.* Large parts of the distributed system will disappear without warning. Civilian organizations generally want to reconstruct lost information, but the Army will be more concerned with graceful degradation, allowing the system to continue working at reduced capacity with reduced information. This will mean carefully thought out plans for storing abstracts of detailed information in a variety of places, for operating at partial capacity, for operating on the basis of defaults when needed, and for guessing at probable instructions and data when contact has been lost.
- *Range of data, inference, and hardware types.* No other organization is likely to face the Army's range of computations, from raw sensory data being processed on tiny, low-cost machines, to immense numerical optimizations, to subtle logical inferences. All interfaces rely on some sort of standardization; at the application level, standardization implies a common model of the world. Each application will extend that model in some direction, but the fundamental set of concepts through which the battlefield is represented will have to be the same for every application. Achieving this basic model will be an enormous task.

Human–Machine Interfaces

Computers can free humans to create, decide, and control. Computers can also bury them in detail while isolating them from reality. The difference is in part a matter of good interface technology, summarized in two technology areas: human factors and hypermedia.

Human-factor topics include visual display, force-feedback control, low-data-rate information presentation, and multisystem controls. Hypermedia refers to the coherent use of a variety of types of information presentation, including drawings, photographs and video, synthesized voice, and tactile sensations. Hypermedia applications permit the user to "navigate" among the different locations and types of information. They also provide direct "links" between information representations. When the user encounters an unfamiliar term, for example, he can choose between seeing a picture of it, reading a dictionary definition, or being presented with a minitutorial on it.

Fusing these capabilities can bring multiple resources together into a coherent interface that permits the user to access immense amounts of information in ways structured by the user himself, information that has been designed to allow the user to absorb information quickly. Concurrent tutorials, functional diagrams of accessible systems, and pictorial information (e.g., maps, sketches, and reconnaissance photos) could all be linked together and made accessible to commanders, planners, controllers of unmanned systems, and other individual soldiers.

Technology Attributes

Visual displays utilize the most powerful of the brain's processing systems; they are the key to effective systems. Problems include the bulk and resolution of display units. *Occulometry-driven areas of regard* use systems that track eye motion to automatically direct sensors in the direction the operator wishes to scan, reducing operating workload.

Force-feedback controls increase the operator's feel for the machine's reaction to his control inputs. *Optimized low-data-rate information presentation* aims at providing the operator with high-resolution imagery and feedback despite limitation^ on communication system data transmission rate.

Multisystem control for workload optimization dynamically allocates tasks between operator and intelligent machine, based on task type, intensity, and criticality. This process would, for example, enable an operator to control multiple unmanned systems.

Status of Developing Technology

At present, the human factors expertise and technology for integrating multimedia are nearly non-existent, although some of the building blocks of hypermedia, primarily output, are appearing on personal computers such as Apple and Next. Geographical Information Systems (GISs) are a new commercial item supported by cheap workstations with high-resolution color displays, large disks, fast processors, and plentiful digital and analog map data.

The current types of visual displays are principally arm's-length CRTs (cathode-ray tubes) and control panels. Heads-up displays the size of a lipstick tube, which project onto eyeglasses, have just appeared commercially. Operator nausea problems are common in binocular and other three-dimensional displays. Terrain data bases can be utilized, but not in real time. With respect to the use of senses other than vision, binaural acoustic displays are used to maintain awareness of the environment. Tactile displays are very crude, and olfactory displays are non-existent.

Operators now control single remote systems. Wideband (60 megabit) data links are required. Controls are mainly analogs of manned system controls. Steering involves joysticks, steering wheels, and manual switches. Manipulator systems use joysticks, kinematic replica master controllers (sometimes force-reflecting), and manual switch boxes.

Future Capabilities

By the year 2020, user interface media and modes will be customized to the user's job function, expertise level, and personal preferences. One operator will be able to control multiple systems simultaneously with a high degree of efficiency. The distinction between tele-operation and robotics will disappear; controls will switch between pure program control, operator monitoring, and operator control, according to circumstances. Controls will be optimized to the user's needs, rather than reflecting the physical structure of machines. Electromyographic control will be practical, though only research will determine if it is desirable.

Stereo heads-up displays will be standard, built into most individual helmets. Map and other information will be displayed in high resolution at the point of maximum interest, as determined by gaze tracking, with simpler and bolder pictorials being used at the periphery. Users will switch freely between or superimpose symbolic data and simulated and real scenes. Color-coded dots, which expand into detailed information when pointed to, will replace standard unit symbols.

Real-time animation and sound outputs will cue incoming fire and enable commanders to visualize, hear, and even smell distant battlefields. Synthesized speech will supplement visual displays. Where useful, output media also will include music, holograms, and olfactory, tactile, or direct brain stimuli.

"Structured voice" will be the standard input medium, that is, menus will be displayed from which the user chooses by voice. In more complex situations, such as operation order preparation, the computer will exploit its knowledge of the format and situation to disambiguate speech. Vocabularies in use at any moment will be small, but the total effective vocabulary will be very large.

Computer-aided drawings will convey nonverbal information. Displays will change scale automatically to ease drawing tasks, lock drawn lines onto terrain features on order, and display complex symbols on voice order supplemented by pointing. Most drawing may be in air or on any convenient flat surface, the heads-up display superimposing the picture, and the "stylus" being tracked acoustically. The user will request either two-dimensional or three-dimensional mode. Users will share virtual workspaces, drawing on and pointing at the same picture, even when physically separated, and without obscuring each other's view.

Other input media will include analysis of facial and body gestures from TV images, direct monitoring of physiological data, and brain-wave reading.

Computer Warfare

Computer warfare will involve at least four components: information security, electronic virus injection, sabotage, and modeling and exploiting computational predictability. Other DOD components also have a high interest in these issues, and the Army may be able to piggyback on them to considerable extent. However, because of the range and number of systems the Army will be using in 2020, it faces some unique problems and will have to develop its own expertise.

The battlefield of 2020 will be rich with information systems for situational awareness of both friend and foe, plus command and control; that information must be secured. Part of the answer is secure operating systems. The Army CECOM is developing an Army Secure Operating System (ASOS), a family of secure operating systems to be certified at the A1 and C2 levels (DOD, 1985).

If every soldier will carry a cigarette-pack-sized information and communication system, we face the security issue posed by the capture of these communication systems in battle. A soldier who is captured with his equipment intact, being drugged and/or tortured, can essentially provide the enemy with all the information to which his information unit has access. Changing encryption keys periodically and frequently, and echeloning access and content of information based on the likelihood of compromise, will mitigate this danger. Coded access, physiological monitoring, and self-destruct mechanisms may be required.

Because of the need for extreme dynamic flexibility as the battle rages and individual commanders fall, we must also provide for successors to assume command roles and have their information access adjusted. One concept suggested is that of an *IDS (Information Distribution System) Suspicious System* that would work to counter the compromise of an information node and its information, while still permitting the normal functioning of the remaining portions of the system.

Protection against virus injection is largely similar to information security, but it adds the requirement for watchdog programs to detect the presence of dangerous enemy programs injected into the network.

Sabotage is similar to virus injection but involves viruses or more subtle bugs introduced by the programmers at the time the program is written. Conventional security clearance procedures are the first line of defense, but because of the amount of damage a single subverted programmer could do, we will need to find ways to structure our systems to prevent damage from spreading. Program redundancy—multiple programs by different programmers running in parallel, the answers being checked against each other—is the classic defense against accidental bugs and should help defend against deliberately introduced ones as well. Clear, simple, well-documented, and tested code is another important defense.

Enemy utilization of the predictability of our programs is a subtler issue. An outstanding example is intelligence programs that monitor for enemy indicators and superimpose templates. These programs can be exploited by an enemy smart enough to change tactics. The principal defense here is for human operators to confirm, not blindly accept, the recommendations of machines. It also will be necessary to allow programs to be modified in the field, to take advantage of new experience. Some degree of randomness in the programs will help as well.

BATTLEFIELD ROBOTICS

Robots, Violence, and Unpredictability

Current automation technology dictates a relatively clean, stable, and predictable environment. Industrial robots work in well-known and environmentally stable conditions. Complex tasks are performed from fixed positions with carefully calibrated reference points. Mobile robots usually perform extremely simple and uncomplicated tasks, such as delivering mail along fixed routes. The Technology Group predicts that by 2020 the Army could field an entirely new robotic capability—provided the requisite critical research is supported that will make possible both autonomous and computer-enhanced manned systems.

The violence of the battlefield leads to great uncertainty about the environmental conditions. Constantly shifting local features and terrain, smoke and obscurants, explosions, and other effects will be used to confuse robotic sensors and disturb their calibrations and reference conditions. Most important, the enemy will deliberately confuse our systems and exploit their predictability. This will render autonomous operations less reliable. It will be necessary to build systems capable of constantly reexamining their environmental conditions and location and of questioning their own assumptions. Techniques to be employed will range from extreme system simplicity to highly sophisticated planning systems, robust integrated sensors in all of the spectra, and cooperating systems that have good models of the knowledge embedded in their own and other robots. Flexibility to adapt to the environment and robustness against variations will be critical.

Still more critical will be cost. Even in 2020, unmanned systems are unlikely to be as capable as manned systems. They will be useful because, if appropriately designed, they can be far more numerous than manned systems. Since World War II, Army R&D has aimed for qualitative superiority. By 2020 the Army can have quantitative superiority as well, by supplementing manned platforms with large numbers of unmanned systems. Achieving this depends more on imaginative design and tactical innovation than on fundamental technical breakthroughs.

Unfortunately, Army robotics development has often focused on replacing humans, usually in tasks deemed too dangerous for humans. Inevitably this means large, expensive systems, less effective than their manned counterparts, which can be justified only in special cases. But computer-controlled systems have little in common with manned systems; we must learn to exploit their unique characteristics. For reasons presented below, the most important battlefield systems will evolve from land mines rather than devolve from human capabilities. The sensors, weapons, and propulsion they employ will be very different from those used by people.

The following pages discuss four robotic functions: sensing, computing and communicating, shooting, and moving. The argument is made that the power of battlefield robotics lies primarily in the ability to put large numbers of sensors in places where humans cannot go and to integrate the information from networks of sensors to form a coherent picture. The ability to directly destroy enemy forces is important but secondary; the ability to move is last in the order of priority.

Progress in battlefield robotics depends on progress in development and integrating technologies. In particular, success will depend on reversing the current trend toward fewer, more complex and expensive systems. Finally, all the technologies discussed below are also applicable as computational enhancements to manned systems. Current efforts in target acquisition systems, automatic return-fire capabilities for tanks, and so on, should be continued.

Sensors and Their Integration

The problems of sensor fusion, sensor integration, and signal processing for a single sensor are included in this category. The Army of 2020 will have vast requirements in all of these categories.

The Army will need to exploit an enormous variety of sensing systems. Although passive vision in the visible and infrared spectral ranges has received the most attention, it is the most difficult to use. Active imaging systems include radar and laser-imaging systems. These simplify the problem dramatically by providing relatively unambiguous range and velocity information. Sometimes they return information not available from passive vision. Sonar is similar in effect and cheaper at present, but it suffers from low resolution and speed-of-sound limitations.

Acoustic and seismic sensors often can identify enemy or friendly systems unambiguously. These sensors can locate systems quite accurately if the systems are making noise. Trip wires and other contact sensors can probably be improved with modern technology to provide more information, such as range along the wire. Inductive and capacitive sensors can distinguish large mechanical systems.

By 2020, these sensors will have better resolution and signal-to-noise ratios. They will be more compact, require less power, and be much cheaper. However, they will require greater data and signal processing capacity to exploit their new sensitivity and accuracy. New applications will place greater demands on these sensors and their corresponding signal processors. Some autonomous vehicles, for example, will require high-performance vision systems operating in extremely hostile environments. Research is required in vision systems to support high-resolution applications in obscured or camouflaged environments. Current AI research in understanding and recognizing objects puts little stress on dealing with hostile environments.

Once the signals have been sensed and converted into data, these disparate sources of data must be processed into an integrated picture. This problem of sensor integration is similar to the parallel processor management problem or the network management problem, but it occurs at a system level. Different sensor systems from different commands and applications must be combined to offer an overall understanding of the situation. The current understanding of this overall problem of sensor integration is only rudimentary; it requires much greater research emphasis. The problem is largely computational; we lack both theory and hardware to quickly compute the implications of real, complex battle scenes.

One technique is to balance the information required, the knowledge already available, the cost of getting more information, and the cost of being wrong. For example, laser rangefinders the size of a cigarette pack are now available for a few hundred dollars. These are too slow for "vision," as normally conceived. However, if good maps are available they can confirm locations and correct for dead-reckoning drift by ranging to known surfaces. They can take a limited number of measurements to a suspected enemy vehicle, and determine if the measurements fit the vehicle geometry. They will occasionally be wrong, but that matters only if the price of being wrong is high.

A second technique is to integrate multiple sources of information. The enemy can fool trip wires with grappling hooks, and pyroelectric or interrupted-beam sensors with smoke or fire. But it is much harder to fool both at once. The fundamental requirement is a model of the battlefield that allows the different signals to be correlated. These models may exist only in the mind of the tactician and designer; the trip wire of a mine is based on a simple model that says that anything tripping an armed mine is probably hostile. Alternatively, the computer may incorporate a sophisticated model that allows it to identify and track friendly and hostile objects. Such tracking can gradually refine and confirm the assumed identity of the enemy, defeat local countermeasures, and destroy the enemy at the optimum time and location with the optimum weapon.

A third technique is to use the same sensor for multiple functions. For example, some current navigation systems use radio signal propagation time to determine distance to known points, but the clocks required are extremely accurate and expensive. Acoustic sensors might provide the same information at lower cost and also detect enemy movements, but their short range would require a much larger number of sensors. Hence, the acoustic sensors might not be justified for either friendly or enemy tracking, but might be justified for both. A need-based development process makes it difficult to recognize such opportunities for synergism.

Although identification of friend or foe (IFF) will assume increasing importance, no single method appears to be entirely satisfactory. The Technology Group envisions a territory-based network of computers that tracks every object on the battlefield, handing off targets and friendlies as these move across tracking boundaries. Humans may either reserve final weapons commitment to themselves or establish fire criteria for selected weapons, target types, and areas that need different degrees of target confirmation based on the threat condition and the probability that an unidentified friendly is in that area.

Computer Programs for the Battlefield

Two general approaches have emerged for programming mobile robots. The first approach is generally modeled on human planning and reasoning. A sophisticated, relatively complete model of the world is established and updated in computer memory. Decisions are made by simulating the effects of the alternatives in the world model, then taking the one offering the highest simulated payoff. This approach, which has received most of the research attention, tends to require increasingly large computers.

The second approach is modeled instead on sensor systems with simplistic decision-making capabilities. A variety of simple stimulus–response behaviors is built up in layers, with high-level layers modifying or combining the behavior of low-level layers. For example, a land mine has the "if triggered, fire" behavior; this might be modified by some simple heuristic on the number of other mines that have been fired in the area and the number of times the mine has been triggered, so as to try to conserve mines until a mass target is presented.

Both approaches will be needed for the foreseeable future. Large central systems will need complex planning capabilities in order to interface effectively with humans. Small, distributed packages will depend on the second approach. Research is needed in interfacing the two approaches, as well as in moving either one out of the laboratory and into the hostile battle environment.

Weapons for Unmanned Systems

Unmanned weapons involve a set of priorities different from manned weapons. Most obviously, they can be self-destructive. They can also be less reliably lethal, since soldiers' lives do not immediately depend on their effectiveness. They can be too bulky, heavy, and awkward for human use. Their signatures need not be hidden. However, they must be low cost, since they are unlikely to be as individually effective as manned weapons. And they must be mechanically simple and reliable, since humans generally will not be available to clean them, clear jams, and so on.

Explosively propelled projectiles may be the most important unmanned-weapon concept, achieving armor-piercing velocities with low weight and cost at the expense of destroying the launcher. Rocket launchers involve fewer moving parts than conventional guns, which must be designed to be reloadable.

Guided missiles can be launched straight up, with no moving parts in the launchers. They are conventionally deployed with human crews, in part because they are expensive enough to require human security. However, their cost will continue to drop, and the automated networks that this Technology

Group envisions should provide substantial security to isolated systems. By 2020, single, isolated tubes hidden in ground cover are likely to be more secure than batteries mounted on vehicles; the trade-off will be between numbers and mobility.

UAVs as well as some ground vehicles can deliver lethal payloads directly on target without the need for separate weapons. Small ground vehicles and stationary antipersonnel systems will use specifically designed guns, with improved reliability, reduced cost, and sometimes increased firepower compared to current designs.

The essential trade-off is range versus cost and flight time. A long range makes it more difficult for the enemy to achieve penetration by overwhelming local systems. It may also decrease the probability of enemy detection of the systems, although the greater bulk of long-range systems may make them more detectable in a battlefield without a secure rear. Long-range systems, if guided, can be as accurate as short-range systems, but they take longer to arrive at the target, which may move into cover. They are also more expensive per pound of projectile; hence, they require more positive enemy identification before commitment.

Longer range usually means a greater distance from the bulk of the enemy's fire, which saves lives and allows soldiers to concentrate on their mission rather than their fear. These concerns, however, are irrelevant to unmanned systems. Even so, systems placed well to the rear will still remain easier to move and control.

These trade-offs imply a mix of systems. We must guard against the peacetime tendency to design only a single system for each mission. Unmanned systems, properly conceived, are cheap and quickly developed; they are also vulnerable to countermeasures and rapidly rendered obsolete. Where a manned system should usually be designed for broad competence, to protect its crew under varying conditions, an unmanned system normally should be more specialized. It is the variety of such specialized systems, their mass, and their synergy that will defeat the enemy's countermeasures, disrupt his plans, and erode his strength.

Mobility

The key mobility problem is overcoming obstacles. This depends on mapping, sensing, and the physical ability to bypass or crush the obstacle. Mapping has been addressed by the Support Systems Panel. This Technology Group only notes the need for maps that have multiple scales of resolution, can be enhanced in the field, and whose object-oriented representations make them easy to use for tactical decision-making. Fusing map information with sensor information to gain a good local picture of the ground will require continuing research.

The Technology Group has discussed sensing and sensors already. In addition, obstacle detection is much more difficult than the detection of a moving enemy, though easier than detection of a stationary, cold enemy. Of the passive sensors, only vision seems applicable, but it remains too slow and unreliable for high-speed ground movement on natural terrain. Active sensors can be tuned to detect particular kinds of obstacles, such as wet ground or vegetation thicker than some minimum diameter.

The mechanical issues are quite different for air and ground systems. Large air vehicles, whether autonomous (cruise missiles and homing missiles) or tele-operated (drones) are well established, since air is a relatively homogeneous medium with few obstacles. The cost and bulk of the terrain maps and computation required for cruise-missile-type navigation will continue to fall, permitting autonomous operation first by ultralight aircraft, then by vehicles the size of model aircraft. Flying low, slow, and in great numbers, these aircraft will threaten enemy vehicles, if not infantry. They will be fairly difficult to detect or hit and certainly will be able to detect the weapons that fire on them. By 2020, we may even be able to build actuators, sensors, and computers onto single silicon chips, resulting in bee-sized vehicles.

Lighter-than-air vehicles can provide long-term surveillance, but aerial vehicles are easier to detect than ground vehicles. Aerial vehicles cannot exploit simple motion detectors to locate the enemy, since they themselves move. Tethered lighter-than-air systems cannot be easily emplaced in the best location for their sensors, nor can they reorient on local threats or progressively search an area. Because of these limitations on aerial vehicles, the Army will need to explore options for autonomous ground vehicles.

At present, natural-terrain land locomotion is possible only for large systems. The small-scale obstacle density is high for small conventional vehicles, which cannot crush through vegetation or climb over logs and rocks, as do large vehicles. Autonomous and more effectively tele-operated large-vehicle movement has been demonstrated, but these vehicles will remain less effective than their manned counterparts. The Group anticipates that they will be used only in relatively specialized roles—for example, in reconnaissance missions where the information to be gained justifies the vehicle loss but where human morale would suffer if manned equipment was used. Like their manned counterparts, these systems will be highly vulnerable to unmanned attack.

Accordingly, natural-terrain land mobility for small systems is among the Army's key challenges. Previous work has focused primarily on legged locomotion. In principle, legs offer rough- and soft-terrain ability approached by no other mechanism. However, they remain mechanically very complex and energetically inefficient. They also require excellent sensors and complex computations to avoid tripping, unless enough legs are used that tripping doesn't matter. Legged vehicles may walk or run. Running alternates ballistic motion through the air with bouncing on the ground, and is in principle more efficient than walking, but also demands much better computation and sensing and more powerful actuators. It has been demonstrated only on flat surfaces with tether-delivered power. It seems likely that both methods will be used in 2020, but perhaps only for more specialized applications (e.g., in mountains).

Leaping, followed by reorientation on landing, is the mechanically and computationally simplest small-scale mode of rough-terrain locomotion assessed by the Technology Group. Current analyses suggest that a 20-pound vehicle might move at 3 to 5 miles per hour in 90-foot leaps, with a range of 15 to 30 miles and a 10-pound payload. Both in flight and when stationary, the vehicle will be difficult to hit in most terrains, and it will cross quite large obstacles. It will be an effective munition delivery system, acting, for example, as a self-propelled antitank mine. However, it will perform poorly on very steep slopes or in dense forest. It is incapable of fine positioning or stealthy movement and will require good mapping in order to avoid leaping into inescapable positions.

Wheeled or tracked vehicles that are elongated or articulated can increase the available force per unit frontal area, in order to crush through vegetation. Their length is effective in crossing gaps, and articulation allows them to push up and over solid obstacles. They are also likely to have low ground pressures.

Autonomous motorcycles will be mechanically simple but computationally complex, because (like running vehicles) they must be balanced dynamically. They may perhaps be fitted with mechanisms allowing them to leap obstacles and right themselves after falling. They can exploit a vigorously developing civilian technology and may be superior to four-wheeled vehicles on narrow and bumpy trails. They may be able to assume the road-based reconnaissance mission.

Mission-Specific Packaging

Despite the rapid and exponential improvement in hardware performance and size, many operational data processing problems remain intractable in the field because of power, cooling, and weight demands. This is especially so with very large signal processing systems composed of very large numbers of processing nodes. Even when these nodes consist of ASICs or microprocessors, the power, packaging, and cooling requirements can swamp the capability of available platforms for delivering these large systems in an operational field. The systems can be too heavy, too large, or consume too much power. Many future systems can be imagined that will require far more operational time on target than can be sustained by current or future platforms. Additional processing power will always contribute to resolution and accuracy, so computational demands can be expected to continue to increase in order to meet new mission demands.

Packaging, viewed as a discipline within applications engineering, does not ordinarily get the support of basic research laboratories (such as the Army Research Office). Certainly, very little support from the National Science Foundation (NSF) can be expected; packaging lacks the intellectual appeal to compete for NSF funding. The Army can and should play an important role in providing support to this field of computing engineering. Emphasis should be placed on providing packaging technologies for architectures of thousands of processors, with large-backbone high-bandwidth networks, many memory components, and considerable heat generation. Although processor counts of 10,000 can be postulated today, the Army should aim for supporting signal processor systems of over 100,000 nodes in 2020. Research should be directed at maintaining systems, either airborne or on the surface, at the target site for over 24 hours and should address both the problem of providing power and of dissipating heat.

12

Other Critical Technologies

In this final chapter, the Technology Group discusses a variety of technology research areas that the Army should monitor closely but probably does not need to lead. Progress in these areas will have important commercial implications, so the Army can remain alert for useful results without having to apply scarce resources to achieve them.

MACHINE LEARNING AND NEURAL NETS

Programs that "learn" have wide potential applicability to the Army's problems, from recognizing an enemy to organizing a logistics effort.

From research on machine learning in the 1980s has emerged an enormous variety of software systems, most of which make use of a specific machine learning paradigm, such as concept learning, discovery learning, or explanation-based learning. The next 30 years will see an increasing focus on the development of integrated learning systems that are designed to address general (rather than domain-specific) learning problems. Problem representations will be far more sophisticated. Unsupervised learning of interesting relationships in large data bases or knowledge bases will become practical. Integrated learning systems, able to make use of a variety of different learning techniques, will adopt different learning strategies based upon the problem at hand. The extensive corpus of "general knowledge" available to these systems will provide encyclopedic data bases of general problem-solving heuristics, as well as facts about the world.

However, there is still no general, effective theory of learning. A useful characterization is "in order to learn something, you have to already almost know it." Learning takes place only within a framework; if the framework is missing, or poorly suited to the learning problem, learning is unreliable.

It is also critical that learning programs be given appropriate examples from which to learn. A limited set of examples may produce unwanted and incorrect generalizations, even if the framework is adequate. We do not rely solely on examples to teach humans; rather, we seek to "program" them with underlying principles and use examples mainly to illustrate those principles.

Finally, even when learning is correct, it may be very difficult for the human user to understand what the computer has learned. Large learned systems promise to be very difficult to debug or modify as conditions change.

For all of the above reasons, it is unlikely that learning will replace programming, even in 2020. Rather, learning will be one element of the system developer's toolbox, to be used in combination with more conventional programming styles.

Neural nets can be viewed as a particular mechanism for machine learning. By analogy with the components in biological nervous systems, the two kinds of processing elements in a neural net are called *neurons* and *synapses*. A synapse receives one input and performs an operation on it to determine the synapse's output. A neuron receives inputs from many synapses, combines them in some way, and performs an operation, usually nonlinear, on the result.

As the basic terminology suggests, neural nets are generally acknowledged to be closer to biological computation than are conventional program architectures (though still not very close). This analogy is sometimes used to argue that they will prove superior in providing "real" intelligence. The history of attempts to emulate biological systems suggests that this argument is fairly weak.

As learning systems, neural nets seem to be characterized by a fair degree of robustness: the ability to learn even when the "teacher" has a poor understanding of the material to be learned. They have achieved some spectacular successes in pattern recognition but, in general, remain relatively slow learning mechanisms. This situation should change to some extent with the success of current research into hardware designed specifically for neural nets. As with other machine learning systems, it is extremely difficult for the user to understand what neural nets have actually learned.

The terminology of neural nets, with its "neurons" and "synapses," reflects a functional analogy with the animal nervous system as presently understood. Whether or not this analogy remains apt, neural-net architecture represents an alternative computing paradigm to either single or multiple (i.e., parallel) processors that follow the conventional von Neumann paradigm. How[illegible], neural nets are not the only alternative to von Neumann computing; another option may be dynamical systems that realize in hardware a solution to a system of partial differential equations. So, beyond the issue of neural-net applicability is the more general question of how to construct new computational paradigms in hardware. As experience in realizing alternative computational approaches accumulates, the time span between theoretical exploration of a new possibility and its use in solving real problems can be expected to decrease.

The future of neural-net systems and other computing paradigms is difficult to predict. The Army needs pattern-recognition systems and probably will want to apply neural nets or other learning mechanisms for this purpose. Substantial breakthroughs may dramatically increase the applicability of these technologies. In the meantime, the Army's most difficult task may be understanding how to interface these programs with more conventional systems.

DATA BASE MANAGEMENT SYSTEMS

Data base management systems (DBMSs) of 2020 will evolve greatly from those of today, but along dimensions that are already defined by current research on relational, object, distributed, and knowledge DBMSs. Existing relational DBMS technology will be superseded by fully knowledge-based, hyperdocument DBMSs that can represent:

- data structures such as tables, large textual documents, images, video and audio information, and maps;
- complex compositions of these basic data types, using such data constructs as objects or knowledge frames; and
- associated inferential procedures such as triggers, methods, and production rules.

Such a system will make inferential additions and modifications to the data base, analyze itself for consistency, and monitor accesses for security breaches.

Equally important will be the move to fully distributed DBMSs, which will have automated maintenance of multiple copies and automatic updating and routing of data. Dynamic optimization throughout the network will be based on decisions to store information locally, recompute it locally, or retransmit it from a remote node. Using these optimization techniques, each user class (e.g., echelon, function), as well as each individual user (e.g., soldier, vehicle, weapon system), will be able to request a tailored "view" of the global data repository, with that view incorporating such factors as response time; age, precision, and granularity of the data; and display mode.

ULTRA-HIGH-PERFORMANCE SERIAL AND PARALLEL COMPUTING

Modeling and simulation in Army laboratories and development centers have an ever-increasing need for very sophisticated computer and network systems. The two major areas involve (1) scientific computing as a tool for material development and (2) simulation of combat activities or war games for force development, planning, and guidance in arms reduction agreements.

Simulation allows the evaluation of design concepts before actual hardware is assembled. Many R&D mission tasks can be characterized in terms of nonlinear partial differential equations in space and time (e.g., propulsion phenomena, flight stability, aerodynamic characterization, penetration, blast, armor design, vehicle dynamics, and structural analysis). Solving these equations for specific Army systems concepts, to predict performance and optimize design, is one of the most difficult classes of scientific computing problems. The process of weapon system design involves a complex and intricate decision-making process. In addition to considering novel design concepts, decisions include choosing specific design parameters such as materials, lengths, diameters, positioning of subcomponents, shapes, spacings, and a myriad of additional factors. The numerical-solution methodology for these problems requires very fast computers with very large memories—single simulations requiring 10 to 200 hours on a Cray-2 and tens of millions of 64-bit words of random access memory.

The more than four decades since the Electronic Numerical Integrator and Computer (an Army development) have seen computing power grow by a factor of 10 million. At the same time, each generation of scientific computer has been easier for the scientist to use. Further speed gains from serial computers are limited by factors such as switching speed and signal propagation between logic chips; progress is expected to slow substantially. The most promising alternative is parallelism, which can vary from a small number (less than 100) of very fast processors (large-grain processing) to a very large number (greater than 10,000) of slow processors [massively parallel processing (MPP) systems].

Large-grain or conventional supercomputers are typified by the product line of Cray Research, Inc., where the maximum number of processors is eight. In this architecture, individual processor speed is greatly enhanced through *vectorization*, a procedure that allows each processor to perform numerous "similar" operations simultaneously.

Massively parallel architectures include the Connection Machine (from Thinking Machines Corporation), which has up to 64,000 processors. This computer typifies the single-instruction, multiple-data (SIMD) architecture. NCUBE Corporation's NCUBE 2 has "medium-grain" parallelism (100 to 1000 processors) and the multiple processors and multiple-instruction, multiple-data (MIMD) architecture. Thus far, however, these architectures have been difficult to use; they have been used predominantly by small teams of highly trained researchers.

The dominant use of supercomputers by the three services, the national laboratories, and NASA has been in simulations that involve partial differential equation models. Typical are the material response codes for conventional and nuclear explosives, high-velocity impact, and computational fluid dynamics—problems that also drive the Army's need for high-performance computing.

Successes have been reported in solving the simple underlying models for these applications on the medium-grain and MPP architectures. It is not yet clear whether these successes can be duplicated on problems that contain localized phenomena—such as shock waves over a portion of the computing grid, special equation-of-state calculations, or localized reasoning—which tend to reduce the measure of a problem's inherent parallelism.

Amdahl's law provides an upper limit on the speedup provided by MPP as a function of this inherent parallelism. Accordingly, the claims of performance made by any vendor apply only to the specific problems solvable on the architectures being compared.

Despite the considerable research effort of the past 20 years on parallel architectures, despite the availability of some parallel-processor architectures, and despite the current research at about a hundred universities in the United States, the problem of organizing and exploiting a parallel-computer architecture for a general-purpose problem remains largely unsolved. Hardware architecture, operating system, and applications compiler problems abound; very little is known about optimization; and the general-purpose compiler for adapting problems to a given architecture is still a gleam in the eye.

Theoretical work for single-processor systems is well understood. For certain architectures of multiple processors and networks operating under certain conditions, certain theoretical behavior is also understood. Unfortunately, given all the research described above, there is no theoretical basis for understanding the general parallel-processor architectures. Of course, special-purpose systems can be designed and optimized to a given problem. In addition, general-purpose machines continue to improve in terms of speed, cost, and capability, so that an increasing number of special problems can be solved on a general-purpose machine.

However, the number of signal-processing problems and other types of special problems clearly will continue to drive Army requirements. In 2020, the Army will need machines composed of varieties of architectures. Research is required in both performance and management of these systems. Tools are needed to provide rapid designs, and simulation tools are needed to evaluate the performance of these designs in a given problem environment. The Technology Group can envision tools that would accept a problem definition, prepare and evaluate a series of different designs, optimize based on given criteria, and provide foundry instructions for writing the silicon masks. Research also is needed in how to program these special machines and how to adapt a given problem rapidly and optimally to a given architecture.

The Army will have more opportunity to benefit from research in commercial and academic centers than it has in the past. Because of the tight coupling across the problem to be solved, the software to address it, and the multiprocessor hardware architecture to run the software optimally, the Army will need to support research directly. All of the hardware vendors have active programs in architecture; NSF, DARPA, and the other departments also have important research efforts under way. In addition, Japan is investing in similar research, as are the European Economic Community (through the European Strategic Program for Research and Development in Information Technology) and several industry consortia (e.g., the Microelectronics and Computer Technology Corporation and the Software Productivity Consortium).

PLANNING

By 2020, planning technology will be capable of producing complex plans in complex domains. Search techniques will exploit the available hardware power. Exact solutions will be found for many scheduling and planning problems that are now handled heuristically. However, the most dramatic progress in planning technology will be evident in the increasing breadth of knowledge that is integrated and used in generating and revising plans. Automatically generated plans will adapt to a very wide variety of constraints and contextual information. All of the following approaches may be used in the course of generating different portions of a single plan:

- Memory of past events and past planning successes and failures will be used in planning. Case-based reasoning and analogical reasoning will play important roles.
- Contingency plans will be explored in great depth before selecting the best course of action. Plans will be designed to reduce uncertainties and avoid potentially harmful consequences from unpredictable future events.
- Replanning and adaptation to unforeseen events will occur rapidly while preserving the unaffected portions of the previous plan. Multiple dependencies between subtasks will be recorded as part of the plan and constantly checked during plan execution.

MANIPULATOR DESIGN AND CONTROL

By the year 2020, manipulators with redundant kinematics will have greater than 10 degrees of freedom, full modularity, mission configurability, standardized mission modules, and integrated power electronics. Capacity-to-weight ratios 10 times that of the current state of the art may be achieved. Modal properties and force position control will be optimized. Range of motion will become substantially more precise over time, with a projected range by 2020 of 0.1 micrometers to 1.8 meters. Significantly improved electrical actuators may be in use, with torque-to-weight ratios increased tenfold. High-temperature superconductors and electrostatic muscles may be in use. Direct drive may be commonplace. High-strength plastics and other nonmetallic materials will be employed.

KNOWLEDGE-BASED SYSTEMS

The field of knowledge-based systems, including expert systems, has progressed tremendously in the past 30 years. There are about 30 operational knowledge-based systems in DOD and thousands throughout the world. By the year 2020 the field will have moved far beyond today's systems, which exhibit very shallow, brittle reasoning in extremely narrow domains. The advances will be enabled by more sophisticated representations (e.g., of time and space) and inference techniques, by the dynamic integration of multiple techniques, and by successes in the areas of automated learning and knowledge acquisition. There will be increased understanding of which techniques work for various classes of problems. Continued advances in the speed of computation will support large-scale searches of problem spaces and knowledge bases.

The new breed of reasoning systems will reason much more deeply and broadly. They will contain knowledge bases that represent both surface-level heuristics for quickly solving typical problems and deep models of the domain that allow more extensive analysis based on first principles when necessary. Inference engines will involve multiple strategies for processing this knowledge, including access to multiple, cooperating knowledge bases about a variety of domains. Thus, these systems will at last approach a general problem-solving capability, although still restricted to one class of problems, as contrasted with human capabilities. Knowledge-based systems in 2020 will be capable of:

- handling broader, more general, knowledge representation structures;
- modeling time much more richly;
- performing inferences under hard, real-time constraints; and
- doing distributed problem solving across processes, processors, and physical locations.

NATURAL LANGUAGE AND SPEECH

Human, or natural, language processing includes understanding and generating written and spoken texts, as well as translating between languages. Today we are just beginning to see limited operational systems in these areas, except for generation, which is a much simpler problem. By 2020, systems will be capable of understanding substantial (e.g., multiparagraph to multipage) texts such as report sections and long messages in well-defined domains. Real-time continuous speech understanding will be achieved in noisy environments with large (e.g., greater than 1000-word) vocabularies but within focused application domains. Translation will be feasible, although again only in focused domains.

Reliability will remain the essential issue. Natural language is inherently ambiguous; computer languages are not. It is this very ambiguity that gives natural-language its unparalleled expressive power, but it also produces errors. Hence, natural language technology is most likely to be used for control purposes only in limited domains, where error detection is possible. It is already appearing in "pre-translation" systems, which can translate technical writing accurately enough that it is substantially easier for the human user to correct the machine translation than to perform the entire translation. And it will be used extensively in "watchdog" systems, which scan voluminous data for items to be brought to human attention.

References

DOD (U.S. Department of Defense). 1985. Department of Defense Trusted Computer System Evaluation Criteria, Washington, D.C.

Shafer, G. 1976. Mathematical Theory of Evidence. Princeton, N.J.: Princeton University Press.

Taguchi, G. 1986. Introduction to Quality Engineering. White Plains, N.Y.: Unipub.

PART III

ELECTRONICS AND SENSORS

ELECTRONICS AND SENSORS TECHNOLOGY GROUP

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13

Summary of Electronics and Sensors

The rate of progress in electronic sciences and related areas, such as computer science and electro-optics, is expected to continue to be astonishingly rapid. Over the decades, advances in these technologies have improved performance by several orders of magnitude. In contrast, other technologies of importance to land warfare, such as ordnance, propulsion, and armor, have advanced at steady but more modest rates.

These differing rates of advance imply that future trends in land combat may be dominated by advances in electronic technology. As an example, extremely capable, remote sensing of targets at long range and high precision could in turn enable precision attacks on enemy targets at ranges well beyond the line of sight. Historically, land warfare has been restricted, for the most part, to visual line-of-sight targeting and weapons. However, both air and naval combat have already evolved in the direction of long-range weapons. There is no reason to doubt that this evolution will also occur in land warfare.

Figure 13-1 shows the dramatic increase in targeting ranges, and therefore in depth of combat, that can be expected by 2020. The key to this evolution is the development of electronic sensing and target recognition systems that can operate beyond the visual horizon. Defense against these new forms of land warfare will depend on the ability to provide electro-optical concealment through a combination of stealth, electronic countermeasures, and mobility.

Given these developments, land warfare is likely to continue to evolve from the closely engaged armored forces seen in World War II to extended battles in depth, involving a high degree of mobility and concealment. This evolution will be driven by the advent of long-range airborne and space-based surveillance; unless enemy long-range surveillance and counterfire systems can be destroyed, forces operating in the open will require long-range, standoff, precision.

Of equal importance will be the impact of long-range weapons targeted on fixed logistic centers such as airfields, transport depots, and command centers. Unless a tactical cruise or ballistic missile defense system is fielded, Army field operations may become dependent on mobile logistics basing, combined with measures to deny long-range, real-time surveillance. Parenthetically, mobile air basing will probably necessitate the use of tactical aircraft with vertical takeoff and landing capabilities.

Table 13-1 relates the critical Army warfighting capabilities for this new era of warfare to the electronic systems needed to support those capabilities. The advances in electronics and electronic sensors described in the following sections will have substantial impacts in many, if not all, of these areas. How these advances may change the possible form of future air/land warfare

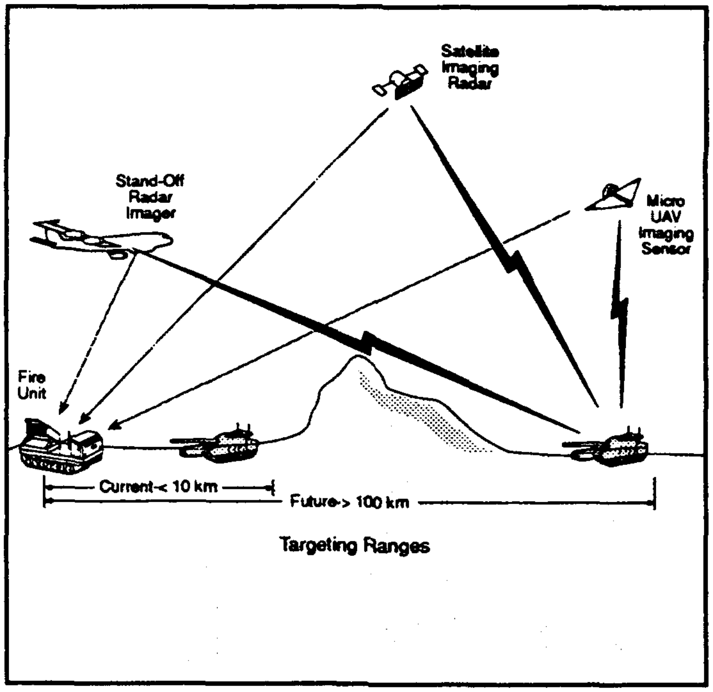

FIGURE 13-1 Remote electronic sensor targeting capabilities forecast for beyond the year 2000.

requires careful thought. In some cases, the advances are basically evolutionary in nature; others offer possibilities for revolutionary changes.

The detailed discussions of these potential technology developments are separated into four sections:

- electronic devices—monolithic microwave integrated circuits (MMIC), superconductive electronics, vacuum micro devices, computer memories, application-specific integrated circuits (ASIC), analog-to-digital converters, digital signal processing microcomputer chips, wafer-scale technology, and electronic design automation;
- data processors (signal processors, target recognizers)—multiprocessor computer technology, and neural network technology;
- communication systems—robust/survivable communications satellites, and augmentation/restoration communications satellites;
- sensor systems—unmanned air vehicles for ground surveillance and radar detection of moving targets, airborne radars for detection and recognition of stationary targets, acoustic-array sensors, magnetic sensors, air defense radars, and space-based surveillance and target recognition radars.

TABLE 13-1 Future Warfighting Capabilities and Supporting Electronics and Sensor Systems

Warfighting Capability	Supporting Electronics Capability	Relevant Electronic Devices and Systems
Indications and Warning of Enemy Intentions	Passive and active radar reconnaissance of enemy dispositions (air- and space-based)	Airborne radar, spaceborne radar, neural networks, data processors, monolithic microwave integrated circuit (MMIC), wafer-scale integrated circuits (ICs)
	Machine intelligence analysis	
Combat Surveillance	Passive SIGINT* and active radar surveillance	Airborne radars, acoustic sensors, neural networks, data processors, MMIC, wafer-scale ICs
	Data fusion technology	
Concealment	Low-radar-observable weapon design	Classified technology, LPI communications satellites
	Low-probability-of-intercept (LPI) communications	
	LPI surveillance systems	
Deception	False electronic target generators	MMIC, wafer-scale ICs
Effective Communications and Command	LPI antijam communications	LPI communication satellites, MMIC, wafer-scale ICs
Long-Range Low-CEP Weapons*	Weapons guidance and weapons control	See Part IV: "Optics, Photonics, and Directed Energy"
	High-power directed energy	
	Electrically energized guns/launchers/energy storage	
Platform Speed and Maneuverability	Electric platform drive	See Part VII: "Propulsion and Power"
	Electronic platform control systems	
Mass of Forces and Weapons	Low-cost weapon guidance	See Part IV: "Optics, Photonics, and Directed Energy" wafer-scale ICs
Adequate Logistics Support	Electronic diagnostics of equipment failures	Wafer-scale ICs, data processors, computer memories, neural networks
	Decision aids for equipment repair	
	Data systems for spare parts management	
Doctrine Development	Electronic simulators of air/land battles	Data processors, computer memories, wafer-scale ICs
	Training in equipment operation	

* CEP = circular error probability; SIGINT = signal intelligence

Electro-optical materials, devices, and sensors are not discussed in this Technology Forecast Assessment (TFA). Part IV: "Optics, Photonics, and Directed Energy" should be consulted for technology projections on these topics.

The final section of this chapter selects and aggregates these electronic technologies into three foci, which this Group estimates will have the greatest impact on future surface warfare:

- terahertz electronic devices;
- teraflop digital processors (for signal processing and automatic target recognition); and
- high-resolution-imaging radar sensors (including airborne and space-based sensors for surface surveillance and recognition of fixed and moving targets).

Finally, it should be noted that new types of devices can be expected in the time frame beyond the year 2000. These will incorporate basic science discoveries made in the 1990s. They might involve, for instance, the use of quantum devices, the development of an optical transistor capable of being used in complex logic circuits at speeds greater than a terahertz, and the development of three-dimensional integrated/photonics circuits. Part I: "Long-Term *Forecast of Research*" *should be consulted for* further information.

14

Electronic Devices

ELECTRONIC MATERIALS

Bulk Semiconductors

The performance of electronic devices and circuits is ultimately limited by the properties of the materials from which they are fabricated. Although conductors and insulators play important roles in device operations, the most critical materials in almost all present devices are semiconductors. Semiconductors are used to form the active regions of the device because their electrical conductivity can be modulated reliably by orders of magnitude and at low power.

Among the key properties of semiconductors that influence device characteristics are electron mobility, peak electron velocity, breakdown voltage, energy gap, and thermal conductivity. Table 14-1 gives values of these properties at room temperature for high-quality bulk samples of those semiconductors likely to be of greatest importance in devices and circuits manufactured during the next 10 years. The materials are listed in order of decreasing level of development, from silicon to diamond.

At present, silicon is the semiconductor used in most electronic devices, even though silicon ranks below the other materials (except silicon carbide) in the important properties of electron mobility and peak electron velocity, which determine the frequency of device operation. Gallium arsenide (GaAs) is the only material other than silicon currently used for integrated circuits. Silicon achieved predominance because of early successes in the development of silicon-based devices, including the finding that the properties of the silicon–silicon dioxide interface are almost ideal for the fabrication of metal-oxide semiconductor transistors. These successes led to extensive development efforts in materials processing and in device design and fabrication. The development work in turn led to an extremely large manufacturing capacity, with accompanying reductions in unit costs. For example, silicon wafers 20 cm in diameter are commercially available; by contrast, the largest commercial GaAs wafers are only 10 cm in diameter.

Because a high concentration of development resources and manufacturing capacity tends to be self-perpetuating, silicon will remain the semiconductor of choice for most applications for the foreseeable future. Significant improvements in device operation can still be achieved as a result of

TABLE 14-1 Key Properties of Semiconductor Materials

Material	Electron Mobility ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	Peak Velocity ($cm \cdot s^{-1}$)	Breakdown Field ($V \cdot cm^{-1}$)	Energy Gap (eV)	Thermal Conductivity ($W \cdot cm^{-1} \cdot {}^{\circ}C^{-1}$)
Silicon (Si)	1500	1.0×10^7	3×10^5	1.12	1.50
Gallium Arsenide (GaAs)	8500	2.0×10^7	4×10^5	1.42	0.46
Indium Phosphide (InP)	4600	3.0×10^7	6×10^5	1.35	0.68
Silicon Carbide (SiC)	500	2.5×10^7	4×10^6	2.8	5.00
Diamond (C)	2000	2.7×10^7	1×10^7	5.5	15.00

developments in areas such as lithography, contact and interconnect technology, and packaging. However, the next 10 years may see the performance of some types of silicon devices reaching the limits determined by silicon's intrinsic properties.

For some applications, more dramatic improvements can be expected because the inherent advantages of other semiconductors are great enough to motivate their development and eventual substitution for silicon. This process is already taking place in the area of high-frequency transistors, where GaAs is being used because its electron mobility is more than five times higher than that of silicon. Other potential semiconductor materials are the Group IV heterostructures, such as silicon germanium, which may find use in infrared detectors. Successful development of diamond also could lead to its eventual use for such devices because its extremely high breakdown field strength (nearly at nature's limits) would permit ultrasmall devices. Additional potential applications for semiconductors other than silicon include high-temperature and high-power devices. Silicon carbide or diamond would be advantageous for high-temperature devices because of their high energy gaps. Diamond would be advantageous for high-power devices because of its extremely high thermal conductivity.

Thin-Layer Semiconductors

For many years, wafers prepared by chemical vapor deposition of thin silicon layers on silicon substrates have been used routinely in the fabrication of semiconductor devices. While polycrystalline layers may be deposited if desired, the experimental conditions may be adjusted to produce epitaxial growth, which yields high-quality single-crystal layers whose thickness and impurity doping can be precisely controlled. These chemical vapor deposition layers are thick enough to exhibit bulk properties.

More recently, a number of powerful new techniques have been developed for the growth of single-crystal semiconductor layers from the vapor phase. The techniques include molecular beam epitaxy, organometallic vapor-phase epitaxy (also known as metallorganic chemical vapor deposition), and hybrids of these two. These techniques allow deposition of highly uniform layers, not only of elements and binary compounds but also of solid solutions such as gallium aluminum arsenide (GaAlAs) or silicon germanium (SiGe). These capabilities permit the fabrication of extremely complex multilayer structures with properties that differ dramatically from those of any bulk material. These techniques make possible GaAs high-quality layers on silicon substrates as well as quantum-well-strained layer-composites of Group III–V semiconductor materials.

The effect of such structures on device development already has been substantial. For example, they have been used in the fabrication of high-electron-mobility transistors (HEMTs), heterojunction bipolar transistors (HBTs), and resonant tunneling devices for use as active devices at millimeter-wave frequencies (see below). Over the coming years, the ability to provide increasingly sophisticated structures can be expected to improve device performance dramatically.

MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

The availability of good-quality, highly reliable semiconductor materials such as GaAs and indium phosphide (InP), the development of advanced epitaxial techniques (e.g., molecular beam epitaxy), and improvements in lithographic techniques have made possible microwave and millimeter (10 to 100 GHz) integrated circuits for small-signal and power amplifier applications. Such devices offer significantly greater reliability than the older traveling-wave-tube vacuum-tube microwave amplifiers. Specifically, the following devices have been developed:

- field-effect transistors (FETs);
- HEMTs;

- permeable-base transistors (PBTs); and
- HBTs.

MMICs will allow the development of phased-array radars, communication terminals and satellites, and signal intercept systems with far smaller (by factors of 10 to 100) sizes, weights, and costs than those of hybrid microwave systems. Figures 14-1 through 14-4 show simplified cross-sectional drawings of contemporary microwave FETs, HEMTs, PBTs, and HBTs. Microwave FET integrated circuits with up to 10 devices have been built for phased-array radar transceivers. Contemporary commercial performance is indicated in Tables 14-2A and 14-2B.

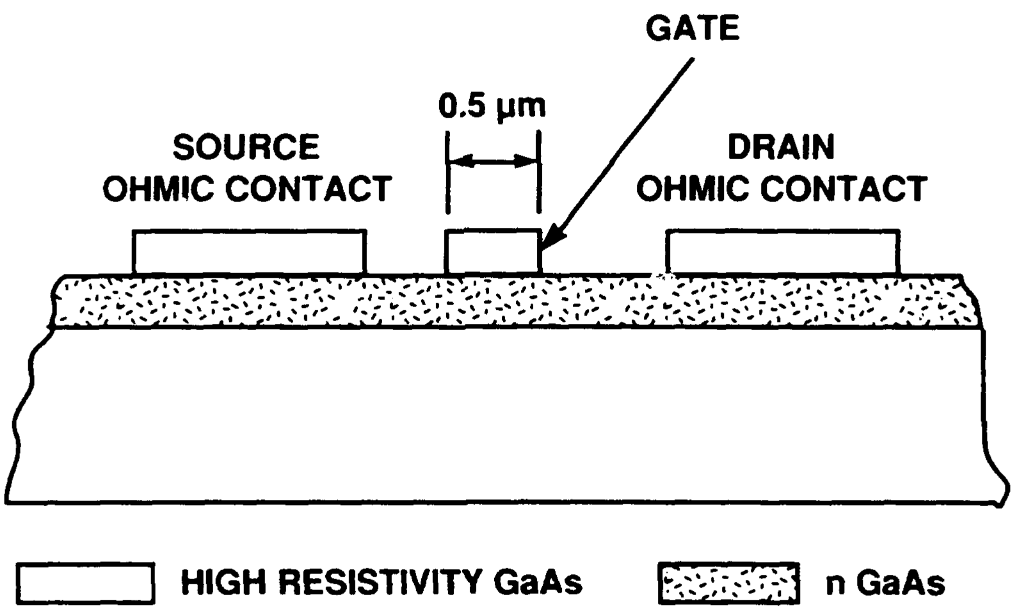

FIGURE 14-1 GaAs FET. Typical gate lengths of high-performance devices are 0.5 μm.

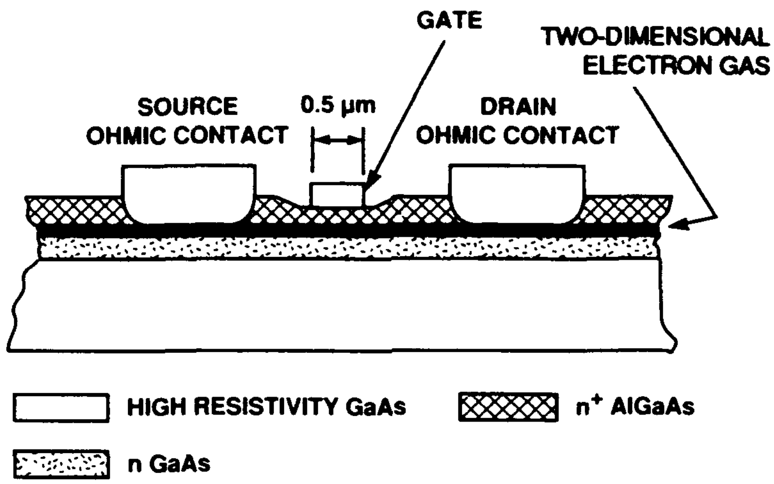

FIGURE 14-2 GaAs/AlGaAs HEMT. In contrast to the FET, the conductive channel is formed from a high-mobility, two-dimensional electron gas. Typical gate lengths of high-performance devices are 0.5 μm.

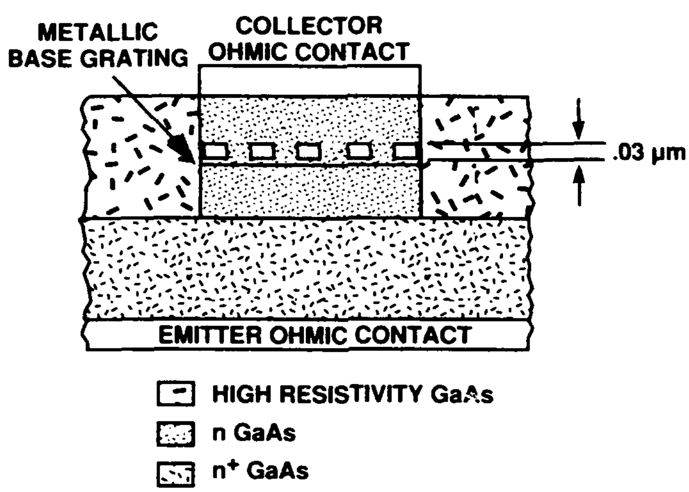

FIGURE 14-3 GaAs PBT. The PBT is a vertical device in which current is controlled by a submicrometer periodicity grating. The typical thickness of this grating layer is 0.03 μm in high-performance PBTs.

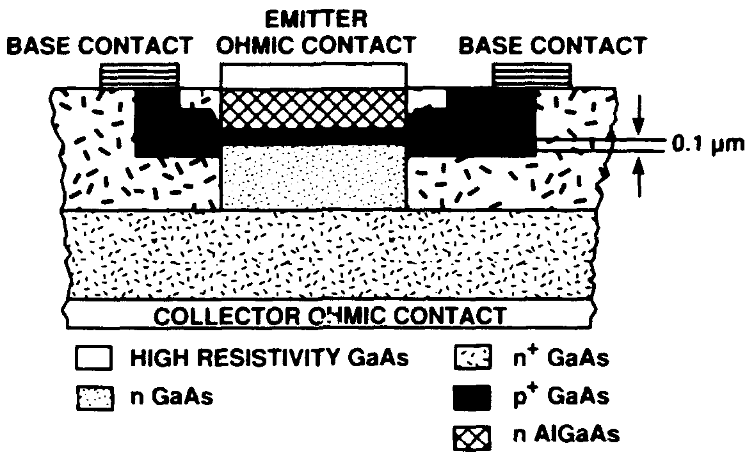

FIGURE 14-4 GaAs/AlGaAs HBT. The HBT is a vertical device in which the current is controlled by a p^+GaAs layer. The typical thickness of this layer is 0.1 μm in high-performance HBTs.

TABLE 14-2A Performance Characteristics of Existing Small-Signal, Single-Stage Amplifiers

Frequency (GHz)	Associated Gain (dB)	Noise Figure (dB)
10	12	1.0
20	9	1.2
50	6	2.0

TABLE 14-2B Performance Characteristics of Existing Single-Transistor Power Amplifiers

Frequency (GHz)	Output Power (W)	Power-Added Efficiency (%)
10	5	30
30	1	20
100	0.04	16

Figure 14-5 shows the projected frequency capability for future microwave semiconductor devices, as a function of the year in which they will be introduced. Analog integrated circuits employing approximately 500 of these devices with higher densities can be expected to be developed as transceivers of phased-array radars, electronic intelligence receivers, and communication satellites and terminals.

In the future, MMICs will make possible the development of lightweight phased arrays of transceivers capable of a variety of sensing and communications functions. Among the possibilities are the following:

• Small unmanned investigator air vehicles may incorporate multi-use apertures ("smart skins") capable of supporting radars for detection of stationary or slowly moving ground targets, as well as electronic intelligence receivers for detection of enemy radar and communication emitters.

• Moving-target indicator (MTI) and synthetic-aperture radar (SAR) imaging radars may be based in space for deep surveillance beyond the view of air vehicles.

• Millimeter-wavelength communications may provide covert, antijam, beyond-line-of-sight links between manpack terminals and lightweight

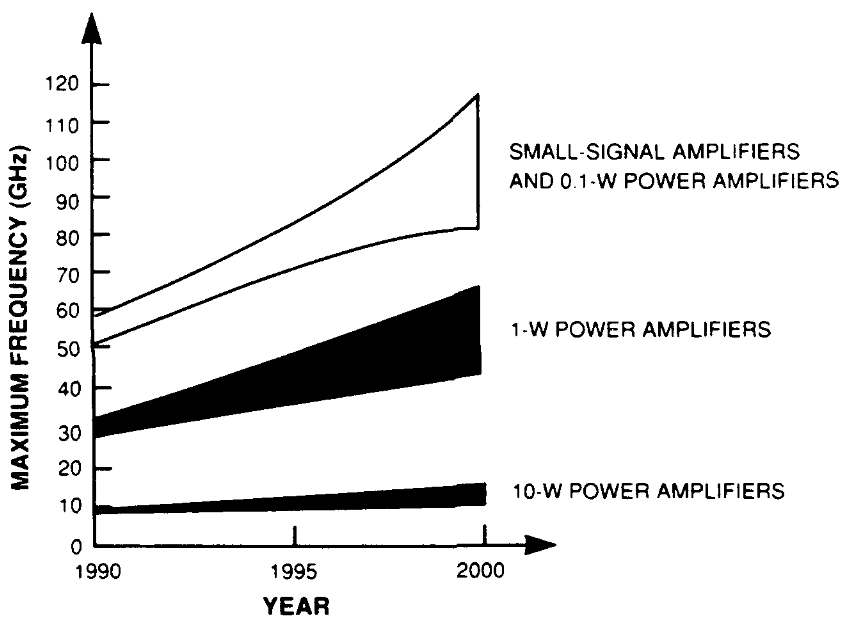

FIGURE 14-5 Projected maximum frequency of single-transistor commercial amplifiers.

(1000-pound) satellites compatible with the Military Strategic Tactical Relay System.

- Agile-beam, extremely high frequency (EHF) terminals may provide high-performance tactical links from aircraft to aircraft and from aircraft to satellite.

SUPERCONDUCTING ELECTRONICS

Superconducting thin films have extremely low microwave surface resistance. This property permits the implementation of filters that are highly frequency-selective (i.e., have high quality or "Q" factors) and of long delay lines in compact form. Superconducting tunnel junctions can be used for low-noise mixers and detectors as well as for low-power, high-speed digital logic and very sensitive magnetometry.

The low radio frequency (RF) loss of the superconducting films permits a 10:1 to 100:1 miniaturization of microwave circuitry in the range of 1 to 30 GHz. In addition, circuit performance parameters (such as filter Q, insertion loss, or tapped delay line length) can be achieved that are impossible using conventional techniques. At higher frequencies, compact planar circuits can replace waveguides.

Superconducting mixers and detectors provide the lowest-noise performance in the region above 100 GHz. Superconducting quantum interference device (SQUID) magnetometers are orders of magnitude more sensitive than other devices.

Josephson digital logic is based on devices that have switching times of a few picoseconds and consume only microwatts of power. Both speed and circuit density are projected to exceed that of semiconducting logic.

The performance of two devices currently produced using the niobium technology are as follows:

<u>Dispersive delay line (chirp filter)</u>

Bandwidth	2.6	GHz
Dispersion	38	ns
Time-bandwidth product	100	
Phase accuracy	3°	rms
Amplitude accuracy	0.1	dB
Side-lobe level (in pulse compression)	33	dB
Insertion loss (including coupling loss)	T5	dB

Resonator

Resonant frequency	500	MHz
Quality factor	2×10^6	

While improvements in many of the above parameters (such as bandwidth and dispersion) are expected from further development, the primary anticipated improvement is an increase in the maximum operating temperature from 4.2 K to 77 K. Figure 14-6 lists some of the devices and circuits that are expected to be realized in the new high-temperature superconductors over the next decade. Also plotted are the expected evolution of two important figures of merit: the surface resistance of thin films and the level of integration of digital integrated circuits.

Superconductive microwave circuits will make feasible communications, radar, and electronic warfare systems that are more compact and more sensitive. Multi-gigahertz instantaneous bandwidths permit radar range resolution of a few centimeters. High-Q resonators make possible Doppler discrimination against clutter and chaff. Wideband signal processing functions can provide covert, spread-spectrum communication and instantaneous spectral analysis of hostile emitters. Superconducting analog preprocessors with very wide bandwidth and using frequency chirp and other networks are

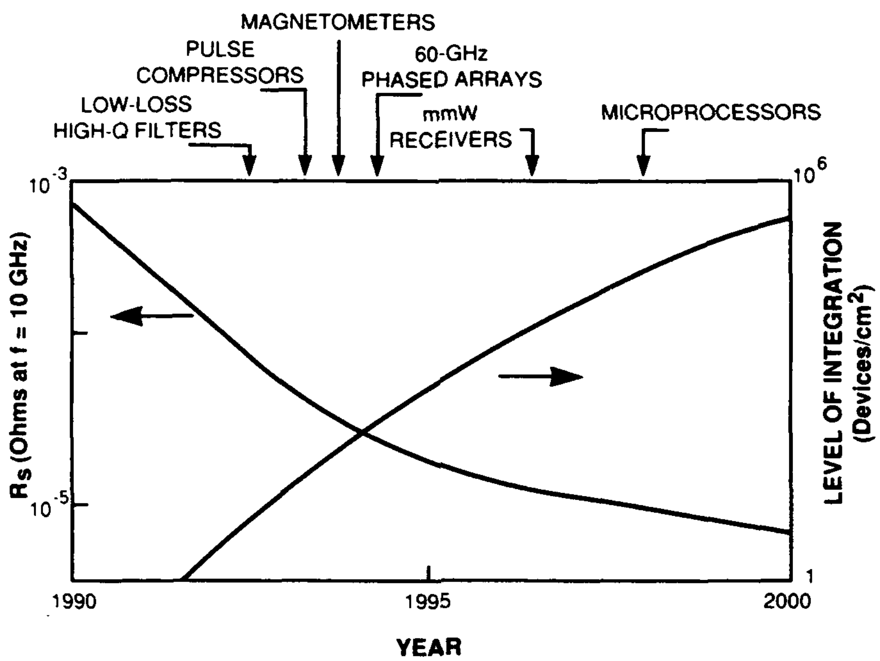

FIGURE 14-6 Superconductive electronics.

likely early applications. Superconductive magnetometers are being studied for use in detection and tracking of submarines; comparable applications to large ground vehicles, such as tanks, would be of interest to the Army. Superconductive digital circuits have the potential to provide for high-speed computers that are more compact and operate at low power. However, the full potential will not be realized until a high-speed three-terminal superconductor device is developed.

Miniature liquid nitrogen coolers weighing 100 to 200 grams are already available to cool superconducting electronics.

MICRON-SIZE VACUUM TRANSISTORS

The development of reliable cold cathodes with high current densities (>100 A/cm^2) will make possible micron-size vacuum transistors. These vacuum transistors, which have the same principles of operation as larger vacuum tubes, will have high-frequency and high-power capabilities not obtainable with any semiconductor. The devices could include:

- high-frequency (>100 GHz), high-power (>10 W) triode structures;
- tunable oscillators (>500 GHz); and
- vacuum transistors integrated with silicon and GaAs devices.

A simplified cross-section of a vacuum transistor is shown in Figure 14-7. Such vacuum devices will allow the development of radars and communication systems at frequencies and power levels not presently obtainable. These devices can be integrated with present silicon and GaAs technology in unique radar and communication systems.

Figure 14-8 shows the projected maximum voltage and power capabilities of various semiconductor and vacuum transistors as a function of cutoff frequency. Currently available cold cathodes can provide current densities on the order of 1000 A/cm^2, but they are unreliable and not easily fabricated into micron-size vacuum transistors. The few vacuum devices made to date do not perform as well as common silicon transistors. If a suitable cold cathode can be developed, vacuum transistors could realize their potential in less than a decade.

High-frequency, high-power vacuum transistors could replace the presently used traveling-wave tubes, with a substantial reduction of size, weight, and power consumption. Such devices could enhance high-resolution radar systems and space-based line-of-sight communication systems.

In addition, vacuum transistors should be extremely radiation-hardened. In all likelihood, they will be harder than any semiconductor device, since they depend on majority carriers in metals and vacuum.

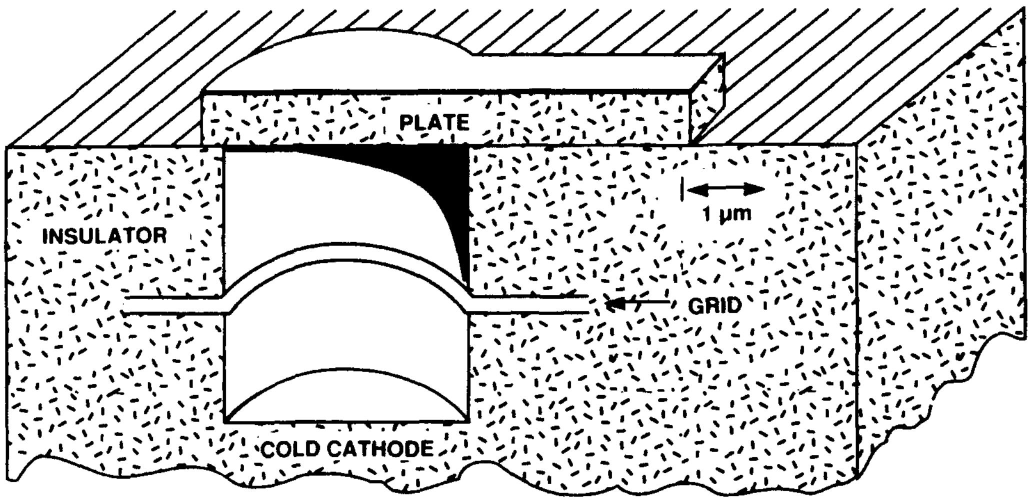

FIGURE 14-7 Vacuum transistor. Electrons emitted by the cold cathode are accelerated through free space by the plate voltage and controlled by the grid.

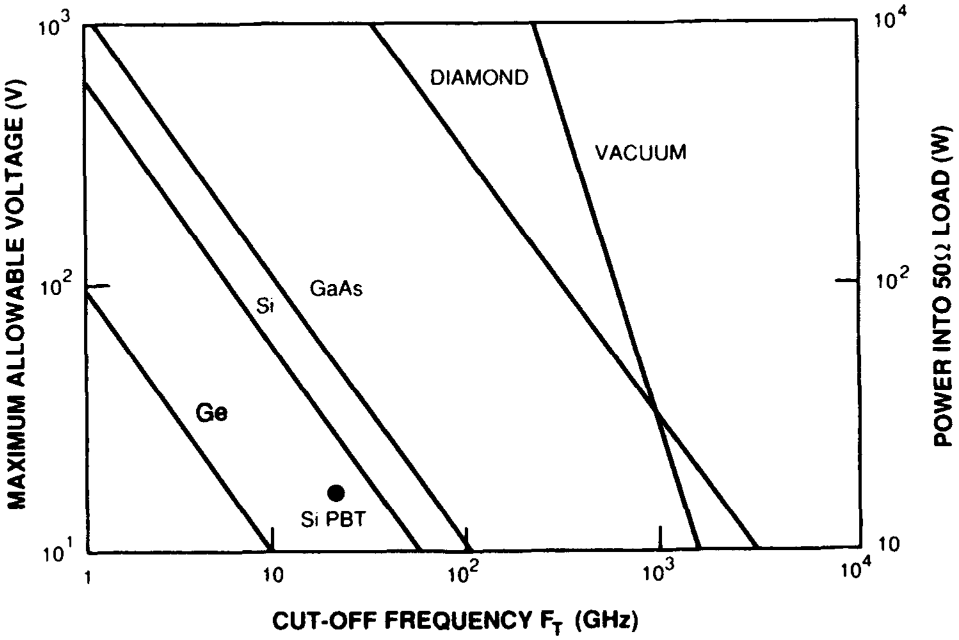

FIGURE 14-8 Projected voltage and power limits for semiconductor and vacuum transistors as a function of cutoff frequency.

ADVANCED ELECTRONIC-DEVICE CONCEPTS

A variety of fledgling technologies may have an important impact in the coming decade, but only their outlines can be discerned now. Materials technology has supplied the foundations for many of the advances in electronic devices to date. High-quality heteroepitaxial interfaces have made possible all the leading millimeter-wave transistor families. Thin films of high-temperature[1] integrated superconductors, GaAs transistors and lasers on silicon, and metal-well resonant-tunneling layers may make possible equally important future devices.

We appear to be moving toward the capability of growing crystalline layers of almost any material on any substrate. For example, the future may hold the monolithic integration of superconducting circuitry with semiconducting devices, ferroelectric or ferromagnetic memory cells with transistor logic, multiwavelength lasers with semiconductor electronics, or liquid-crystal modulators with diode lasers. Optical computing and neural networks are two established disciplines that could easily benefit from the integration of optical devices with high-speed processing and memory. Such advances will be the subject of intense study in the coming decade; they will probably result in new device concepts as well as new architectures for combining devices.

Bioelectronics is a field that promises to bring computation to the cellular level. Microelectronics technology has been employed to better understand the interaction of neuronal networks grown directly on microcircuits. From these beginnings, one can conceive of systems employing biological material for data processing and electronics for stimulation and readout. Such an advance would parallel the ongoing development of neural networks. One significant problem is that of growing a large number of neurons in a functional architecture while preserving a geometry that can be electrically addressed. However, in this era of rapid progress in genetic engineering, the coming decade is not an unreasonable time scale on which to expect dramatic developments in research on neuronal networks. System applications are likely to come some time later. The consequence could be the dawn of a new age in computational ability. (This area of research is discussed further in Part V: "Biotechnology and Biochemistry.")

COMPUTER MEMORIES

Nearly all current computers employ either silicon-based dynamic random access memory (DRAM) or static random access memory (SRAM). Currently,

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[1] "High-temperature" here refers to the critical temperature T_c at which a material becomes superconducting.

these are fabricated on silicon wafers 15 cm in diameter, with about 300 chips per wafer and the area of a chip approaching 1 cm^2. The individual memory cells are accessed by two sets of orthogonal selector lines (about 1000 in number for a 1-Mbit chip). The static memories employ an FET flip-flop, whereas the dynamic memories use a capacitor that is charged through an FET. The dynamic memories must be regenerated at intervals of roughly 4 ms. Figure 14-9 shows sketches of the SRAM and simpler DRAM cells.

The use of high-resolution lithography currently allows the fabrication of several million memory cells on a single chip. Cost and power consumption per bit have fallen dramatically, making possible the production of very powerful miniature data processors for military applications, such as signal processors, target identifiers, flight controllers, and data stores.

Typical contemporary capabilities are indicated in Table 14-3. Further reductions in the lithographic feature size to the order of 0.2 to 0.3 μm can be expected, compared with the 0.7-μm size currently used. Together with increases in the chip size, substantially larger memories per chip can be expected in the future. In addition, the use of GaAs substrates will provide a further speed increase.

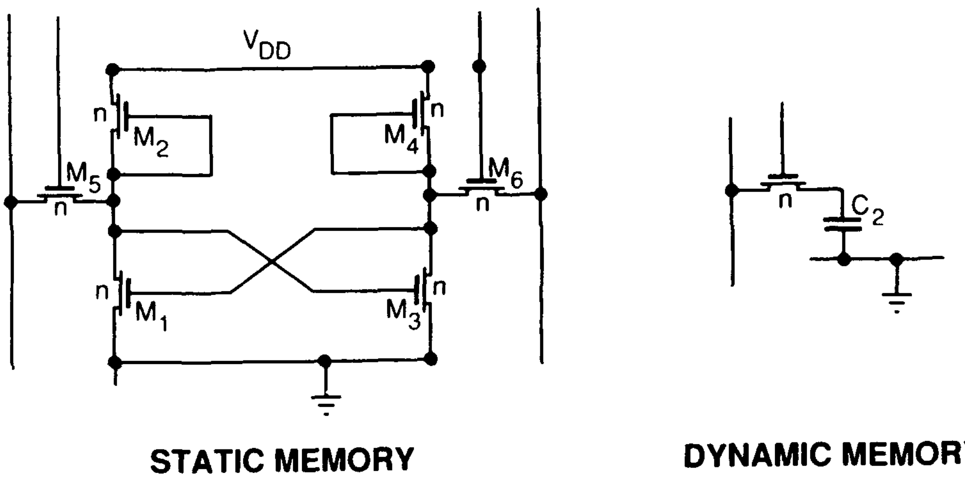

FIGURE 14-9 Schematic drawings of static and dynamic random access memory cells.

TABLE 14-3 Contemporary Capabilities of Dynamic and Static Random Access Memory

Capability	DRAM	SRAM
Size/chip	4 Mbit	250 Kbit
Access time	30 ns	20 ns
Power:		
active	175 mW	385 mW
standby	5 mW	110 mW

Figure 14-10 shows the expected increases in memory size per chip as a function of time for DRAMs and SRAMs in silicon, as well as projections for GaAs and silicon carbide memories.

In addition to the volatile memories discussed above, military systems need nonvolatile memories for applications where electric power is unreliable. Ferroelectric memories may be able to fill this important need.

The chief impact for future military computers of more compact computer memories will be a dramatic reduction in size and increases in capability. Most of the size of a military computer is currently occupied by memory. In addition, peripheral rotating disk memory can be converted into chip memory with further reductions in size and freedom from effects of vibration and acceleration. Computers using these memory advances should make possible a number of new military sensor systems. Examples of new capabilities for surface, air, and space-based radars include:

- suppressing side-lobe jamming of radars;
- suppressing radar clutter to permit detection of stealth aircraft; and
- automatic target recognition.

APPLICATION-SPECIFIC INTEGRATED CIRCUITS

Application-specific integrated circuits (ASICs) are used as substitutes for subsystems normally made of standard integrated circuits. ASICs can be grouped into three broad categories: programmable logic devices (PLDs); gate arrays or standard cells; and eventually wafer-scale integrated circuits. These three generic types span a range of capabilities and costs. At the low end, PLDs are readily available, low-cost devices that are electrically programmed or tailored to a specific application. Gate-array and standard-cell devices occupy the middle range of capabilities and cost; they are programmed at the mask phase of production in a process taking several weeks. At the upper end of the spectrum are multichip modules and wafer-scale products. The latter

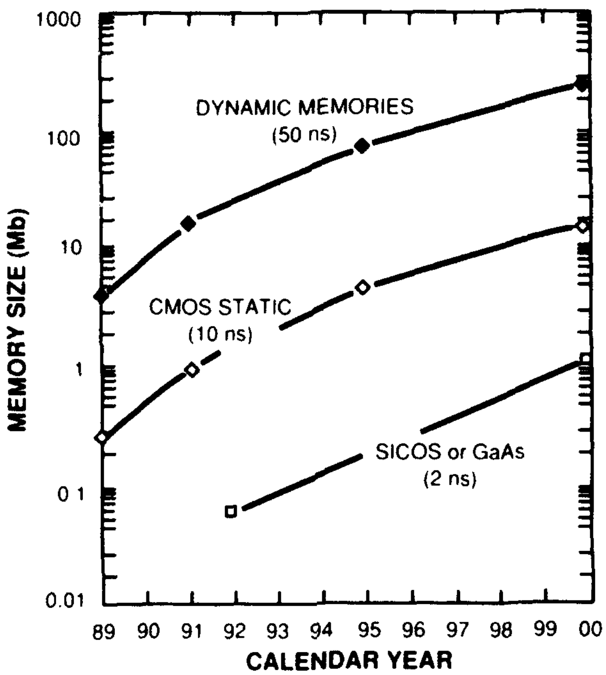

FIGURE 14-10 Memory technology projections for silicon dynamic random access, silicon memory and static random access memory, and memory chips based on GaAs or silicon carbide/silicon oxide.

devices, which are just emerging from the laboratory, offer the greatest capability but have the highest cost and turnaround time.

The use of ASICs in a digital system results in fewer components; higher reliability; and lower cost, weight, and power than the use of standard integrated circuits. These attributes provide tremendous advantage to military systems, which are constrained by size, weight, and power and are concerned with cost and reliability.

Figure 14-11 shows the current capability of ASICs in terms of the number of equivalent gates and "flip-flop toggle rate." The latter quantity is more descriptive of the underlying technology than a system clock rate, which depends strongly on the specific interconnection of gates. One might conservatively derate the toggle rate by a factor of 10 to get a reasonable estimate for the system clock rate. This scale is shown on the right-hand side of the figure.

The arrows represent the product range offered in several technologies: GaAs, emitter coupled logic (ECL), bipolar complementary metal-oxide semiconductor (BICMOS), and complementary metal-oxide semiconductor (CMOS). As a reference, the goals of the Very High Speed Integrated Circuit

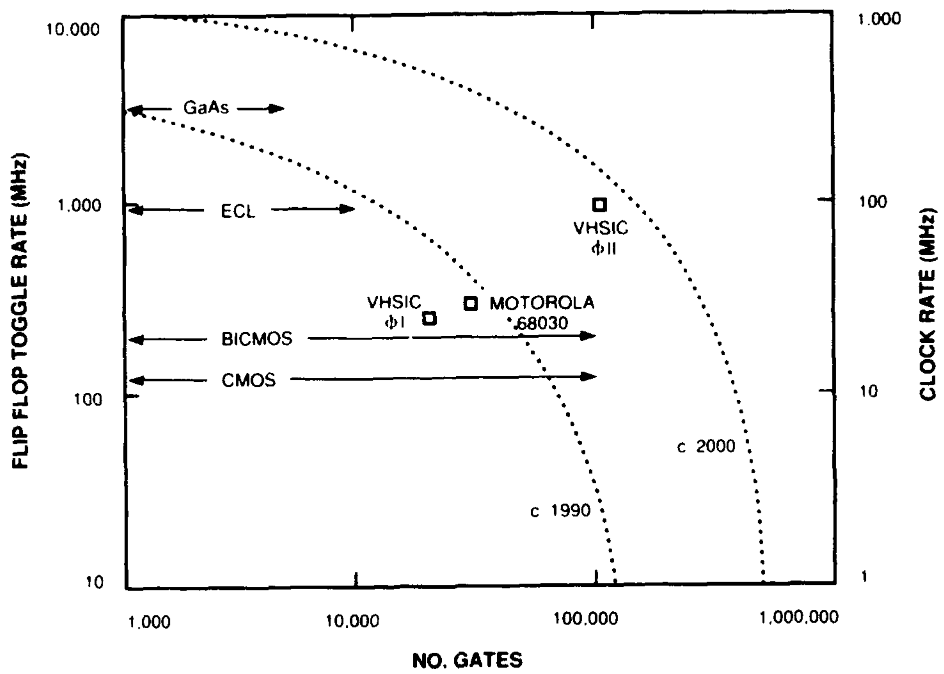

FIGURE 14-11 Capabilities of application-specific integrated circuits.

(VHSIC) Program are indicated, along with the capacity of the Motorola 68030. As indicated by the left-hand curve, most contemporary products are bounded by about 100,000 gates, with clock rates ranging up to 1 GHz for the smaller specialized-niche products (such as GaAs).

PLDs are available with up to 1000 equivalent gates. These inexpensive chips can be personalized in the laboratory using low-cost, easy-to-use programming devices; the whole operation takes a few hours. Gate arrays and standard cells, with roughly 10,000 gates, cost about $100,000 and take anywhere from six weeks to six months for fabrication. Wafer-scale products can contain upward of a million equivalent gates. These products can implement whole systems on a single substrate, but their cost (about $1 million) and turnaround time (about one year) make them prohibitive except for the most demanding applications.

As VHSIC technology diffuses throughout the semiconductor industry over the coming decade, the upper limit on gate arrays should expand to perhaps half a million usable gates per chip and a 50-MHz clock speed. Again, smaller arrays will operate in the multi-gigahertz regime, as indicated by the right-hand curve. Radiation-hardened devices will, as usual, lag the commercial sector by several years. It is not unreasonable to predict that the capabilities of radiation-hardened ASICs in the year 2000 will be no greater than the capabilities of today's state-of the-art commercial devices.

ASICs will have broad impacts on warfare because they offer the potential for reducing the size, weight, power, and cost of any military system that makes extensive use of digital integrated-circuit components (e.g., avionics). At the same time, reliability should improve because of the smaller number of components and connections.

ANALOG-TO-DIGITAL CONVERTERS

Analog-to-digital converters (ADCs) are the interface between the analog world and the digital processing systems used to interpret that world. ADCs are a vital element in all digital processing systems. As sensor technology expands, either in terms of bandwidth (in the case of radar systems) or focal-plane size (for electro-optical systems), the need for ADCs with wideband, high dynamic range continues to grow.

As ADC capability expands, systems designers have more freedom to exploit advances in sensors and communication systems. For example, radar systems can use wide bandwidths, thereby improving the range resolution of the system while reducing the probability of intercept. Electro-optical systems can use larger focal planes sampled at higher frame rates to provide improved coverage.

Figure 14-12 shows the current state of the art for a sample of ADCs in terms of sample rate and number of bits. The 1990 contour is simply an approximate bound on the sample shown. What is not obvious from this figure is the trend toward monolithic, multistep converters rather than flash converters, to conserve silicon "real estate." The commercial sector is driving ADC development with its need for video-rate (10–50 MHz) products with modest dynamic range (6–8 bits). The advent of high-definition television with its many (proposed) digitally implemented features will only increase this direction of research.

The contour for the year 2000 in Figure 14-12 reflects the estimated evolution of the field over the coming decade. Multi-gigahertz ADCs will be readily available for specialized applications, and high-precision (16 bit) ADCs will move into the multi-megahertz regime. However, most of the improvements in commercial devices will be associated with the expansion of high-definition television.

Military systems, on the other hand, require not only high sampling rates but also high dynamic range (12 or more bits) to accommodate the wide range of signal levels encountered in the military environment. Some board-level

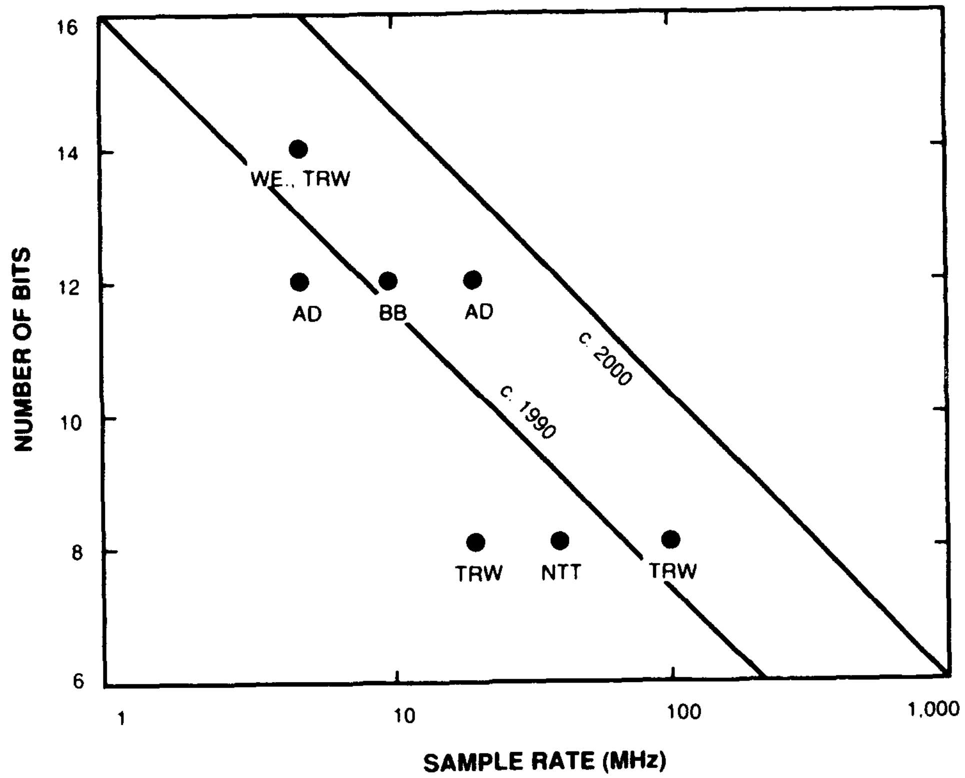

FIGURE 14-12 Analog-to-digital converter technology, where AD = Analog Devices, BB = Burr-Brown, NTT = Nippon Telephone & Telegraph, TRW = TRW, Inc., and WE = Westinghouse.

products are available for this operating regime, but they can be used only where size, weight, and power are not at a premium. Current research is pushing to develop monolithic products with at least 12-bit resolution and multi-megahertz sampling rates.

Radiation-hardened devices with capabilities similar to the ADC now being developed under Strategic Defense Initiative Organization (SDIO) sponsorship should become available by the year 2000. The goal for this 12-bit, monolithic ADC is a 10-MHz sample rate while satisfying the SDIO Level I radiation requirements.

DIGITAL SIGNAL PROCESSING MICROPROCESSOR CHIPS

Many modern signal analysis systems are based on a class of processing chips known as digital signal processing (DSP) microprocessors. These integrated circuits are very similar to conventional high-performance microprocessors, except that their architecture and instruction sets are optimized for signal processing applications such as filtering, spectral analysis, and convolution.

For DSP applications, the DSP microprocessor offers significant advantage over a conventional microprocessor. It not only has a high peak computation rate (generally rated by the number of multiply-accumulate operations per second) but also has an architecture that allows it to sustain an average computation rate close to the peak rate in a typical DSP task. These features include built-in floating-point capability, special instructions such as bit reversal, and zero-overhead loops that allow high efficiency in the innermost loops of the program. These chips also typically have special-purpose input/output ports that allow them to be integrated into compact systems. More recently, these chips have been supported by high-level languages such as C, making it possible to go rapidly from a simulation to a real-time implementation.

The current capabilities of DSP chips are as follows:

- arithmetic—32-bit floating point;
- multiply-accumulate rate—12 million to 15 million floating-point operations per second (MFLOPS); and
- input/output ports—1-bit serial (16 MHz).

Over the next five years, the Technology Group expects evolution of these chips to follow other general trends in the semiconductor industry toward smaller feature size and faster clock rates. The other dimension that will be exploited will be parallelism. The design of the central processing unit elements will include the communications necessary to exploit the parallelism, a feature that is lacking in the current generation of DSP chips. Hybrid integration techniques will be used to combine multiple processors, with their associated memories, on a single substrate to provide compact powerful systems.

In 10 years the Group expects to see chips capable of 100 million instructions per second (MIPS), based on GaAs, become available for dedicated front-end applications. Fiber optics will provide gigabit interprocessor capability, eliminating the communications bottleneck among processors. Figure 14-13 shows the expected trend in processing power for single chips and multiprocessor systems made up of arrays of up to 1000 processors. Software design methodologies to support the high level of parallelism will be developed over this period.

The chief effect of the DSP chips on warfare will be to increase the sophistication and reduce the size of military systems that exploit signal processing technology, including radar, sonar, communications, image

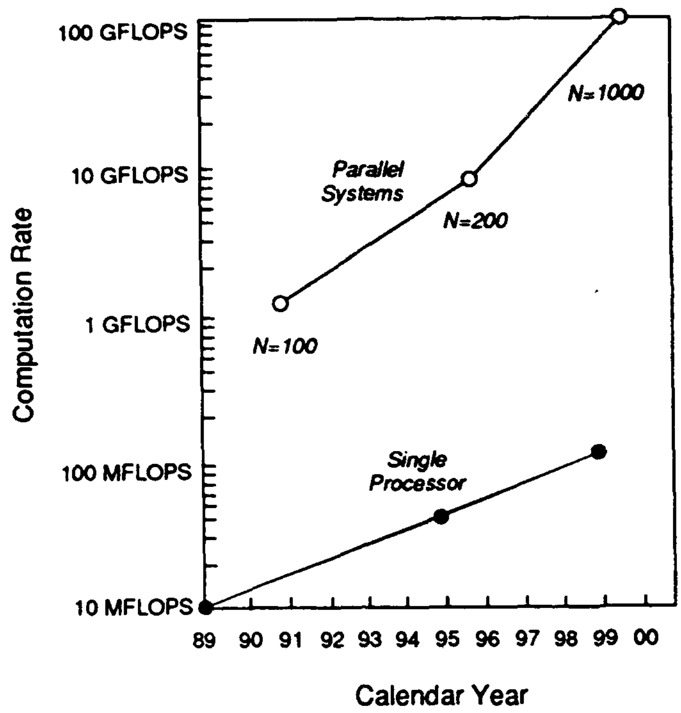

FIGURE 14-13 Projections for digital signal processing.

processing, and reconnaissance systems. Examples of new capabilities that will be possible with these chips are the following:

- compact "smart" weapons with onboard target recognition;
- advanced low-probability-of-intercept communications techniques;
- speech recognition for command and control; and
- sophisticated radar and sonar systems for detection of stealth aircraft and quiet submarines.

WAFER-SCALE TECHNOLOGY

As noted above, wafer-scale technology (WST) represents the high end of generic ASIC technology. Typical applications of WST utilize circuits as whole systems that are capable of substantial computation. WST is being developed for both monolithic and hybrid devices. Hybrid WST offers the advantage of being able to mix and match a variety of different chip types onto a single substrate. Monolithic WST has the individual chips integrated directly into the substrate; it thereby avoids the reliability problem associated with chip-to-substrate bonding.

WST allows one to bypass many of the fabrication steps required to implement digital systems, while offering smaller size, weight, and power with improved reliability. Consider this typical fabrication sequence for a digital system: a number of different integrated-circuit designs are fabricated on different wafers; the wafers are diced and the circuits tested; the good circuits are packaged and eventually wired together on a conventional printed-circuit board. A monolithic WST system bypasses much of this sequence. Here the various circuit types are laid down on a single wafer and directly interconnected after testing; the dicing, packaging, and wiring are eliminated. A hybrid WST circuit is intermediate in that the different circuit types are manufactured separately, then diced, tested, and bonded onto a single silicon substrate, which then substitutes for the printed-circuit board.

Figure 14-14 projects the capability of monolithic WST systems over the coming decade. For example, a WST fast Fourier transform (FFT) unit was demonstrated in 1986 with a throughput of 300 million operations per second (MOPS) on a wafer 7.5 cm in diameter with 5-μm feature size and a power dissipation of 3 W. The design for the matrix update systolic experiment (MUSE), which is based on a 2-μm feature size, is expected to yield about 2 billion operations per second on a 12.5-cm wafer. A solid-state disk memory of 16 megabits is expected within the next two years. Hybrid WST offers similar capability but with added flexibility, through its ability to use a variety of circuit types. Minimizing defects in such circuits probably will require the use of fabrication systems in which the wafers are kept in a vacuum system through all stages of processing. This will require the development of dry resists and other advanced dry-processing techniques.

The mid-1990s should see wafers increase in diameter to 15 cm, with feature size shrinking to far less than 1 μm, and clock rates increasing to 25 MHz. These improvements combine to yield a computation rate of 50 billion to 100 billion operations per second, at a dissipation of about 25 watts per wafer. Figure 14-14 displays the projected capabilities of a focal-plane processor compared with today's FFT and MUSE devices.

For embedded systems, measures of computation per unit of power, size, or mass are of special interest. Assuming that a single 15-cm wafer can be packaged in a cylinder 5 cm high, efficiency figures of about 3000 MOPS/W, 100 MOPS/cm^3, or 200 MOPS/g are obtained. However, significant advances in packaging technology and thermal management are needed to achieve these goals.

WST will make practical a number of military applications, particularly space-based applications that are now beyond reach for reasons of size,

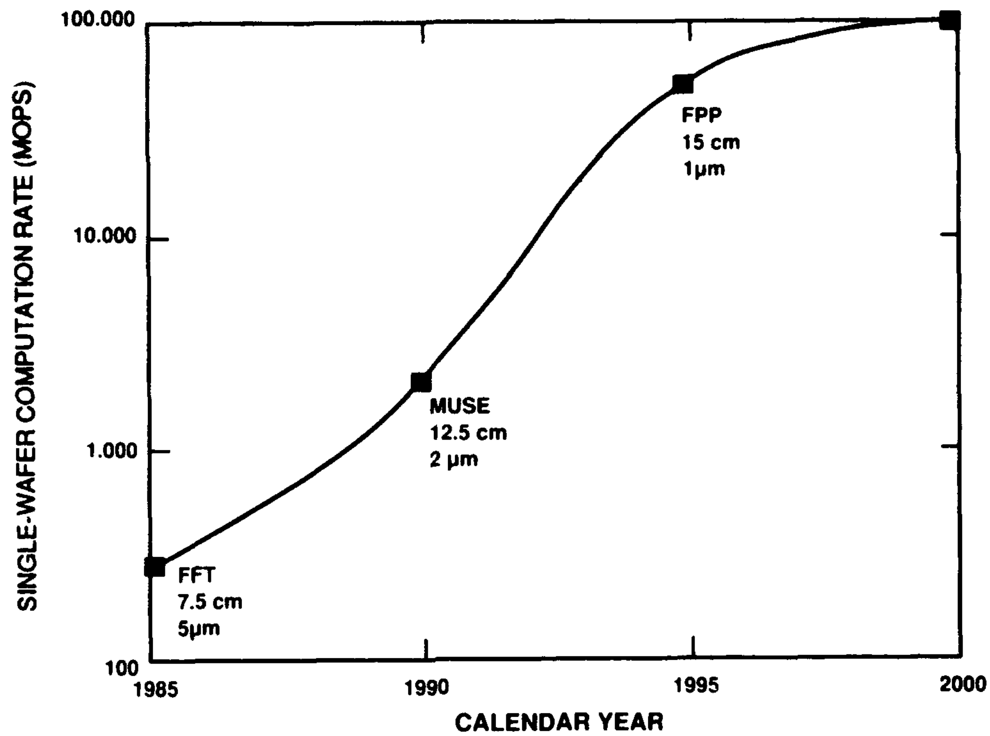

FIGURE 14-14 Capabilities of wafer-scale technology. FFT is a fast Fourier transform processor, MUSE is the matrix update systolic experiment, FPP is a focal-plane processor.

weight, and power. For example, the 12.5-cm wafer (MUSE) described above will provide an adaptive nulling system with the unprecedented ability to support 64 degrees of freedom, while dissipating only 20 watts. Expanded capacity to deal with jamming scenarios that are even more stressing can be accommodated with several wafers connected in cascade. Similar improvements can be expected in other radar, communications, and electro-optical applications.

ELECTRONIC DESIGN AUTOMATION

The tasks in building an electronic system are specification, design, design verification, fabrication, hardware test, and documentation. These tasks must be performed at several different levels in a hierarchy that includes, from top to bottom, levels for system, subsystem, integrated circuit, logic cell, and transistor. At each level, different abstractions must be dealt with, including behavior, timing, and physical implementation. Historically, electronic design automation (EDA) programs have operated at a particular level and on one of the abstractions; the user had to learn to use all of these programs and create new descriptions for each program, a process that led to imprecision and errors.

There is now much emphasis on using industry-standard data formats so that one tool will create a description that can be the input into another EDA program. One widely used standard is Electronic Design Interchange Format. Another important standard is VHDL (VHSIC Hardware Description Language), which was developed under DOD auspices. VHDL is an ADA-based language in which a designer can specify behavior, timing, and structural information about a system or circuit. As more simulation, verification, and synthesis tools are developed that accept a VHDL description as input, the designer can use them with assurance that they are all working on the same description. Such a complete description also serves as documentation of the design. Also, programs that synthesize a design at one level from a higher-level design are beginning to be used.

At present, the best-developed EDA programs are those used for mask-programmable gate arrays and electrically programmed logic devices. Circuits are generated from a logic diagram or net list; since these circuits are predefined and well characterized, logic and timing simulations are very accurate. Gate arrays as large as 100,000 gates are customized in this manner.

In addition to computer-aided design for digital circuits, extensive computation tools are under development for computer-aided design of analog charge-coupled device circuits as well as MMIC circuits. Although these design tools lag those used for digital circuits in terms of complexity, they can be expected to increase significantly in capability over the next decade.

A photograph of any modern complex integrated circuit clearly shows many separate modules connected together to form the complete circuit. Some of these modules are generated automatically from a functional description. For the one-million-transistor Intel i486 processor chip, the programmed logic array and read-only memory sections were generated automatically, the data path was hand-crafted, and a placement and route program was used to connect them together. In terms of devices laid out per week, automatic layout was 100 times more efficient than hand layout.

Several programs are available that synthesize data paths and entire circuits. They are used when quick turnaround is more important than highest performance and silicon efficiency. An important advantage of synthesis methods is that circuits are easily changed in response to logic changes or technology upgrades. Logic and circuit simulators are critically important tools. Newer logic simulators are easier to use and have better interfaces to test equipment. Hardware accelerators are used to speed simulation of very large circuits. Mixed-mode simulators, which simulate a system with some modules described by behavior and others by transistor layout, allow continual validation while the design becomes more detailed. It is common to run compilers and application programs on simulated processors so that the software and circuits can be designed and debugged in parallel. Two-dimensional and three-dimensional simulations of devices and integrated-circuit fabrication simulators are used in development of new devices and processes. Programs have also been developed for integrated-circuit testing. Such programs are particularly important for WST circuits, to determine reconfigurations that will avoid fabrication flaws.

R&D efforts in EDA focus on synthesis of circuits from high-level descriptions, design for testability, and the automatic inclusion of self-test. There is much work on development of integrated sets of EDA tools and a common framework of user interfaces and data access methods, which would be used by many different programs. Since simulation of circuits and devices is very compute-intensive and inherently parallel, researchers are developing programs for the new parallel machines. Synthesis programs for commonly used analog circuits are being developed.

Commercial trends in this field are toward simplification. Most EDA programs (except for the largest routers and simulators) are used on workstations. Vendors previously built special workstations, but now nearly all programs run on standard workstations, with UNIX systems most common. The industry traditionally has comprised many small and specialized companies, but now larger organizations are being formed through mergers in order to market unified sets of tools. Semiconductor producers and large-system houses use a mix of in-house and commercial programs, but commercial programs are adequate for many designers of military equipment.

15

Data Processors (Signal Processors, Target Recognizers)

MULTIPROCESSOR COMPUTER TECHNOLOGY PROJECTIONS

Computers perform operations on data to provide outputs for many uses, including displays for human operators and control signals for weapon systems. Different types of computation are used in measuring the capability of computer systems for different applications. *Numeric computing power* is a measure of how fast computers can perform mathematical operations on data, which is a very common and useful function in a variety of systems. *Symbolic computing power* is related to the response rate of application systems (e.g., expert systems, robotic systems). A rapid change in computing power is currently under way because of a new generation of very-large-scale integrated (VLSI) chips. This trend will continue through the year 2000.

The advantage of the new VLSI chip technology is either increased computing power in packages similar in size to present computers or the same computing power in smaller packages. Either way, the result is more capable systems that can solve harder problems, perhaps in less time than present systems. Figure 15-1 shows the processing power of currently available multiprocessor computer systems, measured in millions of floating point operations per second (MFLOPS), a good measure of numeric computing power. The current limit appears to be in the range of a billion operations per second (GFLOPS).

The use of the new-generation reduced-instruction-set computing (RISC) VLSI chips such as the Motorola 88000 family will result in faster computers for both numeric and symbolic computing. Figure 15-2 shows projections of MFLOPS versus time, based on GaAs and RISC chip technology. Figure 15-3 projects the symbolic processing power of these chips in terms of a symbolic benchmark called "Browse." The Browse benchmark is related (roughly) to how fast an expert system with 100 simple rules would run.

The primary effect of increased computing power on warfare systems will be a significant increase in the capability of computers embedded in mobile systems. New applications will include robotic or autonomous systems, "brilliant" weapons, and very capable systems for automatic target detection, recognition, and tracking. Use of expert-system techniques in fielded military systems will result in effective computer assistants to handle routine decision-making and control functions, relieving humans to handle more difficult problems.

Software engineering for machine intelligence, expert systems, and robotic systems is discussed in Part II: "Computer Science, Artificial Intelligence, and Robotics."

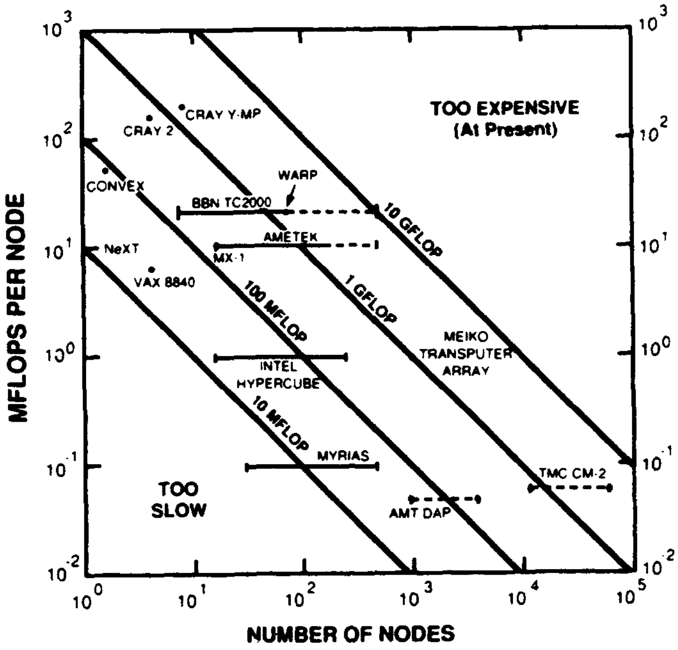

FIGURE 15-1 Survey of present numeric processing power.

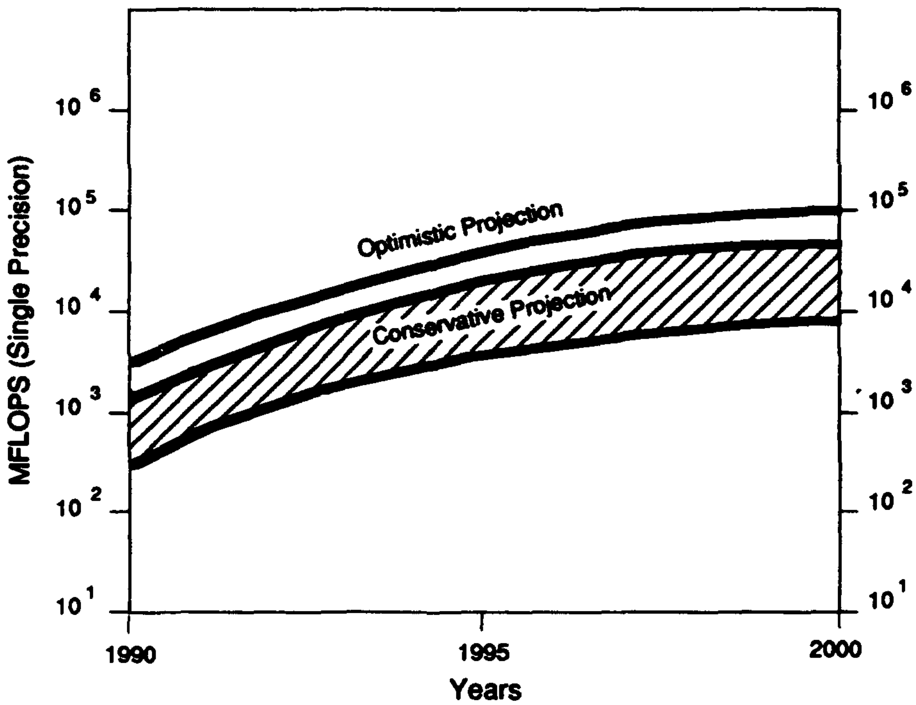

FIGURE 15-2 Projections of numeric computing power.

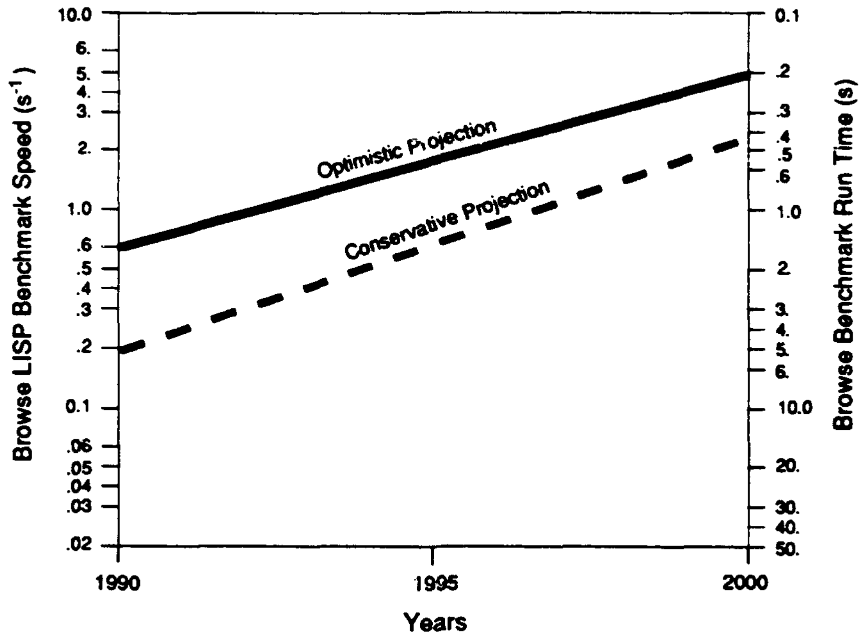

FIGURE 15-3 Projections of symbolic computing power.

NEURAL NETWORKS

Neural networks represent an approach to information processing that is inspired by biological systems. Input data are processed in a highly parallel fashion in a network of simple processing elements (neurons) that may be sparsely or densely interconnected. In a neural network, the function is determined by the interconnection topology and the connection strengths. The promise of neural networks is high-speed information processing through parallelism, robustness to element failures, and direct hardware implementation of networks in VLSI hardware for realization of compact processors. Certain neural networks can be "trained" to produce desired responses, in a manner somewhat analogous to programming a computer. The technology first emerged in the 1950s but subsided as artificial intelligence grew in application prominence. It has re-emerged in the 1980s with major perception and adaptive control. Neural nets can be described in algorithmic form and programmed on a digital computer; alternatively, they can be implemented in analog VLSI circuits, with great advantages in processing speed and compactness.

The potential advantages of neural network technology are high-speed information processing through massive parallelism, insensitivity to variations in element characteristics, trainability/adaptability, and (when implemented in VLSI circuit technology) compactness relative to other standard methods of fabricating information processing systems. The Technology Group emphasizes that the neural network field is still in its very earliest stages of development, compared with the development history of multiprocessor computers.

Current realizations of neural nets are almost entirely in the form of computer simulations, achieving on the order of 10^7 to 10^8 connections per second. (The measure of the processing power of a neural network is the number of connections that can be applied to neuron inputs per second. Each connection applied is equivalent to a multiply-and-add operation.) Although only experimental hardware exists at present, a number of efforts are maturing to the point of including neural-net chips in a commercial information processing system.

As computer speeds increase, neural network simulation capability will also increase. The emergence of neural network hardware in the form of custom VLSI chips will require an explicit commitment to advance the state of the technology. New techniques are required for neural-net chips, such as stable analog VLSI circuits and adaptive synaptic weights. Figure 15-4 shows current neural-net hardware capabilities, taken from a 1988 DARPA neural network study, and extrapolates them into the future, assuming a serious commitment to develop this technology.

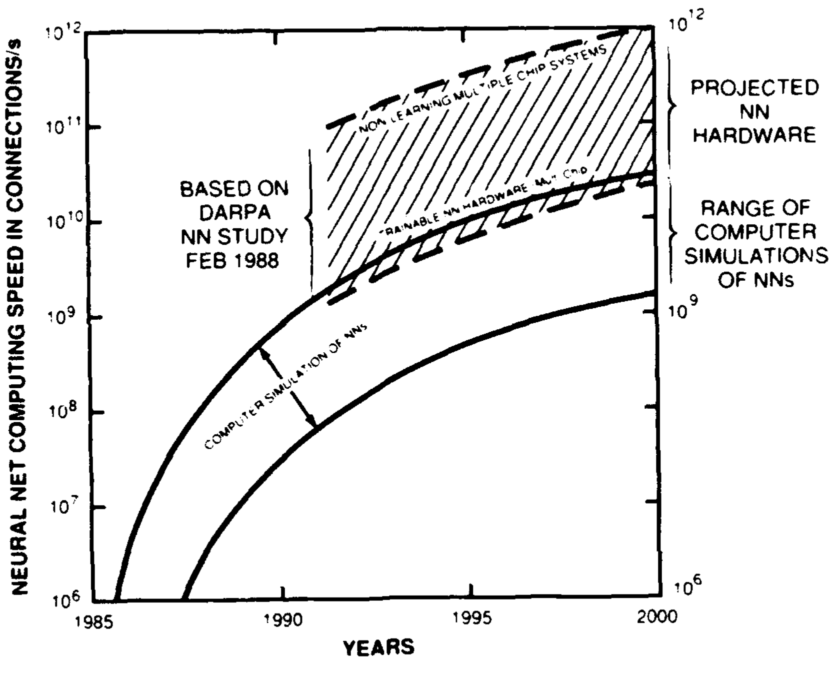

FIGURE 15-4 Projections of neural network computing speeds.

Neural network technology could have a major impact on information processing systems of all types in the future, but the impact on military systems could be revolutionary. The advantages of high-speed processing in the form of rugged, extremely compact hardware, with little dependence on software, are immediately obvious in the context of such applications as "brilliant" weapons, autonomous systems, and automatic sensor data processing. Image processing, pattern recognition, speech recognition, and adaptive signal processing and control are among the early potential applications of neural-net hardware.

For more information on neural networks, see Part I: "Long-Term Forecast of Research," Part II: "Computer Science, Artificial Intelligence, and Robotics," and Part IV: "Optics, Photonics, and Directed Energy."

16

Communications Systems

ROBUST/SURVIVABLE COMMUNICATIONS SATELLITES

DOD's Military Satellite Communications Architecture for the post-2000 period calls for the continuation of the current services at ultrahigh frequency (200–400 MHz) and super-high frequency (7–8 GHz), as well as the initiation of a significantly better protected robust/survivable segment and a complementary augmentation/restoration capability. This description concentrates on the robust/survivable portion, which will operate at extremely high frequency (EHF) (4 and 20 GHz) and which will require the following advanced-technology payload subsystems:

- agile, adaptive uplink antennas;
- lightweight, low-power frequency generation circuitry;
- highly integrated signal processors; and
- efficient, high-power, agile downlink transmitter/antenna subsystems.

The robust/survivable communications satellites will provide a number of advantages:

- antijam, antiscintillation, covert communications via operation at EHF and the utilization of wideband spread-spectrum techniques and autonomously adaptive uplink antennas;
- low (<2400 bps), medium (4800 bps to 1.544 Mbps), and high (>1.544 Mbps) data rates;
- agile uplink/downlink beams to serve widely separated users concurrently;
- worldwide connectivity without ground relays (i.e., through the use of crosslinks); and
- increased physical survivability via appropriate levels of hardening and/or proliferation.

Current communications satellites provide good long-range connectivities, but their capabilities will be drastically reduced under jamming or link-propagation attacks. To correct this situation, an initial EHF capability for critical communications is being developed. However, the current state of the art is such that the resulting EHF payloads are large and heavy, while their development and procurement costs are high. For example, the estimated weight and power requirements for a representative EHF payload for a future robust satellite are 1940 pounds and 2000 watts. Such a satellite would provide capabilities for low, medium, and high data rates (>100 Mbps total) without crosslinks.

By incorporating advanced technologies, EHF payloads can have significantly increased utility as well as considerably lower weight and power requirements. Such payloads will be able to:

- support antijam communications at low, medium, and high data rates;
- provide agile uplink/downlink beams to serve many widely separated users concurrently; and
- be implemented within the current weight/power allocations for ultrahigh-frequency and super-high-frequency satellites.

Table 16-1 lists key technologies that must be utilized to accomplish these objectives. As indicated below, the weight and power required for a highly capable EHF payload will be reduced considerably as the advanced technologies are developed.

Time Frame	Weight (lbs)	Power (W)
Current	1940	2000
Near term (1–2 years)	1000	1200
Far term (>5 years)	800	900

The principal impact of robust/survivable communications satellites will be to provide highly protected communications during all levels of conflict. Low-rate (<2400 bps) traffic among mobile platforms and their command centers, medium-rate (4800 bps to 1.544 Mbps) messages among transportable units, and high-rate (>1.544 Mbps) communications among fixed sites can all be reliably supported. Furthermore, these systems will be extremely flexible if the emerging EHF transmission standards ensure that the terminals from all of the services can interoperate and can use any of the available EHF in-orbit resources.

TABLE 16-1 Key Technologies for Robust/Survivable Communications Satellites

Subsystem	Key Technologies	Weight (lbs)	Power (W)	Weight Reduction Factor Via Advanced Technologies
Agile, adaptive antenna	Phased array of MMIC transmit/receive modules; low-noise amplifier (LNA) lightweight switch trees; VLSI processor	100	100	7
Uplink and downlink frequency synthesizer	MMIC; direct digital synthesis	4	12	10
Signal processor	VLSI/ASIC; wafer-scale integration	50	95	5

NOTE: ASIC = application-specific integrated circuit; MMIC = monolithic microwave integrated circuit; VLSI = very-large-scale integration.

AUGMENTATION/RESTORATION COMMUNICATIONS SATELLITES

As mentioned above, the Military Satellite Communications Architecture for the post-2000 period calls for an augmentation/restoration capability to complement the robust/survivable segment. This section concentrates on the augmentation/restoration capability, which will operate at EHF frequencies (44 and 20 GHz) and which will require the following advanced-technology payload subsystems:

- lightweight, low-power-frequency generation circuitry;
- highly integrated signal processors; and
- efficient, high-power, reliable downlink transmitters.

The advantages of these lightweight augmentation/restoration satellites will include:

- antijam, antiscintillation, covert communications via operation at EHF and the utilization of wideband spread-spectrum techniques that are compatible with the robust/survivable satellites;
- low (<2400 bps) and perhaps medium (4800 bps to 1.544 Mbps) data rates;
- capabilities to increase or replace critical coverage in a timely manner;

- responsive launches using small, mobile/survivable launch vehicles that require considerably less launch preparation;
- greater assurance of access to space because of reduced dependency on large, fixed launch sites; and
- lower incremental costs.

The currently planned EHF satellites are quite capable but are also large, expensive, and require many months to prepare an appropriate launch vehicle. Accordingly, they are not able to provide timely and economical increases in (or restoration of) capacity in critical coverage areas.

Using existing technology, a complementary-service satellite with 32 EHF communication channels would have a payload weight of 225 pounds and power requirements of 200 W for a total satellite weight of >1000 pounds. Such complementary satellites are beyond the capability of mobile/survivable launch vehicles, which typically can place 300 to 400 pounds into the elliptical and synchronous-altitude circular orbits that are useful for communications.

By incorporating advanced technologies, highly capable yet lightweight EHF payloads can be implemented. Significant reductions are possible with technologies that can be available within two years. Even further decreases will be possible as additional advances are made. Table 16-2 lists the key technologies and resulting weight reductions. A 32-channel EHF payload/satellite utilizing these technologies would have the following characteristics:

	Payload Weight (lbs)	Power (W)	Total Satellite Weight (lbs)
Near term (2 Years)	80	100	300–350
Far term (>5 Years)	55	70	200–250

The Army and DARPA are working toward a much more capable lightweight EHF satellite that could be rapidly inserted into a geostationary orbit. This satellite would contain 32 low-data-rate and 8 medium-data-rate EHF communication channels with a variable-beamwidth antenna and an autonomous nulling capability. This satellite would have a payload weight of 180 pounds and power requirements of 315 W with a total satellite weight of <600 pounds.

Augmentation/restoration satellites will provide the means for a timely increase in communications capacity over a critical area of operations, as well as a rapidly implementable replenishment capability. They will reduce considerably the cost of incremental changes in the capacity available to a

TABLE 16-2 Key Technologies for Augmentation/Restoration Satellites

Subsystem	Key Technologies	Weight (lbs)	Power (W)	Weight Reduction Factor Via Advanced Technologies
Highly integrated signal processor (32 channels)	VLSI/ASIC; wafer-scale integration	25	45	4
Uplink and downlink frequency synthesizer	MMIC; direct digital synthesis	4	12	10
Highly efficient solid-state EHF transmitter	FETs; PBTs	2	10[a]	2

[a] Achieved by a phased array of low-power transmit/received modules.

region of service. In addition, they can open other "new ways of doing business" such as direct control by the user. They will be fully compatible with the EHF terminals that are currently being developed, as well as with future man-portable versions that are planned. It is expected that such low-probability-of-intercept EHF satellites will replace much of the current beyond-line-of-sight (BLOS) terrestrial communications (e.g., high frequency or troposcatter) because of the covertness and small weight of the EHF satellite circuits. In addition, such an approach to BLOS circuits will provide redundancy and antijam protection, as well as covertness.

17

Electronic Sensor Systems

ACTIVE AND PASSIVE TERRESTRIAL RADAR, ACOUSTICS, SPACE-BASED RADAR, AND ELECTRONIC INTELLIGENCE

This topic is discussed in a classified working paper, which is available from the U.S. Army Materiel Command, Office of the Chief Scientist, 50001 Eisenhower Avenue, Alexandria, Virginia.

UAV GROUND SURVEILLANCE RADARS FOR MOVING TARGET DETECTION

Airborne radars are a principal tool for long-range surveillance of ground targets. An example of the current technology is Joint Systems Target Acquisition Radar System (JSTARS), which will be used primarily for moving-target detection. Unmanned airborne vehicles (UAVs) offer a cheaper platform for an airborne radar but with size, weight, and power constraints. High-speed on-board signal and data processors can be used to reduce the data-link bandwidth required for real-time transmission of data to a user.

The advantages of UAVs to carry surveillance payloads to hazardous locations were demonstrated in 1982 by the Israelis in the Bekaa Valley and in 1991 by U.S. forces during Desert Storm operations. These platforms have proven to be survivable because of their low radar, infrared, and optical signatures. They are much less expensive than manned platforms, and they do not put a human crew at risk. They can fly closer to the enemy and thus permit better visibility of ground activity unobscured by terrain and foliage.

Lincoln Laboratory has built a compact radar for the DARPA-sponsored long-endurance AMBER UAV. This Ku-band radar includes a state-of-the-art programmable processor that performs moving-target detection on tens of millions of bits per second of raw radar data, turning it into tens of kilobits per second of moving-target reports. Tank-sized moving targets can be detected and tracked out to a 15-km range from the radar, with a 360-degree surveillance sector.

The Technology Group expects that, in the next five years, UAV radars will be fielded as adjuncts to the current large, expensive systems. As an adjunct to JSTARS, a UAV radar will penetrate enemy territory to see areas blocked from JSTARS by terrain and foliage masking. Three other future roles for UAV-based radar systems would be stationary target detection, low-altitude air defense, and inverse synthetic-aperture radar imaging of ships.

A UAV-based synthetic aperture radar could provide high-resolution, polarimetric data from stationary targets; such a system would provide multi-aspect angle information that would permit target detection and classification. Ground-based air defense systems working against low-flying aircraft are severely hampered by terrain and foliage masking; UAV-based radars have been proposed for detection and classification of low-flying aircraft and helicopters at ranges up to 40 km. A UAV radar also could provide a ship identification capability similar to that provided by the Navy's P3 Orion aircraft but in a smaller, less expensive package, albeit operating at shorter ranges.

In the signal processing area, the next five years will see the continued development of smaller, more capable processors. This will benefit all radar systems, but will be especially significant for UAV-based systems, where size and weight are the limiting factors. For example, a high-resolution UAV-based synthetic aperture radar will become possible.

The military impact of radar surveillance by UAVs will be better coverage for lower cost in dollars and lives. Increased processor capability will provide high-resolution images of moving and fixed targets; the images can be processed on the platform or by more sophisticated real-time target classification systems. These technologies will give the battlefield commander a much better real-time picture of activity on the battlefield, permitting engagement of enemy forces at much longer ranges.

AIRBORNE RADARS FOR DETECTION AND RECOGNITION OF STATIONARY TARGETS

Automatic target cueing (ATC) and recognition (ATR) algorithms are being studied for the detection, classification, and identification of stationary ground targets by radar. Current detection techniques rely on the brightness difference between a target and the surrounding clutter. The only existing operational capability in this area is provided by human interpreters of radar imagery—as with data from the Advanced Synthetic-Aperture Radar System—and proceeds very slowly. New ATC and ATR algorithms can work with two-dimensional data (where a human can do well), one-dimensional data (such as high range-resolution only), or multidimensional data (such as synthetic aperture radar and passive and active infrared imagery).

Performance of the current baseline constant false alarm rate detector is a strong function of target type and location, clutter environment (especially the density of manmade objects), resolution, polarization, and algorithm details. Representative performance parameters are shown in Table 17-1.

New ATC/ATR technologies are projected to improve greatly on this performance. In Table 17-1, for example, at the same 50 percent detection probability, the false alarm density may decrease by one to three orders of

TABLE 17-1 Representative Performance Parameters for Automatic Target Cueing and Recognition Detectors

Target	Tank
Clutter	Moderate natural, $\sigma^0 = -13$ dB
Resolution	10 m × 10 m
Polarization	HH
Probability of Detection	0.5
False Alarm Density	10 per km^2

magnitude as ATC/ATR algorithms improve with higher-resolution polarimetric data. As these algorithms improve, performance against targets equipped with countermeasures and against tougher clutter becomes adequate for some postulated military applications, as shown in Figure 17-1. Enabling technologies will include neural nets, statistical pattern recognition, and model-based vision.

The use of high-performance ATC/ATR algorithms with high-speed computers will allow real-time detection of targets at large surveillance rates (in km^2/s) that would easily overload a human's imaging and decision capability. This real-time detection capability also permits speedy weapon delivery, enhancing the surveillance platform's survivability. Also, weapons are envisioned with radar seekers using ATC/ATR algorithms to autonomously reacquire and home in on stationary targets. Again, autonomous, fire-and-forget weapons eliminate the need for a man to be vulnerable while designating a target, as in some current systems.

ACOUSTIC ARRAY SENSORS

Geographically dispersed networks of small microphone arrays (apertures of a few meters) can be used to detect, locate, and recognize aircraft, firing weapons, and ground vehicles. Single arrays can provide directional cueing; networks can locate weapons and track aircraft. Enabling technologies include effective data interpretation algorithms for multiple sensor arrays, noise suppression methods for the arrays, small digital

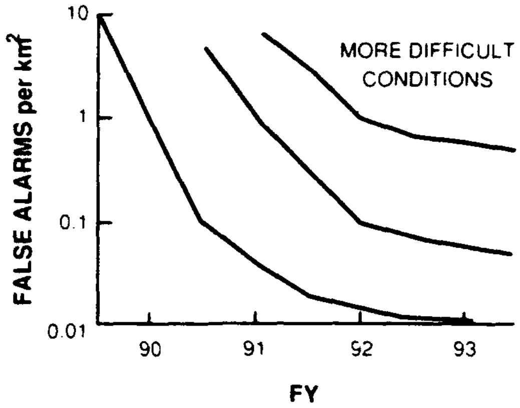

FIGURE 17-1 Expected ATC/ATR performance improvement over time (measured by false alarm density at 50 percent tank detection probability).

processors that can be deployed with each array, and low-data-rate digital communication for information distribution.

Acoustic array networks will passively detect, locate, and recognize targets, including low-altitude stealthy aircraft. They will simultaneously deal with aircraft, firing weapons, and ground vehicles. They are complementary to and will aid other sensor systems. Acoustic array networks improve upon past acoustic systems; networks of arrays will perform better than networks of single sensors in multiple-target situations. Also, aircraft can be located and tracked, not just treated as nuisance noise sources.

Estimates of current capabilities (Table 17-2) are based on field measurements with experimental acoustic arrays and on simulations. No acoustic array network currently exists. Projected capabilities depend primarily upon sensor noise reduction and algorithm developments. Table 17-2 highlights improvements that might be achieved within five years. Additional improvements would be phenomenologically limited and probably modest.

The impacts of acoustic array networks will come through the provision of passive battlefield surveillance and cueing for other systems. Possible applications include:

- increasing low-altitude air defense capabilities by detecting and tracking stealthy aircraft, cueing non-line-of-sight weapon systems, cueing line-of-sight systems before unmasking, recognizing specific types of aircraft, working with surveillance radars to minimize radar exposure, and developing a high-performance passive acoustic/infrared system;

TABLE 17-2 Current and Projected Capabilities of Acoustic Array Sensor Networks

Parameter	Current Capability (experimental 5-m array)	Projected Capability (smaller 2-m array)
Detection range of 5–20 km (average 10 km)	Low wind and quiet background noise	High wind and high background noise (battlefield conditions)
Direction finding of 2–3° accuracy and 15° resolution	Three loudest targets under same "quiet" conditions	3–5 loudest airborne targets and several loudest weapons under battlefield conditions
Target location within 50–1000 meters	Depending on network geometry and source motion	Depending on network geometry and source motion
Multitarget location	One airborne target per array; unknown for transients (weapons) and ground vehicles	1–3 airborne targets per array; several weapon firings per second per array
Recognition	Single helicopters in quiet background	Helicopters in multitarget, noisy environment; recognition and aid for other aircraft

- improving counterfire capabilities by locating enemy artillery with enough accuracy for counterfire;
- improving battlefield situation assessment by providing additional information about aircraft and artillery and shell impact locations and counts.

MAGNETIC DETECTION OF TANKS

Superconducting quantum interference device (SQUID) magnetometers are sensitive enough to detect the magnetic field generated by a moving tank at operationally interesting ranges. SQUIDs can detect fields of about 10^{-4} nanotesla (nT) (1 nT = 10^{-5} Gauss = 1 gamma) and field gradients of less that 10^{-5} nT/meter. The field generated by a tank (actually the perturbation in the earth's field) at ranges of interest would be about 10^{-3} nT.

However, temporal variations in the earth's field during a day are typically 10 to 100 nT. As a result, it is likely that the noise in the ambient magnetic field will obscure the tank's signature.

Figure 17-2 compares the tank signature and the environmental noise in the spectral domain. The tank's spectral energy density was computed on the basis of its trajectory at various ranges and speeds. The upper limit on the environmental noise density corresponds to a single magnetometer, whereas the lower limit was obtained by subtracting a reference noise value measured at a location several miles distant.

It appears that detection of tanks by this technique would be very difficult but perhaps not impossible. Magnetic detection in naval scenarios is probably more attractive because of the larger target mass, the relatively quiet and featureless environment, and the lack of other target signatures. However, it is possible that the noise statistics are highly nongaussian, so that substantial improvement could be gained by signal processing. Also, there is the distinct possibility of characteristic signature components at frequencies greater than 0.3 Hz, where the magnetic environment is relatively quiet. These components

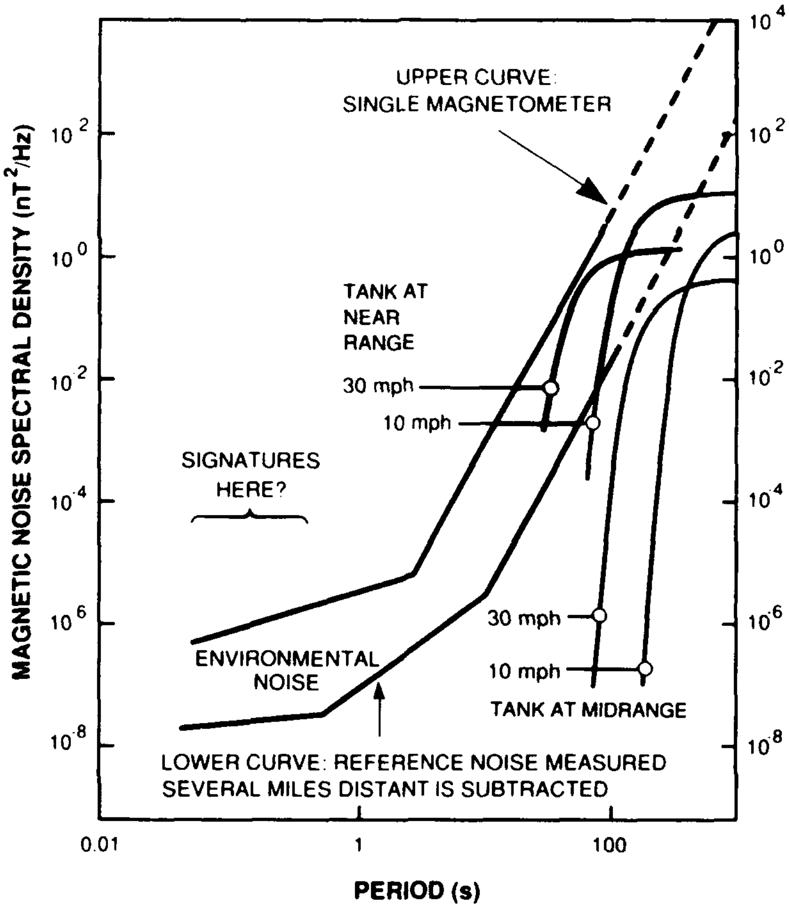

FIGURE 17-2 Comparison of tank signature with magnetic noise spectrum (quiet location).

might, for example, be caused by electromechanical systems in the tank or by vibration of massive components. To better assess the possibilities, measurements of various environments and of potential targets should be made.

ADVANCED AIR DEFENSE RADAR SYSTEMS

Ground-based radars constitute the principal surveillance and tracking sensors for medium-range and long-range all-weather surface-to-air missile weapon systems. These systems must possess three major attributes:

- adequate sensitivity to detect targets;
- adequate ground-clutter rejection capability to reduce clutter residues well below target radar cross levels; and
- the ability to deal effectively with electronic countermeasures.

Current systems include the HAWK horizon-scanning continuous-wave acquisition radar (CWAR); the HAWK target-tracking continuous-wave high-power illuminator (HPI); and the long-range, multifunction phased-array Patriot radar for surveillance, tracking, and missile guidance.

The HAWK system relies on continuous-wave operation to achieve excellent frequency stability. This stability allows targets to be detected and tracked in Doppler velocity and provides very good clutter rejection. The missile relies on semiactive returns from the HPI to home on the target. The Patriot system utilizes a pulse-Doppler waveform for target detection and clutter suppression. The Patriot missile is command-guided to the vicinity of the target and then semiactively homes to intercept. Key technologies incorporated in these systems include high-stability, high-average-power Klystron transmitters (in CWAR and HPI), and multifunction phased-array antennas supported by digital beam steering and signal processing (in Patriot).

CWAR and HPI provide excellent low-altitude surveillance while simultaneously supporting good semiactive missile seeker performance against conventional aircraft. These continuous-wave radars, because of their narrow spectral operating band, are also less vulnerable to broadband noise jamming and antiradiation homing missiles than are equivalent pulse radar systems. The multifunction capabilities of the Patriot radar support simultaneous tracking and engagement of a large number of high-altitude and low-altitude targets. The equipment, which can be rapidly emplaced, requires few prime movers and relatively little manpower.

For many years, the HAWK system had been considered deficient in terms of firepower (i.e., simultaneous tracking and engagement capability) and deployability. Both HAWK and the recently deployed Patriot system are severely strained by evolving threats, including tactical ballistic missiles (depending upon the incoming velocity of these missiles, little or no defended footprint may exist for the surface-to-air missile), low-observable aircraft and cruise missiles (better sensitivity and clutter rejection are required), and modern monopulse electronic countermeasures (which cause a false aimpoint). Ground-based air defense in general is supported by command, control, and communication systems that are vulnerable to countermeasures and are unduly restricted in speed and capacity.

Modern air defense systems need better mobility, more firepower, and the capability to deal effectively with both low-observable targets and tactical (or intermediate range) ballistic missiles. Studies under way may lay the foundation for transforming HAWK into a smaller system that can be rapidly deployed to support light and maneuverable ground forces. This evolutionary system will undoubtedly possess increased firepower and may be more resistant to monopulse countermeasures. A first level of modification to Patriot, to provide limited capability against tactical ballistic missiles, has already proven itself during the scud missile attacks of the Persian Gulf war. Additional changes that improve counter-low-observable capabilities are in full-scale development. More advanced technologies for dealing with low-observable and electronic countermeasure threats to Patriot are in advanced development.

SPACE-BASED SURVEILLANCE AND TARGET RECOGNITION RADARS

A network of survivable space-based radar sensor platforms, suitable for deployment during the first decade of the twenty-first century, would be operated as a national asset for air, surface, and space surveillance. The system would provide stationary-target and moving-target detection, tracking, and classification data to Army, Navy, and Air Force users. All major strategic and tactical targets would be included, such as ships, aircraft, strategic relocatable targets (SRTs), armored and transport vehicles, and cruise missiles. Reliable operation in a severe jamming environment would be assured. The output of the system would be made available to Army field units via secondary links from primary data fusion and control sites. The required readout field equipment probably would be comparable in size and transportability to the terminals currently envisaged for JSTARS data base distribution to command, control, communications, and intelligence (C^3I) nodes within division-size units.

The parameters and enabling technologies for such a systems would include

- satellite constellation—
  - 10 satellites in 900-nmi circular orbits (60° inclination),

- instantaneous access to 76 percent of the earth's surface, and
- 5-minute average access delay elsewhere;
- spacecraft—
  - 10-year lifetime,
  - 20,000-pound in-orbit mass, and
  - 30-kW solar array (rated at beginning of life);
- moving-target-indicator (MTI) radar for detection of ships, aircraft, SRT, armor, countermortar—
  - 8 m × 32 m L-band phased array with 5 kW average radiated power,
  - 5-knot minimum detectable velocity (ships, SRT, armor),
  - 0.3-m^2 minimum detectable radio cross-section (10° grazing angle, 70-knot minimum detectable velocity), and
  - 45-dB clutter cancellation and 50-dB adaptive jammer nulling; and
- synthetic aperture radar (detection and imaging of ships, SRT, armor)—
  - 10-m X-band parabolic reflector with 200-W average radiated power,
  - 5 m × 5 m resolution (stripline SAR),
  - 1 m × 1 m resolution (spotlight and inverse synthetic aperture radar), and
  - 30-km swath (25° grazing angle).

CORPORATE-FED LIGHTWEIGHT PHASED ARRAYS

A corporate-fed phased array radar antenna consists of many radiating elements, each of which is fed by a solid-state transmit/receive (T/R) module. The relative radio-frequency (RF) phase is controlled to steer the radar beam and control its quality. Coupling of the RF signal between the T/R modules and radar electronics is accomplished by means of transmission lines with cascaded power combiners. Direct-current power and command signals must be distributed to the T/R modules.

Phased-array antennas have the advantage of being instantaneously steerable over a wide field of view, allowing rapid search and multitarget tracking. Corporate-fed phased arrays have beam quality superior to that of either space-fed phased arrays or reflector-type antennas. In addition, their low sidelobes and relative freedom from multipath effects provide superior clutter rejection and antijam capability.

Light weight is critical for space and airborne applications. The physical weight of the radiating elements, T/R modules, feed network, and supporting structure must be kept to a minimum. Equally important are the efficiency and power consumption of the T/R modules, which directly affect the weight of the required prime power plant. Current concepts for space applications use stripline or microstrip beam-forming networks with a single T/R module per radiating element. Relatively close antenna flatness tolerances are needed to maintain beam quality. This adds significantly to the weight of the structural support system. Estimated antenna weight factors for space applications are currently in the vicinity of 10 kg/m^2.

A three-ounce T/R module is projected using GaAs MMIC technology. The development of radiation-hardened fiber-optic links with high dynamic range will allow replacement of the transmission-line feed networks. Low-loss, high-efficiency phase shifters will permit subarraying techniques, whereby a single T/R module drives a number of radiating elements, each controlled by a separate phase shifter. Electronic sensing and digital correction of deformations of the array surface will be used to relax structural tolerances. A combination of all these techniques would result in the projected reduction in weight factor illustrated in Figure 17-3.

This technology makes practical for wide-area surveillance an advanced-capability, space-based MTI radar that incorporates multitarget ...acking in dense target environments with a high degree of jam resistance. ... ılso contributes significantly to long-range, low-observable airborne radar. Potential targets include aircraft, cruise missiles, ships, and moving land vehicles. This capability is critical to continental U.S. air defenses, fleet air defense, ocean surveillance, location and tracking of strategic relocatable targets, and various theater surveillance missions.

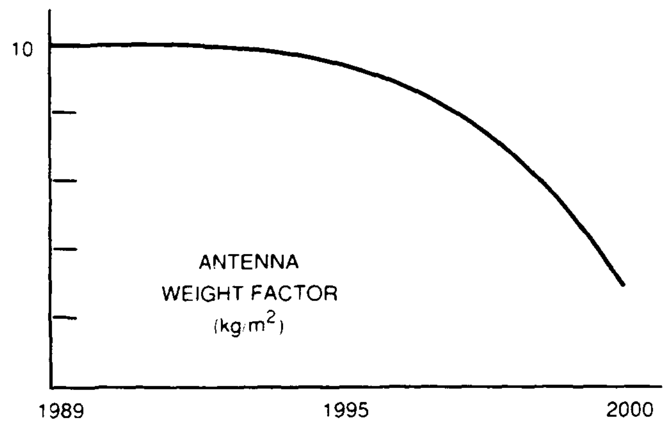

FIGURE 17-3 Projected weight reduction for phased-array antennas.

ARRAY ANTENNA TRANSCEIVER MODULES

The evolving MMIC technology, described above, offers the ability to integrate complex radar T/R functions into a small, lightweight, low-average-power module for lightweight phased-array radar. Important module features include:

- high-efficiency power amplifiers;
- low-noise amplifiers with high dynamic range; and
- phasers and attenuators with integrated control logic.

MMIC circuits will have better performance, reproducibility, and reliability combined with small size, weight, and power consumption. Table 17-3 presents the current and projected capabilities of transceiver modules in terms of several key parameters. The projected transceiver technology will enable practical radar, communication, and sensing arrays that are light, low-volume (conformal), and affordable. Some applications may include:

- space-based radar;
- millimeter arrays on UAVs; and
- agile-beam communication satellites.

TABLE 17-3 Current and Projected Capabilities of Array Antenna Transceiver Modules at Various Frequencies

	Current Technology			Projected Technology		
Parameter	1 GHz	10 GHz	50 GHz	1 GHz	10 GHz	50 GHz
Noise figure (dB)	3	4	8	1	2	6
Peak RF power (watts, max.)	5	3	0.1	15	10	2
Power amplifier efficiency (%)	35	25	10	70	50	25
Transfer function tolerances:						
Amplitude (dB)	0.5	0.7	1.5	0.3	0.5	1.0
Phase (degrees)	6	8	12	3	4	7
Weight (ounces)	4	2	1	1	0.7	0.5

18

High-Impact Electronic Technologies

Three areas of electronic technology have the potential for high impact on future surface warfare:

- terahertz electronic devices;
- teraflop digital processors; and
- high-resolution imaging radar sensors for target surveillance, recognition, and attack.

This set of technologies addresses a wide range of warfare capabilities, including:

- determination of enemy intentions, including likely locations of attack;
- surveillance of enemy force movements;
- recognition or identification of enemy forces; and
- guidance of weapons aimed at enemy forces by intelligent seekers that can find and recognize enemy force elements.

The latter capability may well involve a combination of microwave radar sensors and high-resolution electro-optic sensors.

TERAHERTZ ELECTRONIC DEVICES

This area of advanced technology encompasses electronic devices capable of amplifying frequencies up to 10^{12} Hertz (terahertz), and of switching digital signals within time intervals on the order of 10^{-12} second (1 picosecond). Terahertz devices will be the fundamental components for electronic systems such as radar, communications, electronic intercept equipment, and weapon guidance/seekers. Such devices will play a role in the front-end receivers and transmitters, as well as in the signal processing and automatic target recognition equipment.

There are a number of potential candidates for such devices, including the following:

- compound semiconductor devices: GaAs (FETs, PBTs, HEMTs) and indium phosphide (FETs, PBTs, HEMTs);
- diamond semiconductor devices (a major material problem);
- superconductivity devices (both the older Josephson and possibly new, yet to be invented three-terminal devices);

- vacuum microdevices (long-life, high-current-density cathodes are the main limitations); and
- electro-optical three-terminal devices.

TERAFLOP DIGITAL PROCESSORS

The second major technology focus is high-speed computers for signal processing and automatic target recognition. These are referred to as teraflop computers. It seems clear that a single processor capable of such speeds cannot be designed, since electron devices with switching speeds of 10^{-14} second would be needed. Instead, many slower-speed processors operating in parallel will be needed. If devices switching at 10^{-12} second are feasible, then processors built of such devices may be able to operate at 10^{10} operations per second. To obtain an overall capability of 10^{12} operations per second, about 100 such processors would have to operate together.

HIGH-RESOLUTION IMAGING-RADAR SENSORS

The third major technology focus area utilizes the components and subsystems discussed above to achieve suites of hardened airborne and spaceborne radar sensors capable of finding and recognizing targets at long range. These sensors would be capable of detecting stationary and moving targets. The detection of slowly moving targets through Doppler processing of radar returns is well understood and can be implemented now in either airborne or space-based platforms. Large-scale digital processors capable of between 10^{8} and 10^{10} operations per second are required for wide-area radar surveillance of moving targets.

The more difficult task is the detection and recognition of fixed targets. In this case, spatial resolution of much less than 1.0 meter is required. This demands much higher speeds for the necessary signal processors and target recognizers, if a reasonably large area is to be covered. It is for this class of sensors that processor speeds up to perhaps 10^{12} operations per second may be needed.

Other electronic capabilities, such as low-probability-of-intercept and jam-resistant communications, high-precision navigation, and command-and-control computation and display systems, also will be important. However, these technologies are considerably more advanced than those of long-range surface surveillance, because of prior investments by the Army and other military services, as well as by the civilian sector. However, engineering development and production of the systems are still required.

The ability to precisely locate and identify surface military targets at long ranges—supported by advanced communications, navigation, and command systems—will make it possible to launch precision attacks against surface targets from distances well beyond the range of enemy weapons. Such a capability, which could confer a decisive advantage, could completely transform surface warfare.

PART IV

OPTICS, PHOTONICS, AND DIRECTED ENERGY

OPTICS, PHOTONICS, AND DIRECTED ENERGY TECHNOLOGY GROUP

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19

Summary of Findings for Optics, Photonics, and Directed Energy

This Technology Forecast Assessment (TFA) is divided into three parts: optical sensor and display technologies, photonics and optoelectronic technology, and directed energy devices. A short introduction to the detailed assessments of particular technologies emphasizes their importance to future *smart systems*.

OPTICAL SENSOR AND DISPLAY TECHNOLOGIES

Optical sensor and display technologies receive optical radiation and interpret it for imaging displays to the user. The technological advances in this area include laser radar; multidomain sensors; sensor fusion; infrared search, track, and identification; focal planes with massively parallel processing; and helmet-mounted or similar heads-up displays.

Laser radar provides high-resolution target imaging, target discrimination, and detection of low-observable targets. The current technology includes systems based on carbon dioxide lasers, solid-state lasers that use diode-pumped neodymium, and titanium sapphire lasers. Solid-state laser technology is being extended to an average power of several hundred watts, which will enable laser radars to have very long ranges (depending on the wavelength and atmospheric attenuation). Further development of both carbon dioxide and solid-state laser technology should provide the peak and average power needed for various laser radar applications, while the size of the system will decrease significantly.

Multidomain smart sensors will combine a laser radar with one or more other sensor systems. A laser radar working with a wide-area surveillance sensor, such as microwave radar or a passive infrared search-and-track (IRST) sensor, enhances target detection and identification while reducing false alarms from clutter. Because the system can be configured so that the sensor components share the same physical optics, information across domains can be fused at the pixel level. This can provide a multidimensional information space for subsequent sensor fusion processes. The richness of this information can allow a human observer to detect targets in motion and stationary targets—even those concealed by camouflage or ground cover.

Passive IRST systems, which send out no signal beam that can be targeted by enemy countermeasures, can be used with laser radar for wide-area searches to detect low-flying aircraft against terrain and clouds. By operating in two bands simultaneously, passive IRST can make stealthy or camouflaged air vehicles more detectable.

A multidomain sensor system with laser radar and sensor fusion at either the pixel level or the image level will be part of an automatic target recognition system for detecting and classifying aircraft and missile threats on the tactical battlefield. Systems currently under test for tactical target detection and identification use laser radars in combination with passive sensors in the visible and 8- to 12-μm region, plus millimeter-wave radar. Another application of laser technology for multidomain smart sensors is differential absorption LIDAR. (LIDAR stands for light detection and ranging.) This technology can be used to detect specific chemicals in atmospheric emissions by their absorption of light from one laser beam of a dual-beam system. Current systems are being developed to detect volatile solvents used in clandestine chemical-processing operations (drug processing in particular). The technology is extendable to the detection of other military targets, including facilities that produce chemical and biological weapons, vehicles hidden in trees with their engines idling, fuel dumps, and perhaps ammunition dumps.

Further experience is needed in combining laser radar with passive IRST in a package suitable for Army applications. If a first-generation system can be field-evaluated within the next 5 years, full production of the system should be possible within 15 years. A passive IRST wide-area search system combined with laser radar for ranging and identification would have a major effect on low-altitude surveillance and defense against a range of air targets, including conventional and stealthy manned aircraft, cruise missiles, unmanned air vehicles (UAVs), and tactical missiles.

Only an integrated approach to *sensor fusion* can satisfy the demands of the future battlefield for rapid integration and interrogation of signals from a multisensor suite. Successful response to incoming missiles, aircraft, smart weapons, and satellites will require completely autonomous target detection, recognition, and acquisition. The time requirement may not permit a human in the loop, so the system must provide 100 percent target validation. These time and reliability requirements necessitate the use of multidomain sensors and automatic processing of their images.

With respect to sensor fusion technology, a new concept is the *integrated sensor*. A high-capacity, optical-domain parallel processor—probably of a neural-net design—would be directly interfaced to the high-density focal plane of a multidomain sensor optics package. The output from the processor would feed directly to a fire-control system. Focal-plane arrays are currently available for the infrared region, but integration into a monolithic, switchable structure has not yet been achieved. Optical parallel processing is under development. Signal processing from multiple acoustic receivers, whose output might go to the fusion unit through a secure fiber-optic channel, is another development requirement.

Smart focal planes are another concept for the rapid processing of data from sensor optics. An array of small-area detectors will share space on the focal plane with processing circuitry. An array of microlenses will direct the incoming radiation to the detector array. The focal-plane image will be read out in a massively parallel manner to a sequence of optoelectronic processing planes beneath the focal plane. This parallel-processed readout from the focal plane will avoid the current bottleneck of serial readout and serial processing in conventional serial computers. As conceived, the smart focal-plane technology would allow image acquisition and processing rates greater than 5000 frames per second. The output information will be highly processed already, so communication bandwidths can be reduced. The potential size reduction from current serial processing technology could yield advanced capabilities in a package small enough for use in smart missiles. However, much of the technology to implement the smart focal-plane concept remains to be developed. Suitable algorithms and processor architectures for optical processing of images are still in the research stage.

For infrared scanners, focal-plane arrays of detectors based on *Schottky-barrier materials* can improve the photon collection efficiency of the entire sensor by five orders of magnitude over that of conventional infrared scanners. Although Schottky-barrier materials have a lower quantum efficiency than other solid-state detectors, a focal-plane array in a staring format compensates for that disadvantage by using a large number of detectors. Arrays of 10,000 × 10,000 detectors should be available in the next two decades. Schottky-barrier technology covers all optical wavelengths of interest to the tactical battlefield—visible, near-infrared, and mid-infrared. There are many options for combining them in multispectral arrays or tuning for a particular region. Arrays for the near-infrared region can use skyglow and thermal emission in the 1- to 2-μm range for night vision.

Smart sensors will also be applicable to the soldier's personal gear, as in the *smart helmet* concept. The smart helmet incorporates advanced night-vision sensors, sensor processing, and communications with eye protection, because the information seen by the eye will always be an indirect display.

Notable advances in *display technology* will include the integration of monolithic drive circuitry with lightweight, low-power display arrays. Displays will range from personal "eyepiece" viewers and helmet-mounted heads-up displays to large, multiviewer display screens. Advanced displays will allow a human operator to have true telepresence in environments that are too dangerous or are physically inaccessible. Lightweight displays with a wide field of view will have major military applications.

PHOTONICS AND OPTOELECTRONIC TECHNOLOGIES

Photonics comprises the science and technology to use photons to transmit, store, or process information. Optoelectronic technology couples electronic data-processing elements with optical elements. This area includes fiber optics, diode-laser arrays, optoelectronic integrated circuits, optical neural networks, acousto-optical signal processing, and various other technologies that process optically transmitted information.

Photonic approaches to communications, such as fiber-optic cables, offer several advantages over electronic systems. They are relatively immune to electromagnetic interference and provide very large bandwidths (in the terahertz range). Computing applications of photonic systems can have higher clock rates and large-scale parallel processing. For military *communications network* applications, a fiber-optic network will be supplemented by radio-frequency links to mobile nodes: sensors, satellite relays, and users. The fiber-optic network will be more resistant to jamming, interference, and interception than the more vulnerable radio links. Military applications of fiber optics currently provide rapidly deployable links over distances from tens of meters to kilometers. Time-division multiplexing is used, which limits the bandwidth and compromises the robustness and flexibility of the network. Future military applications will combine wavelength-division multiplexing with time-division techniques, providing a combined peak network capacity in the range of 10 Gbit/s or more and servicing hundreds of users.

Fiber optics may also allow *close integration of wide-bandwidth sensors* with ground operations. In addition to advanced sensors for command, control, communications, and intelligence (C^3I), this capability will also enable *telepresence* by passing high volumes of sensory data between the remote platform and the ground operator, via a connecting optical fiber. Because the high-powered signal processing and computing capabilities needed for data reduction, interpretation, and display can be located at the ground controller's location, the remote platform can be much smaller, less expensive, and therefore more expendable. Among the possible applications are (1) advanced fiber-optic–guided missiles, (2) airborne surveillance platforms with multidomain smart sensors but minimal onboard signal processing, and (3) tele-operated ground vehicles for both reconnaissance and weapon delivery.

Guided optical-wave sensors are an area of fiber-optic technology in which changes in the amplitude or phase of optical waves in the fiber are used to sense vibration (acoustic or seismic sensors), temperature or pressure changes, rotation (gyroscopic sensors), and even electrical or magnetic fields. A notable current effort in this area is the fiber-optic gyroscope. Although it is less sensitive than mechanical or laser gyroscopes, it offers compactness, robustness, and low cost—qualities that suit it to a number of missile applications.

Since the mid-1980s, important advances have occurred in *solid-state laser technology*. An all-solid-state design provides the advantages of high reliability and low maintenance. Mass production techniques for solid-state materials and for laser-array pumps promise low cost as well. At present, designs with longitudinal pumping give the highest efficiencies, but transverse pumping of solid-state laser slabs by two-dimensional diode-laser arrays is better suited for higher power levels, albeit at modest efficiencies. Solid-state laser technology will provide eye-safe laser rangefinders and target designators that are more reliable than those now fielded. In addition, it will lead to new applications, such as the laser radars described earlier, active optical countermeasures (antisensor lasers), and high-bandwidth laser communication from satellites to theater and battlefield commanders. A related area with recent advances is *diode-laser and laser-array* technology. While individual diode lasers are limited in power, arrays of diode lasers can be used to pump solid state lasers. Laser arrays using this approach have achieved spatially coherent output beams of several kilowatts at peak power.

Optoelectronic integrated circuits combine electronic and optical microcomponents on a single semiconductor chip. The purpose of the chip may be to provide an information interface between the two technologies or to create a functional hybrid device. Commercial applications are driving the rapid development of this just-emerging integration of the two technologies. Within 15 years, optoelectronics will be mature for communication and computer interconnect applications. In 30 years, it will have a wide range of applications built on hybrid functionality, such as massively parallel optical processing and wavelength multiplexing.

The best-characterized materials for optoelectronics are gallium arsenide and other semiconductors formed by combining Group III and Group V elements (III-V semiconductors). Ferroelectric liquid crystals are another possibility, particularly for light-modulating applications. Lithium niobate is currently the material of choice for volume holographic storage and interconnects. A key point is that all the semiconductor optoelectronic technologies, even of the III-V semiconductors, are still very immature compared with silicon technology. A substantial and sustained investment will be needed for this technology to mature. In the near term, optoelectronic-processing applications will mostly use arrays in which the logic function is performed by electronic components, while the optical components provide the mechanism for highly parallel interconnections. In terms of combined speed, low power, and high spatial density, optoelectronic arrays based on III-V semiconductors will be difficult to surpass in the long term.

Neural networks constitute another information-processing technology in which photonics will play an increasing role. By analogy with biological neural systems, a neural network contains two types of processing elements: synapses and neurons. A synapse performs an operation on its single input; a neuron receives inputs from multiple synapses and combines them to produce an output. Although photonic or optoelectronic implementations of these elements are at present less developed than electronic alternatives, they offer the potential for far larger numbers of synapses and neurons per component. In addition, photonic elements can support more flexible connectivity patterns, including some that appear essential for neural-net architectures to perform visualization and image-processing tasks. In the long term, the Technology Group forecasts that optical neural networks will be used for real-time automatic target recognition based on multidomain sensor inputs, for understanding speech (i.e., word and pattern recognition), and for complex signal processing.

Acousto-optics uses the crystal vibrational modes of a Bragg cell to encode or decode information carried in the modulation of light beams. The potential information-carrying capacity of modulated light and optical processors can be illustrated by an analog acousto-optical device called a time-integrating acousto-optical correlator. Current versions of this device can process the equivalent of 10^{13} operations per second, which is several orders of magnitude more than existing electronic devices. Optical processor architectures will require less power and will be smaller and weigh less than digital electronic processors. Acousto-optics is also applicable to advanced sensors. The characteristics that can be "read" from a signal intercepted from an emitting platform can be used to identify the specific signal type and determine the location or velocity of the platform. There is no limitation on the wavelength of the electromagnetic radiation that can be processed in this way.

Optical techniques with lasers can be used to control information carried in the amplitude, frequency, and phase modulations of *microwave radiation*. In addition, optical fibers make excellent waveguides for distributing information-carrying microwaves; the available bandwidth can be hundreds of gigahertz. This technology appears promising for control of phased arrays, control of remote antennas, microwave communications requiring extremely high data rates, and secure communications. The Technology Group forecasts that, within 15 years, microwave and optical circuitry will be integrated on a single chip. In 30 years, sophisticated optical computing will be used for various adaptive antenna functions, such as beam shaping, null steering, and side-lobe suppression. Many microwave frequencies will be multiplexed over one fiber-optic network.

In *adaptive optics*, a wavefront sensor is used to measure aberrations in an incoming light signal. This information controls a deformable optical element that adjusts to compensate for the optical aberrations, which would otherwise limit the performance of the optoelectronic system. The advanced techniques for adaptive optics use nonlinear optical materials that perform both the sensing and the compensation functions. Aberrations caused by optical system imperfections or the atmosphere result in substantial signal degradation or loss of laser coherence in nearly all present optical systems.

Adaptive optics will become an essential part of future systems; they will substantially increase the operating range and improve the resolution of laser systems. For military applications, adaptive optics can improve performance of many optoelectronic systems, including antisensor lasers, passive battlefield imaging, active or passive object imaging from satellites, auto-tracking, and optical jammers. Adaptive optics can also improve the projection of laser power from directed energy weapons by correcting for atmospheric aberrations between the beam source and relay mirrors.

Sophisticated countermeasures to laser antisensor threats can make use of *applied nonlinear optics*. This technology also will be important in implementing components required for all-optical processing and computing. The Technology Group forecasts its use for passive laser protection within 15 years and for advanced optical processing components in 30 years.

Binary optics is a technology for creating diffractive optical devices on a substrate by use of lithography and micromachining. It gives the optical circuit designer the capability to create novel elements as well as alternatives to more conventional refractive elements. Binary optics methodology builds on very-large-scale integrated (VLSI) circuit technology; both are well suited to computerized circuit design and manufacturing. Low-cost mass production of binary optic designs is possible through replication, embossing, or molding of subassemblies. In addition, the potential of diffraction devices to compensate for aberrations pushes the range of optical design further into the deep infrared and ultraviolet regions. One important near-term Army application for binary optics is to correct chromatic aberration in infrared imaging systems. Binary optics also has the potential to simplify the production of optical systems for military applications. It should also make those systems cheaper, lighter, and lower in power consumption.

DIRECTED ENERGY DEVICES

Directed energy devices are intended to generate highly concentrated radiation as a means of directing a high level of energy—which may be very short in duration—on a small target area. The radiation may be from the optical portion of the electromagnetic spectrum (as in lasers), from the radio-frequency portion (microwaves), or from accelerated charged particles.

In a technical sense, even laser devices that are used for information functions (laser radar, rangefinders, target detectors) can be considered directed energy devices. However, as used here the term applies to energy-beam technology primarily concerned with delivering a high-energy flux on a target.

Among the technologies needed for a conceptual ground-based laser antisatellite system is a directed energy weapon system that would be either a free-electron or chemical laser complemented with adaptive optics. The *free-electron laser* (FEL) uses a high-energy accelerator to create an intense stream of electrons. The stream traverses a series of alternating magnetic fields, which causes them to emit coherent electromagnetic radiation at a wavelength tunable by the electron's energy and the magnetic field strength. The entire beam-generating process occurs in a high vacuum, which limits self-distortion found in crystal or gas lasers. The distinctive advantages of this high-energy laser include efficient production (greater than 25 percent efficiency) of high average-power output; broad, continuous tunability over a wide frequency range; excellent beam quality; and generation by electrical power, which simplifies logistical support.

By 2020, ground-based—and possibly space-based—FEL systems might conceivably be able to intercept and destroy missiles during their boost phase. (A ground-based system would use space-based relay mirrors to reflect the beam onto targets.) To achieve this goal, difficult technical breakthroughs in beam generation and steering are required. For tactical applications, a high-power microwave beam, using an FEL source, should be available with multimegawatt power.

High-voltage, short-pulse electron-beam accelerators can be used to drive conventional microwave sources (magnetrons, klystrons, backward wave oscillators) to create an intense, narrowband, pulsed *radio-frequency energy beam*. Peak power levels can be as high as several gigawatts, with energies per pulse greater than 200 J. A newer technology uses a solid-state switch to produce a high-power wideband radio-frequency beam (also called a video pulse), which can operate as a repetitive pulse (repeating with a frequency of 10 to 100 Hz).

Continued progress with these high-power, high-energy radio-frequency sources will enable a new class of weapons, in which mission kill is accomplished by burning out electronic components or detonating electro-explosive devices in the target. Potential targets include smart munitions, antiradiation missiles, mines, aircraft, radar and infrared guided missiles, communication nodes, and UAVs.

FEL, high-power microwave, and charged-particle-beam weapons all depend on the development of a *compact accelerator*. The basic concept is to alter the linear transport geometry of the traditional linear induction accelerator into a spiral or circular configuration. This would allow the same accelerator module to act repeatedly on a circling swarm of charged particles, until they reach the desired velocity. Compact accelerator development is being pursued by the Naval Research Laboratory and in two projects currently supported by the Defense Advanced Research Projects Agency (DARPA).

20

Introduction: Smart Systems Using Optics, Photonics, and Directed Energy

The success of future Army missions will depend on the ability to locate enemy targets at will and to deny that same capability to the enemy. The variety of sensors used in this task will include *surveillance sensors* that locate and direct fire to targets in space, in the air, and on the ground; "smart" or *autonomous weapons* delivered by a variety of manned and unmanned platforms; and *fire-control systems* for advanced soldier-in-the-loop and autonomous ground-to-ground and ground-to-air weapons.

These advanced sensors will be highly integrated into *smart systems*. Data from a variety of sensors and domains will be processed and correlated simultaneously, allowing faster assessment and response to enemy threats. Data will be processed at the sensor or be transmitted by microwave and/or optical-fiber links to remote users. Extremely wide bandwidths of optical-fiber systems will accommodate the information necessary for surveillance, C^3I, and weapons control from a variety of optoelectronic systems (Figure 20-1). Information will be rapidly distributed down to the brigade, company, and perhaps even platoon level of Army communication systems for rapid evaluation and response. Countermeasures against these smart systems include (1) in-band jamming by wavelength-agile lasers, (2) interference with data transmission and processing by high-power microwaves, and (3) destruction of components of the system by high-energy laser or kinetic-energy weapons guided by smart fire-control systems.

The technologies derived from optics, photonics, and the research on directed energy weapons are, therefore, of key importance to future Army missions. Optics and photonics provide the base for developing advanced integrated sensors and high-speed processors, while directed-energy weapons provide the long-range, speed-of-light potential for degrading or destroying smart systems.

A computer-aided design environment that embodies detailed information on sensors, processors, and the basic material properties of their components is essential for advanced system design (Figure 20-2). Moreover, this same environment can be used, interactively, to respond to evolving threats. This iterative process will serve as a natural bridge for what, hitherto, has been the artificially separated domains of technology and system analysis.

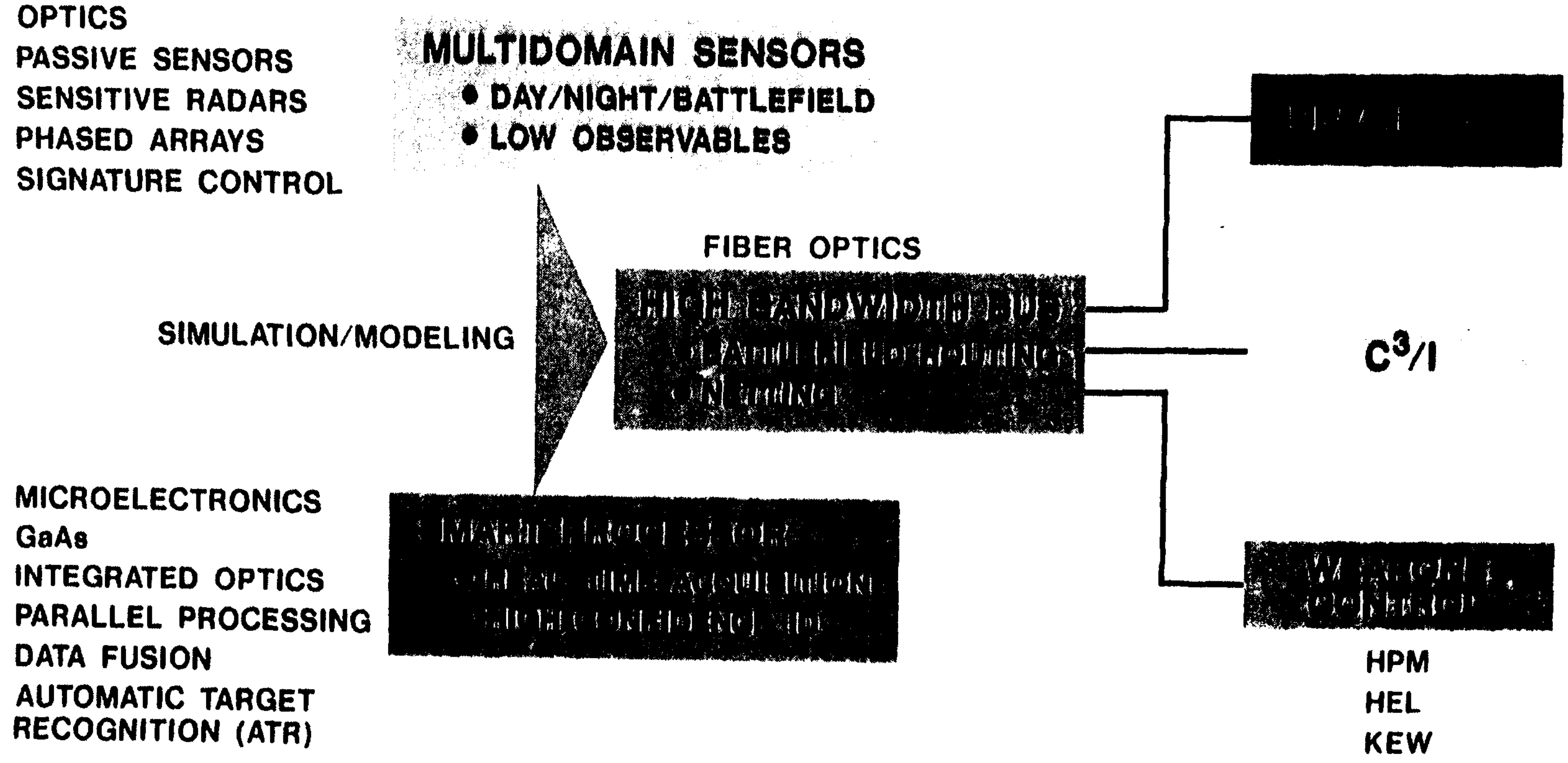


FIGURE 20-1 Information distribution for smart systems.

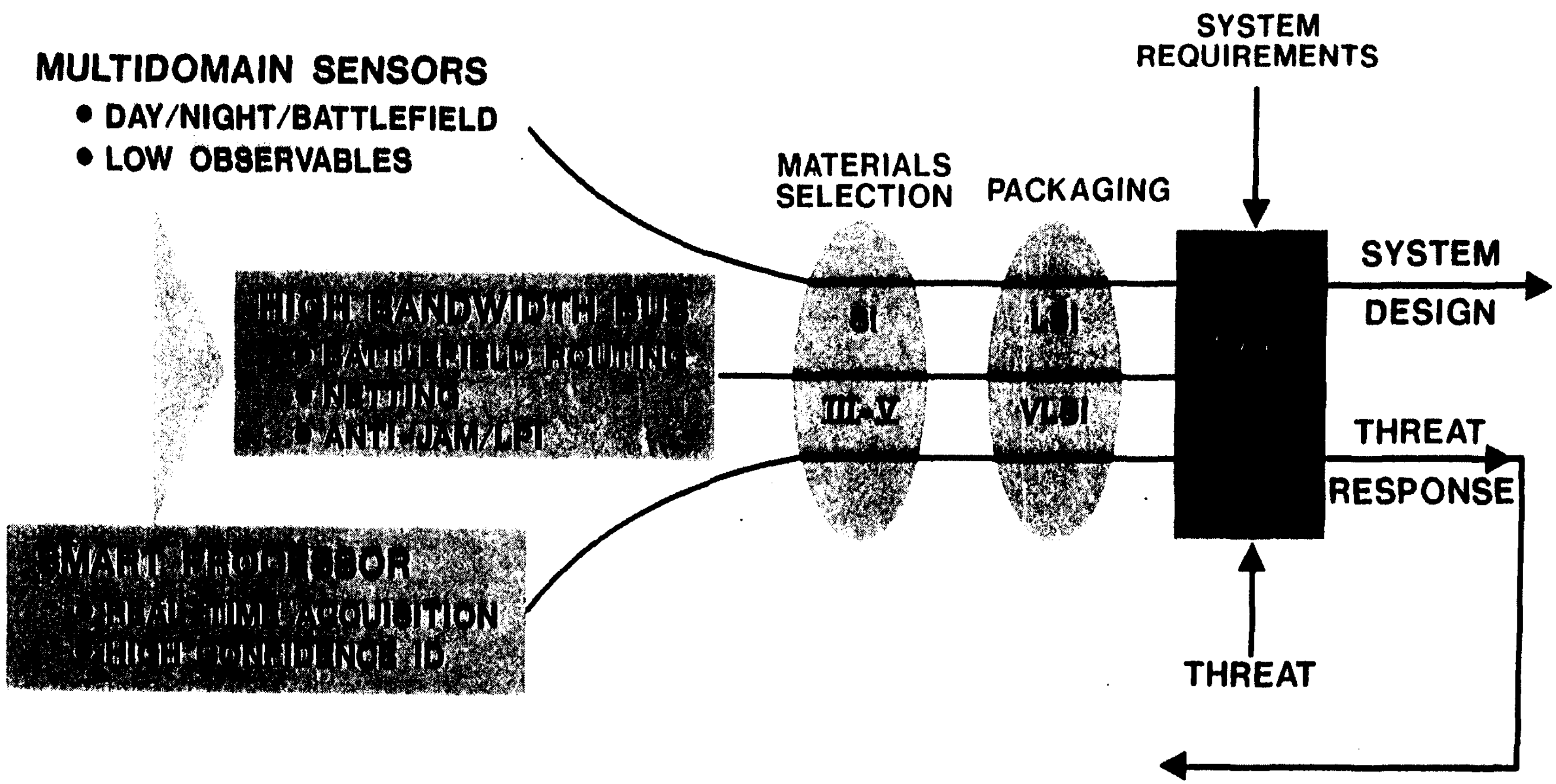


FIGURE 20-2 Computer-aided design environment for smart systems.

MULTIDOMAIN SMART SENSORS

Passive infrared systems supply information on angular direction and emission intensity of objects, and laser radar systems provide information on reflection intensity, range, range extent, velocity, and angle. Moreover, these systems can be configured so that the active and passive components share the same optics, and thus generate a pixel-registered image in a multidimensional space (Figure 20-3).

The richness of this space provides a human observer with the capability to detect targets that are in motion, stationary, or in concealment under camouflage and trees. Experimental systems operating at 10 μm and the near-visible range are currently used to evaluate target detection and suppression of false alarms due to background signals for missions such as smart-weapon antiarmor, air defense, and location of mobile tactical and strategic targets.

The basic technology for these sensors is well developed at 10 μm (Figure 20-4). A combined forward-looking infrared radar (FLIR) and rangefinder can be engineered as a coherent-laser radar/FLIR for use on tanks and air defense weapons. Passive infrared systems operating simultaneously in the 3-μm to 5-μm and 8-μm to 12-μm regions can provide wide-area search capabilities to detect low-flying stealth aircraft against terrain and cloud background.

The Army has a major requirement to develop an IRST system augmented by a laser radar for clutter suppression, identification, and fire control. Because of recent laser-diode development, operation at wavelengths in the visible and near infrared also will be possible.

Schottky-barrier diode arrays that provide high quantum efficiency, uniformity, and production simplicity will be used in the visible, near-infrared, and mid-infrared detectors, along with other detector technologies. Exploitation of skyglow and thermal emission in the 1-μm to 2-μm range will enhance passive camouflage detection. Combining active and passive sensors at a number of wavelengths will make it difficult for the threat to camouflage or reduce signatures (due to Kirchhoff's law of emissivity).

In many Army applications, there is a real need for high-efficiency laser sources. Diode lasers have demonstrated wall-plug efficiencies in excess of 50 percent. Current developments are pushing the technology to a wider range of wavelengths extending from 0.4 μm out to 4 μm. Compact, highly efficient high-power diode-laser sources may be realized either by coherent combining of the output from an array of diode lasers (Figures 20-5 and 20-6) or by developing high-power diffraction-limited individual sources. Recent progress in diode amplifiers (up to 20 W pulsed in a diffraction-limited beam) provides evidence that entirely new capabilities are on the horizon. Short-wavelength diode lasers in the II-IV systems could be important elements in displays and in laser radar. Recently demonstrated mid-infrared (2- to 4-μm) diode lasers

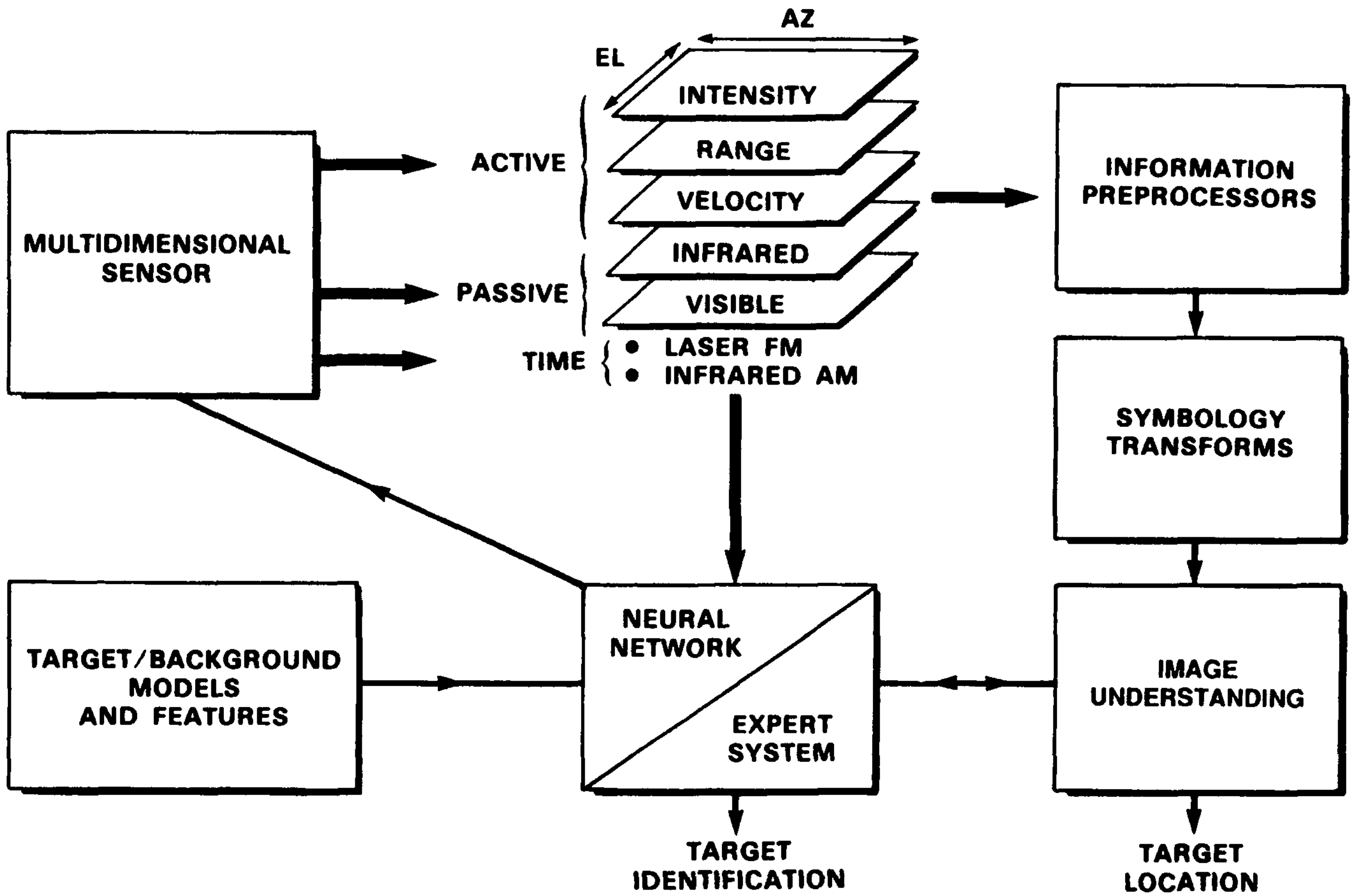


FIGURE 20-3 Multidimensional sensing applied to an autonomous recognition system.

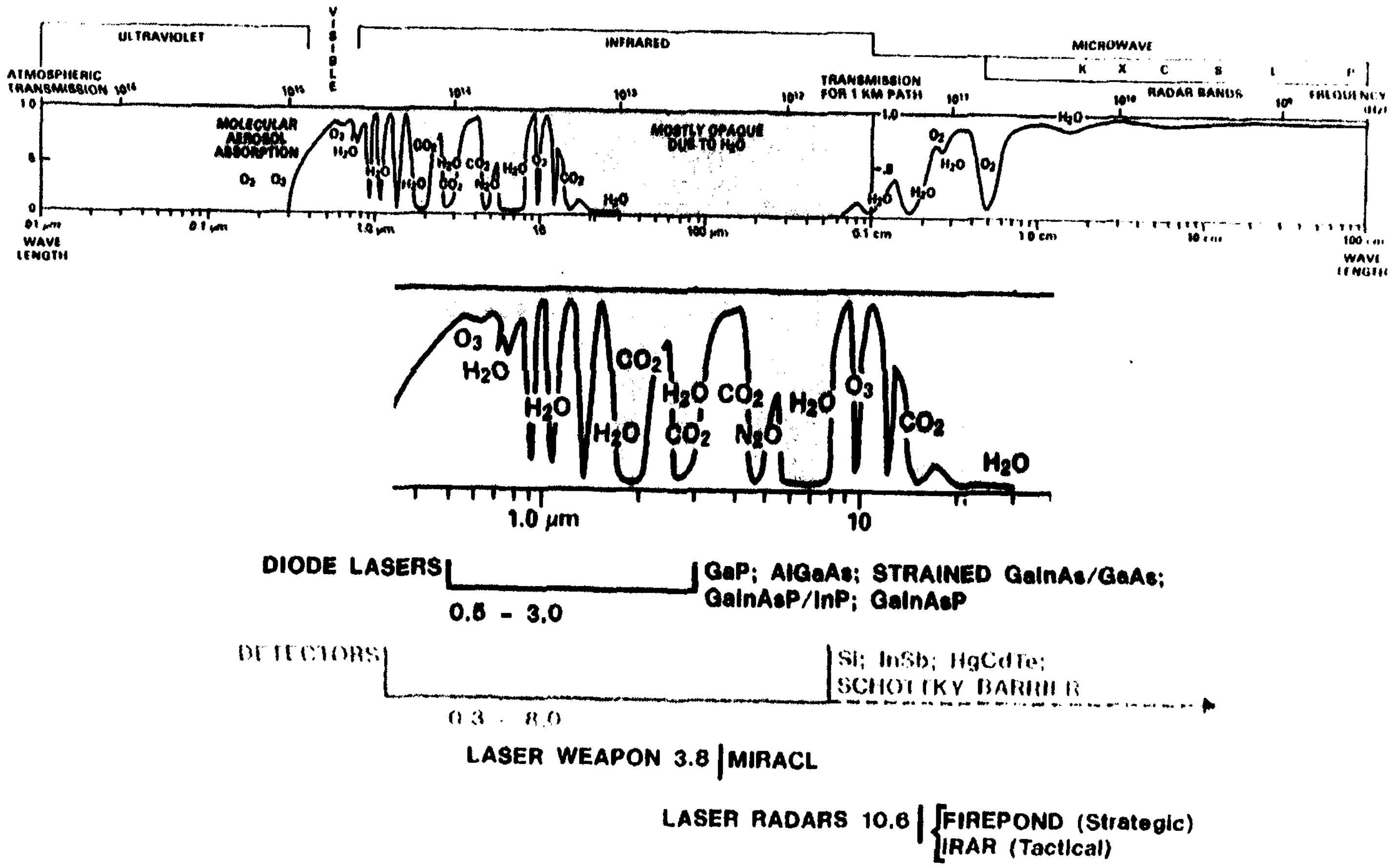


FIGURE 20-4 Spectral range for smart laser systems.

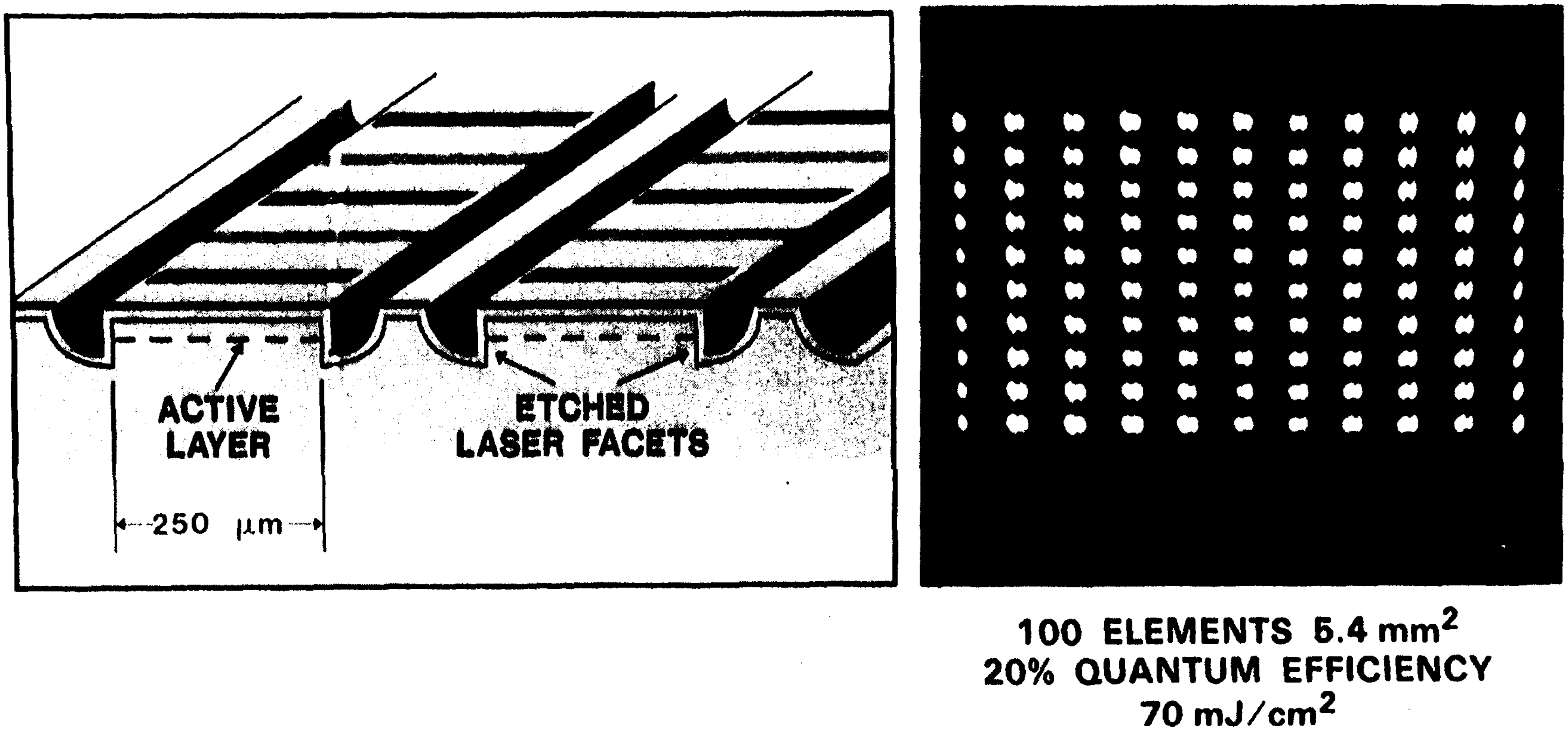


FIGURE 20-5 GaAs/AlGaAs two-dimensional monolithic diode-laser array.

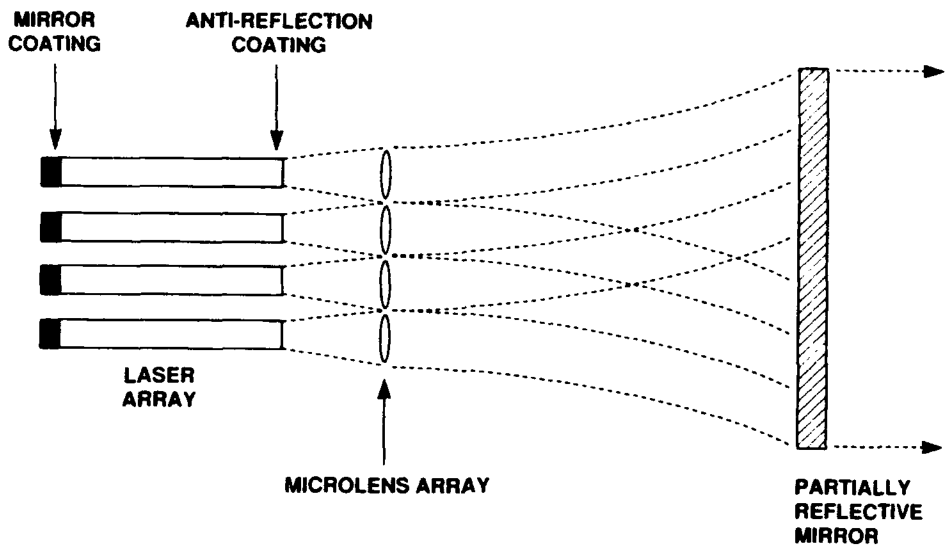


FIGURE 20-6 Technique for coherent coupling of diode-laser arrays.

with low threshold currents and high efficiency will find important applications in infrared countermeasures, laser radar, and LIDAR.

The high efficiency of diode lasers will also be exploited by employing arrays of these lasers as efficient pump sources for solid-state lasers. The latter are particularly useful for generating short, high-power pulses in laser radar, ranging, and designator applications (Figure 20-7). Recent laser development has demonstrated significant new capabilities from arrays of 0.81-μm diode lasers for pumping neodymium-yttrium-aluminum garnet (Nd:YAG). Sustained progress in semiconductor and solid-state laser technology, especially in synthesis and processing of new materials, should yield new pump sources and solid-state lasers with increased power and efficiency and covering a wide range of wavelengths.

As discussed earlier, the multidimensional imagery provided by these systems can be utilized readily by a trained operator. The processing of information in each domain, as well as fusion at the pixel or image level to provide automatic target recognition (ATR), will be a major technological challenge over the next decade. A major hurdle in the development of smart weapons is finding a solution to the ATR problem.

Given that suitable processing architectures and algorithms are found—and intensive research is still required in this area—sensors can then be

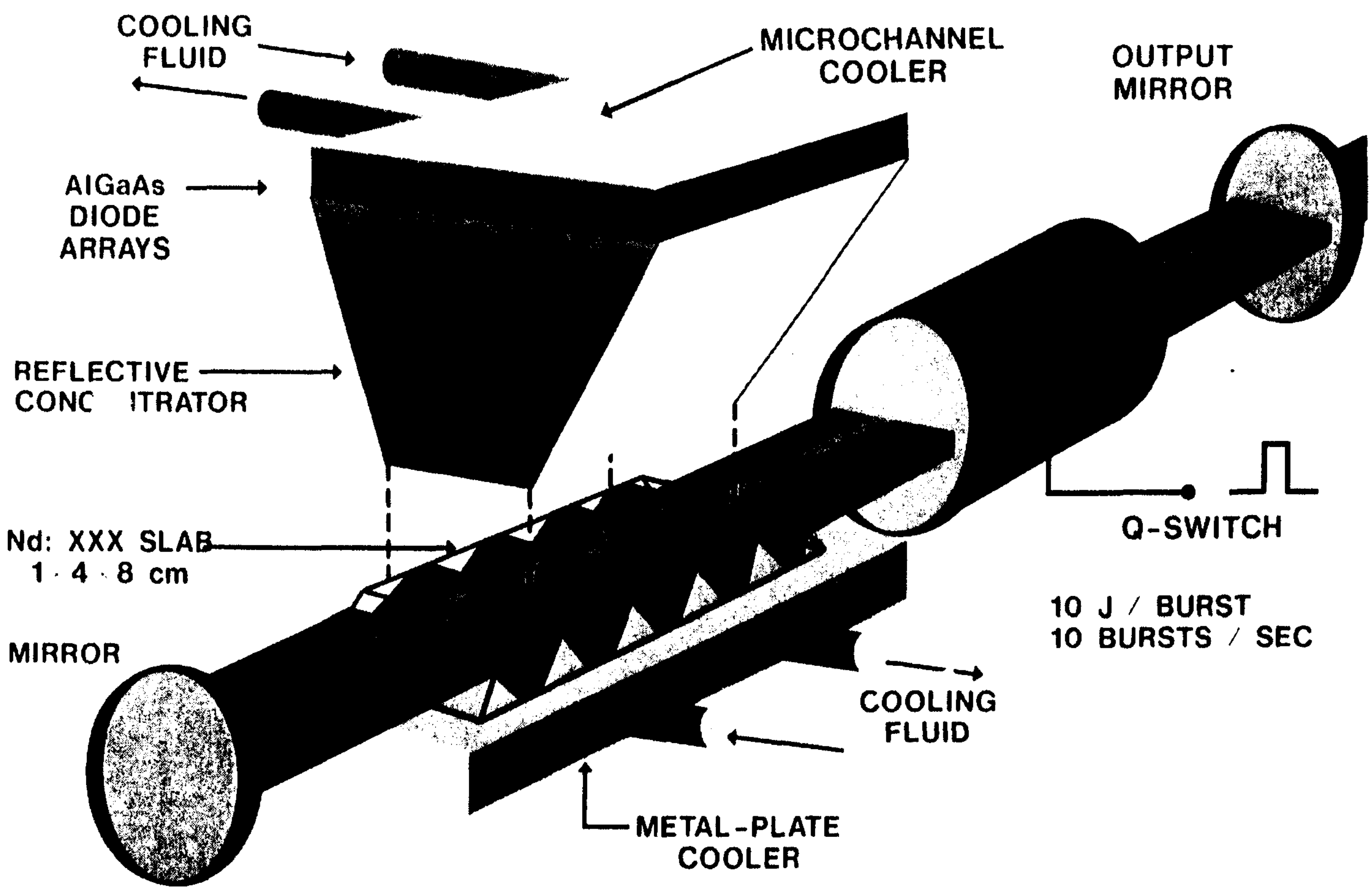


FIGURE 20-7 Solid-state neodymium laser pumped by AlGaAs diode-laser arrays.

constructed with collateral processing. Smart focal planes using micro-optics, detectors, and combinations of digital, analog, and optical processing will provide information outputs for subsequent distribution that are highly processed and thereby reduced in bandwidth.

In addition to smart weapons, the development of other equipment employing smart technology will be possible. Because of the increased use of camouflage and stealth techniques, future battlefields will require technologically assisted, enhanced awareness by the field soldier. In addition, the use of antipersonnel lasers, which are intended to blind or dazzle troops, will require that eye protection be worn. A potential solution to these dual requirements is the development of a "smart helmet" that combines advanced night-vision sensors, data processors, and communications, as well as offering physical eye protection through indirect viewing.

Multidimensional sensing may also involve the use of a laser to detect gas or vapor emission from materials (e.g., ammunition storage areas) or processing operations (e.g., cocaine production areas). For example, diethyl ether, which is used in cocaine production, possesses two characteristic infrared spectral lines. With the aid of a passive infrared system to search for heat sources and a CO_2 laser to measure the differential absorption of these spectral lines, it should be possible to locate cocaine-manufacturing facilities through their emissions alone. The same technique might be used on the battlefield to detect engine exhaust, and even vapor emissions from fuel dumps and ammunition storage sites.

SENSOR FUSION, NEURAL NETWORKS, AND WEAPONS CONTROL

For important data-processing techniques, such as analog Fourier and Fresnel transforms, convolutions, and correlations, special-purpose optical devices show superiority over their digital counterparts. For digital processing, in comparison with the power-per-bit required for a fixed switching time, optical devices are perhaps an order of magnitude faster than semiconductor devices (Figure 20-8). At present, devices do not exist that exploit this speed capability in a compact form such as the microchip; however, this should change over the next decade.

The field of optics clearly has a role in computer component designs that offer modest switching speed but massively parallel processing. The power per bit for such designs in this region is lower than for semiconductor devices and thus shows great promise. Parallel-interconnection capability is good for image processing, for both analog correlations and early stages of vision functions.

Neural networks, especially for associative-memory or pattern-classification applications and constrained optimization, are examples of parallel and optical processing (Table 20-1). One implementation of this concept involves a ring resonator that contains a

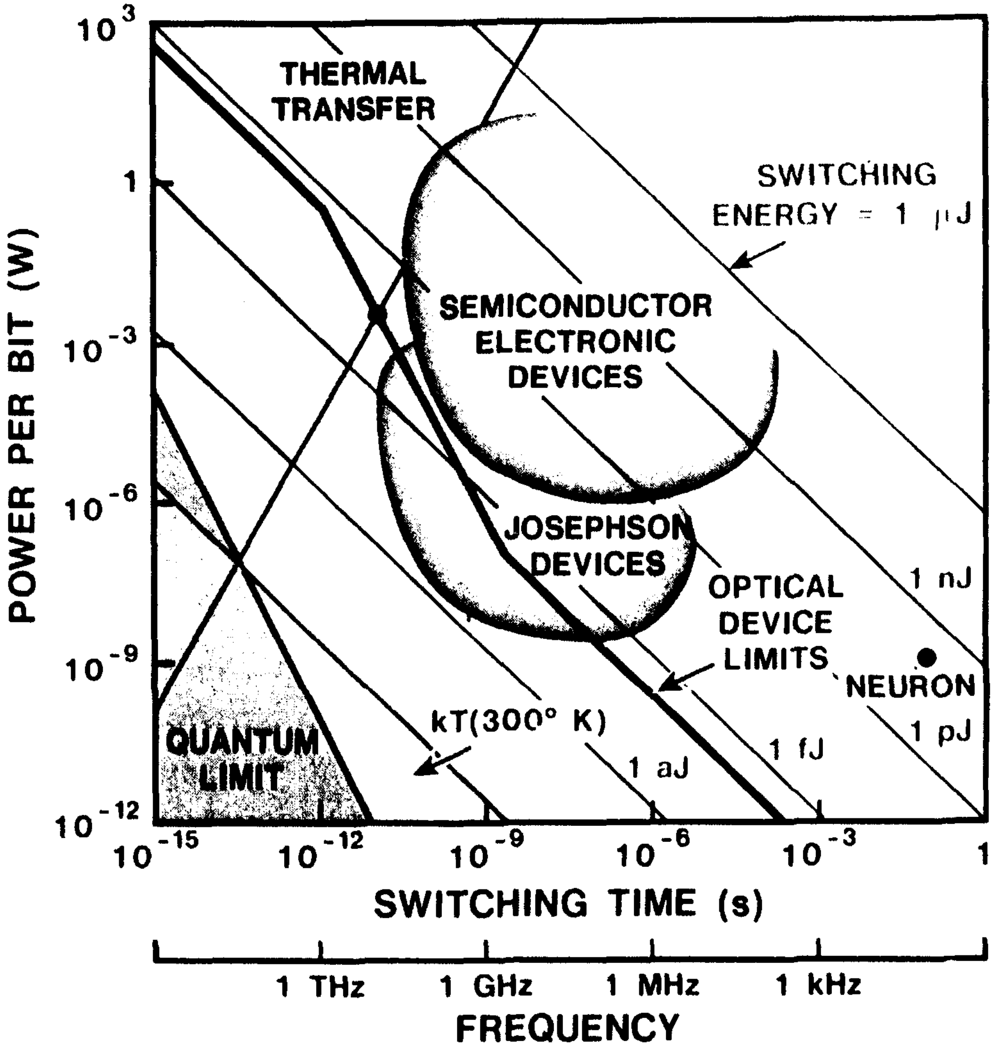


FIGURE 20-8 Operating ranges of switching technologies. Source: Smith, 1892.

TABLE 20-1 Comparison of Conventional Serial (von Neumann) Computing with Parallel Processing Using a Neural Network

	von Neumann (Serial)	Neural Network (Parallel)
Functions	Formal logic Numeric computation	Pattern classification Constrained optimization
Memory (metric)	Random access (words)	Distributed (connections)
Processor connectivity	Nearest-neighbor	Global
Computational mode (metric)	Digital/linear (instructions/second)	Analog/nonlinear (connections/second)
Structuring	Program	Train/"program"
Implementation	Electronic (biological)	Electronic Optoelectronic Optical Biological

saturable two-beam amplifier, two-volume holograms, and linear two-beam amplifier (Figure 20-9). The saturable amplifier, through the use of a spatially patterned signal beam, represents the optical neuron array. The volume holograms enable global connectivity, and the linear amplifier provides resonant convergence. After the neural network is "trained" by exposure to a number of images, the network rapidly compares an input image to the stored image and either identifies the input image or stores it as a new category. Since this massively parallel operation is highly efficient, future image-processing systems will include it as a stage in automatic image processing.

Neural networks, in analogy to a biological system, also hold great promise for the fusion of information from various domains. Multidimensional associative memories and other neural processing techniques will find application over the next decade in battle assessment and management. Unlike with software-rule-based processors, the output response of neural networks improves with training, as more information is encountered and assimilated.

Over the past three decades, the bit rate (bits per second or bps) for digital telecommunications has increased from 10^7 to 10^{10} bps (Figure 20-10). Fiber optics has provided most of the recent increases, and over the next decade the bit rate for advanced fiber-optic systems is anticipated to improve another two orders of magnitude to 10^{12} bps. Current silica-based fibers have

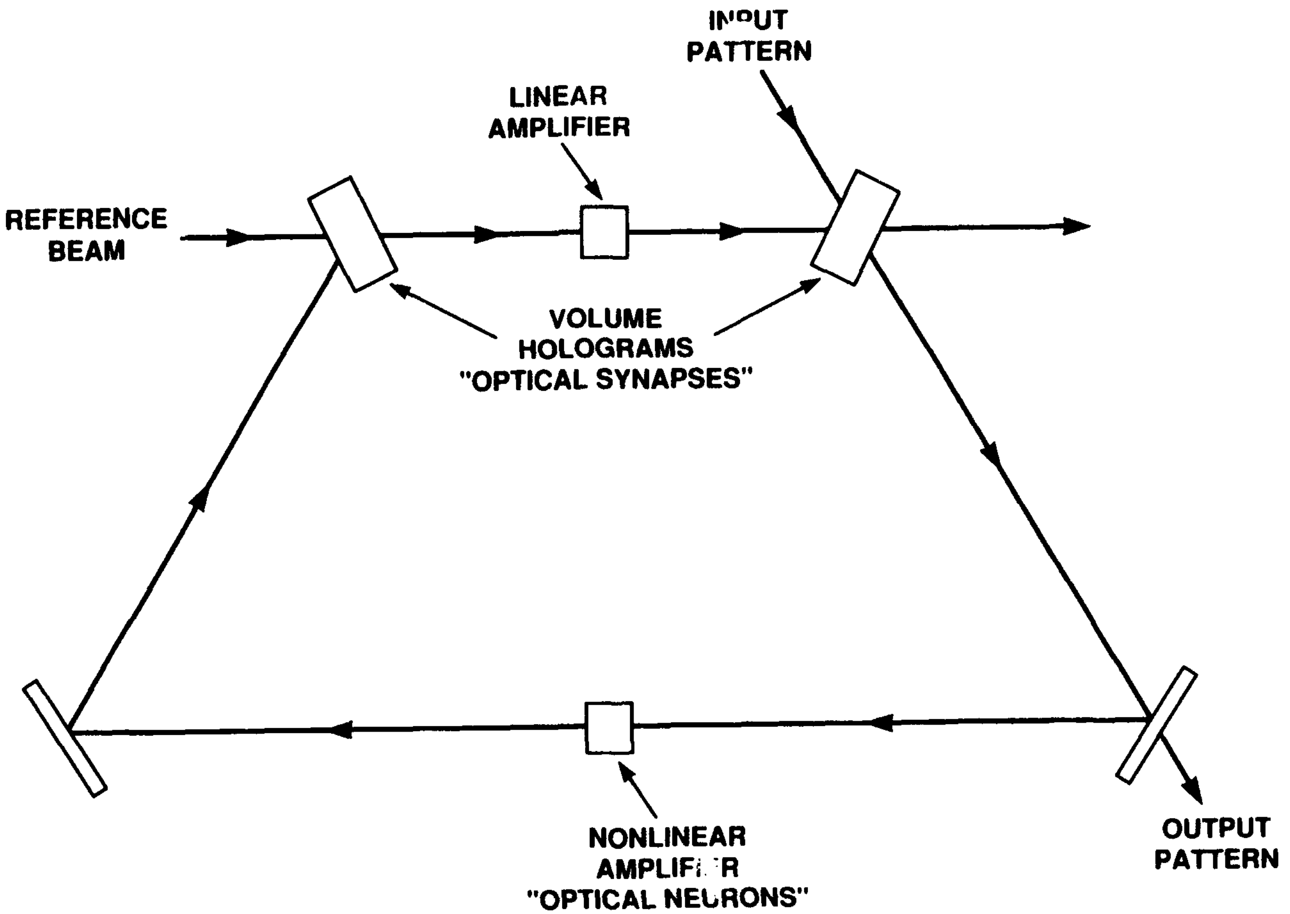


FIGURE 20-9 Example of an optical neural network.

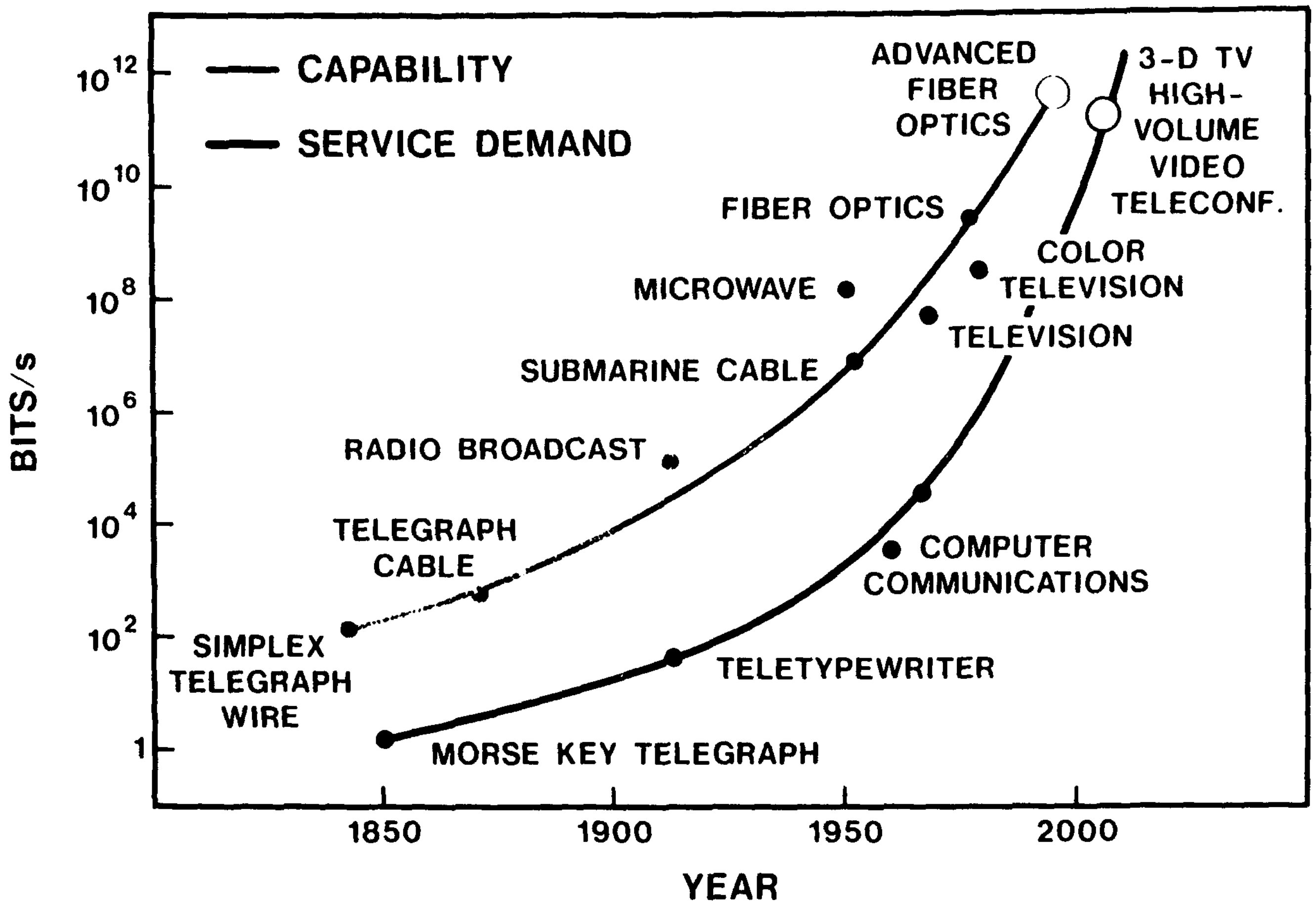


FIGURE 20-10 Long-term trends in telecommunication capability and application requirements. Adapted from Keller, 1986.

a loss factor of 0.1 dB/km, but fluoride-based fibers are expected to provide a loss factor of only 0.01 dB/km.

Fibers can be deployed rapidly and redundantly over large areas. The bandwidth is sufficient to handle battlefield sensor data, even the unprocessed stream from high-resolution radars and optical sensors, and large enough that a survivable system can be established to permit information to be disseminated rapidly to all command echelons. This enormous bandwidth can be exploited to the fullest only if tunable transmitters and receivers in the 1.3-μm and 1.55-μm bands can be developed.

Fiber-optic surveillance nets can be developed using a variety of sensors such as acoustic, electromagnetic field [direct current (DC) to microwave], magnetic, and optical. These sensors can be remotely powered by a laser diode and are, therefore, simple to install and to monitor, and are relatively inexpensive and expendable.

Fiber optics will permit battlefield telepresence, which is only possible with secure, jam-resistant, wide-bandwidth communication links between a computer-assisted human operator and a sensor or weapon platform (Figure 20-11). Fiber-optic systems are uniquely able to provide this capability. Operators remote from the battle area will be able to control defensive and offensive weapons. The fiber-optic guided missile is an early example of such future weapon concepts.

OPTICAL AND RADIO-FREQUENCY COUNTERMEASURES

The effectiveness of optical and radio-frequency (RF) countermeasure systems, such as in-band jamming, burnout of electronics, or structural damage, depends not only on the availability of necessary laser and/or RF power, but equally on the ability to acquire and track a target. Moreover, the system then must identify the target, select an aimpoint, and verify that the jamming or destruction has occurred. The multidomain-sensor system that performs the imaging functions necessary for aimpoint selection and damage assessment contains a laser and/or RF radar that also could carry out countermeasure functions. For example, the system normally would operate in a low-power acquisition mode, but with increased power to the laser and/or radar, it could cause jamming or inflict damage. Advances in laser technologies, especially in diode-pumped solid-state lasers, make this a near-term possibility for the tactical battlefield.

This approach would allow evaluation of the important acquisition and damage assessment functions that are mainly image-understanding problems. If, for example, a laser antisatellite (ASAT) cannot establish that the necessary damage has been inflicted, then the system concept has no value. If this is the case, the ASAT mission is separable and should be pursued in the near term as primarily an imaging problem, on the one hand, and a laser

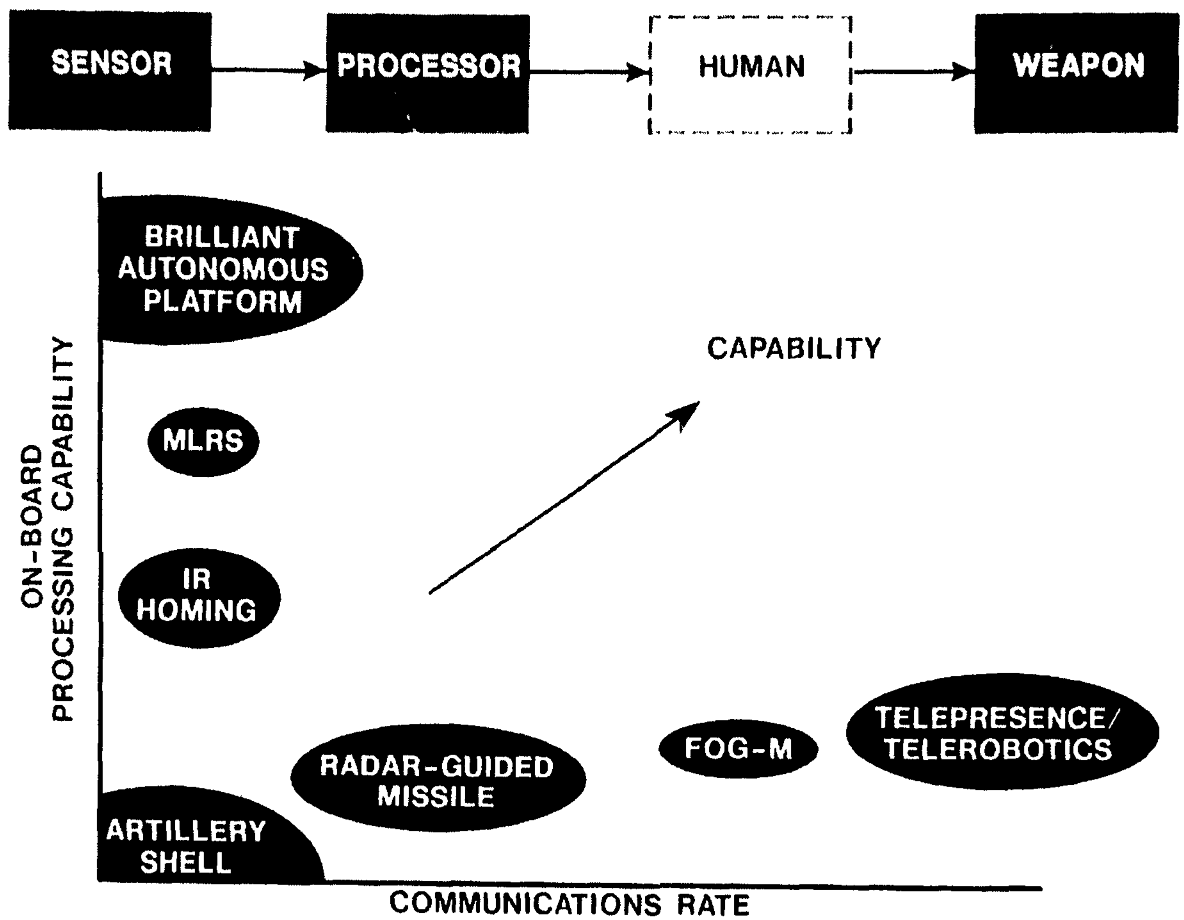


FIGURE 20-11 Sensor and weapon fusion has proceeded through both increased on-board processing capability and increased communications rate.

device development problem on the other hand. For these applications, high-power lasers such as CO_2, DF (deuterium fluoride), iodine, free-electron, and diode-pumped solid-state lasers are potential radiation sources. However, further development of any of these lasers will be needed before they will meet the requirements of specific applications. For example, current long-range laser-radar range-Doppler imaging techniques are under development for the Strategic Defense Initiative (SDI) to achieve target discrimination at 10.6 μm. One future ASAT candidate, a low-power version of an FEL with suitable adaptive optics should be configured for long-range laser-radar studies.

In its present design, the FEL is too massive to serve as a tactical laser. However, there are potential technological breakthroughs that may allow an FEL to be truck mounted. A research program, with a long-range viewpoint, should be initiated to explore and develop low-energy, high-brightness accelerators; short-period wigglers; and energy recovery, recirculation, and other techniques.

All imaging domains, such as passive, laser-range, Doppler, and range-Doppler, should be explored to evaluate their acquisition and aimpoint selection functions. As more laser power becomes available over the next decade, controlled experiments using sounding rocket payloads could be used to test laser impairment and damage assessment. Deployment would then follow if laser ASAT techniques prove superior to other techniques.

Hardening optical sensors against countermeasures is a major challenge for strategic and tactical systems. Nonlinear materials and fast shutters are among the candidates that have been advanced. For personnel eye protection, the safest approach is indirect viewing. Advanced optics and detector technology can provide wide-field-of-view indirect-vision devices for both night and day use, which would be much improved versions of current night-vision goggles.

RF directed-energy technology, both narrowband (high-power microwave, or HPM) and wideband (video pulse), is well advanced. Peak-power levels up to 10 GW have been demonstrated. A critical systems analysis of the applications of these devices, including effectiveness against simply hardened electronics, is required before any progress can be made in predicting their use to the Army. Such an analysis is under way by an interagency task force.

Progress in these fields will depend on advances in (1) multidomain optical sensors, (2) sensor fusion, and (3) smart sensor-systems; other key technology areas in need of development include (4) low-cost, efficient, high-duty-cycle laser-diode arrays, (5) neural-network technologies, (6) wideband fiber-optic communications and networking, (7) FELs or microwaves for radar and high-power weapon applications, and (8) the adaptive optics necessary for antisatellite and anti-ballistic-missile systems (Figure 20-12). Many of these technologies are already under investigation by

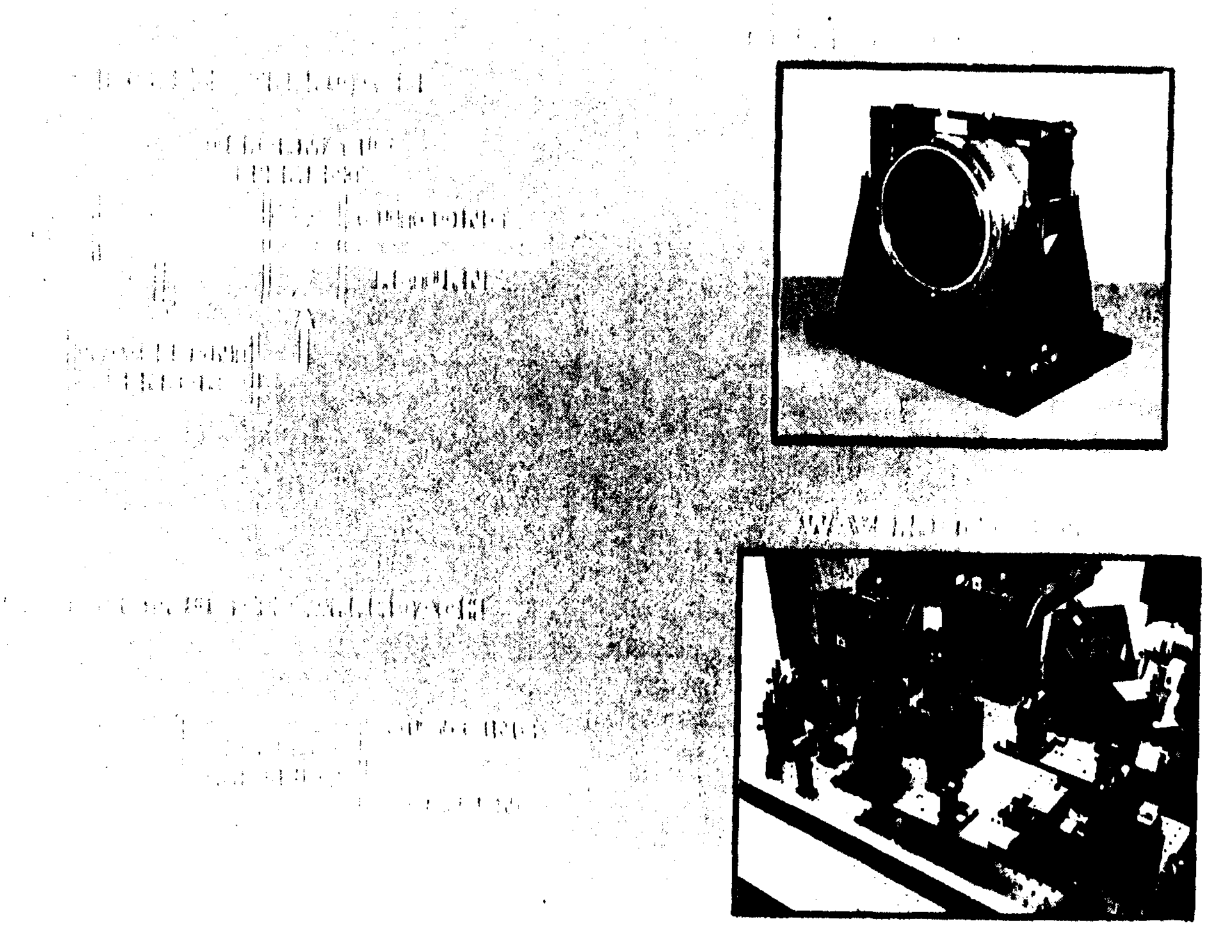


FIGURE 20-12 Adaptive optics technology.

the Strategic Defense Initiative Organization (SDIO) and DARPA. The Panel recommends that the Army work closely with DARPA and SDIO in areas of common interest.

21

Optical Sensor and Display Technologies

LASER RADAR

The recent development of effective lasers, efficient optoelectronic detectors, high-speed processors, and efficient algorithms have made possible new classes of laser radars—for high-resolution target imaging, target discrimination, and detection of low-observable targets. Wire detection and terrain avoidance have been demonstrated using CO_2-based laser radars. To develop the more compact systems the Army will need in the future for target identification and nap-of-the-earth flights in combat and training environments, solid-state lasers operating in the eye-safe region should be investigated. Much of this developmental work has been funded by SDIO, DARPA, and the Services. The specific technologies include:

- compact, electron-beam- and ultraviolet-preionized, self-sustained, carbon dioxide (CO_2) transversely excited amplifier (TEA) laser-radar systems or RF-excited, waveguide-CO_2-based laser-radar systems, all operating near 10.6 μm;
- efficient, lightweight, diode-array-pumped neodymium (Nd) solid-state laser-radar systems operating at 1.06 μm and/or at 0.5 μm; and
- a wavelength-tunable (from 0.7 to 0.9 μm) titanium-sapphire ($Ti:Al_2O_3$) laser-radar system.

Laser radar, employed in concert with wide-area surveillance sensors such as microwave radars and/or passive IRST sensors, can greatly enhance the capabilities of conventional fire-control systems. In Army ballistic-missile defense applications, this radar provides precision hard-body tracking and target-discrimination capabilities. Laser-radar resolution at extended ranges is far better than for conventional targeting radars. In tactical battlefield applications, laser radar is a key element of a multidimensional sensor suite for detecting and classifying targets for theater missile defense, as well as for air defense. Range and angle-angle imaging capabilities provide a method for detecting targets under camouflage. Doppler-signature data enable classification and identification of targets. The relatively narrow field-of-view of the laser-radar system also permits covert operation.

Current capabilities are embodied in a pulsed, wideband CO_2-laser radar that is being assembled at the Firepond facility in Westford, Massachusetts, under SDIO funding. This will serve both as a technology demonstrator and a radar measurement system to evaluate laser-radar discrimination techniques for strategic defense. The goal of the amplifier program is to develop a 200 J/pulse, 10 pulse/second, 30-μs coherent signal (the modulator supports a 2-GHz frequency-modulated waveform) suitable for range-Doppler imaging. Compact, efficient, RF-excited, waveguide-CO_2-based laser-radar systems have been mounted in surface and airborne vehicles to obtain unique Doppler signatures of targets. These systems, in concert with other sensors, also can provide active-intensity, range, and passive thermal-image data that are pixel registered. Also, recent advances in diode-laser technology indicate that these devices will be moving to diffraction-limited power levels of a few watts and may possibly achieve levels up to several tens of watts. As diode lasers in this class become available, many active sensing applications, including turbulence detection, ranging, and target identification, become possible for systems based on compact diode lasers.

Current military applications of solid-state lasers are limited mainly to rangefinders and target designators that operate at a low average power of a few watts. DARPA and SDIO have funded the extension of solid-state laser technology to average-power levels of several hundred watts; this will extend laser-radar applications to very long ranges. Power efficiencies of 4 to 10 percent recently have been realized in a Nd laser pumped by semiconductor lasers. In one laboratory experiment, an energy of 120 mJ was obtained at 30-Hz repetition rate; with 24-percent-efficient diode lasers, the overall efficiency of this diode-pumped, *Q*-switched Nd laser was about 4 percent. In another laboratory experiment, using doubled output from a *Q*-switched Nd:YAG laser to pump a Ti:Al_2O_3 laser, an output energy of 100 mJ at 10 Hz was obtained, with 40 percent optical-to-optical conversion efficiency.

With further development, CO_2 and solid-state lasers promise to provide the peak and average powers needed, while maintaining the high beam quality, spectral purity, and waveform agility required for laser-radar systems. The weight of the entire system is expected to be significantly reduced. In addition, the size and weight of solid-state lasers could be sufficiently small, and the reliability sufficiently high, to make space-based laser-radar systems practical; further, the high overall efficiency and projected low cost of diode-array-pumped solid-state lasers make battlefield laser-radar systems practical.

The use of laser radars will have a significant impact on warfare systems. In particular, they will significantly enhance the fire-control capabilities of Army lethal systems, mobile systems, and airborne systems. Laser radars for target identification and obstacle avoidance, optical air data systems for estimating air speed from aerosol backscatter measurements, optoelectronic integrated circuits and fiber-optic interconnections for efficient packaging are important elements of the Army's future multidimensional, smart sensor systems (see below).

DIFFERENTIAL-ABSORPTION LIDAR FOR DETECTION OF CHEMICAL EMISSIONS

One possible application of improved laser technology would be the development of sensors, based on a hybrid form of LIDAR technology, capable of "smelling" chemical emissions from military targets. For example, a multidomain sensor could be used to locate areas where cocaine is processed by using an airborne differential-absorption LIDAR (DIAL) to identify the diethyl ether emissions that are generated during processing. The site, even in a remote area, generates sufficient thermal energy to be detected by a passive, infrared search sensor; target verification would be performed by a CO_2 DIAL at a range of approximately 1 km.

The primary prerequisite for DIAL detection of a particular substance is that it possess a pair of laser atomic-transition lines, one strongly absorbed by the substance and the other experiencing little absorption. Two such CO_2-laser lines exist for diethyl ether; the relevant transitions are 9R(18) with σ = 2.2 (cm-atm)$^{-1}$ and 10R(20) with σ = 0.054 (cm-atm)$^{-1}$. Another requirement is that the sensor be appropriately compact for this airborne tactical mission, with low power consumption. Based on the Technology Group's experience, this dictates an average laser output power on the order of 10 W or less.

The CO_2 laser is important for the detection of gases because the long-wavelength infrared region in which it emits is particularly rich in absorption lines for many molecules, especially organic molecules. There are also effluents that exhibit absorption spectra in the near- to midwave-infrared region. Development of semiconductor and solid-state lasers operating in this region is important for detection of these gases. These lasers must be compact and rugged for the military environment.

Current capabilities could support such a system. The data rate required for DIAL detection of gases in this scenario is sufficiently low to permit the use of mini-TEA lasers, with their relatively low pulse-repetition frequency (PRF $\leq$ a few hundred Hz). The high peak powers available with these lasers permit the use of direct detection at the ranges of interest.

Killinger and Menyuk (1981) have described such a direct-detection DIAL, and since their system was appropriately sized for this application, it will be used as a model for the mission. They built both one- and two-laser DIALs, but the latter is used because it is critical that the on- and off-resonance beams follow the same atmospheric path and are reflected from the same topographic targets. Since the sensor is on a moving platform, the laser pulses must be nearly simultaneous to meet this condition, not allowing sufficient time for wavelength switching of a single laser. Each mini-TEA laser was approximately 1 ft^3 in volume, with a 20 mJ output energy, a pulse width of 100 ns, and average power output of approximately 10 W. Other relevant parameters were a 30-cm telescope and a 1-mm-diameter, liquid-nitrogen-cooled mercury cadmium telluride (HgCdTe) detector with a detector sensitivity, D^*, of 3×10^{10} cm $Hz^{1/2}W^{-1}$. The field-of-view of the detector/telescope was approximately 1.1 milliradian.

The minimum detectable concentration of diethyl ether, under ideal conditions, would be 3.3 parts per billion (ppb) at a range of 1 km. Unfortunately, because of the effects of atmospheric turbulence, terrain, and the diffuse nature of the target, this result is not achievable, although appropriate pulse averaging can improve the sensitivity. The maximum achievable sensitivity is probably about 200 ppb; whether this is sufficient for the mission depends on the amount of ether released at the target in question. Since the concentration naturally decreases with distance from the target, a considerably higher concentration must be present near the target to allow detection. For example, if the distribution of ether can be considered as spherical with a mean radius of 50 meters from the target, then to achieve a path-averaged concentration of 200 ppb at a range of 1 km would require an average concentration of 20 times that, or 4 ppm, near the target.

The impact of this technology on warfare systems would come through generalizing the technology to other chemicals of interest. The ability to detect molecular contaminants by a DIAL system can be exploited to locate a variety of militarily important targets, such as camouflaged vehicles, fuel dumps from vapor emissions, and perhaps ammunition dumps.

MULTIDOMAIN SENSORS

Optoelectronic sensors can easily provide measurement capability in several different domains, pixel-registered, all in the same physical package. This concept can be expanded readily to include millimeter-wave radar. For example, the coherent signal from a CO_2-based laser radar allows determination of target Doppler characteristics, range, and range extent, as well as area. A passive infrared sensor operating in the 8-μm to 12-μm waveband provides information on target area and temperature distribution. Multidomain airborne systems are now being tested using CO_2-based and GaAs-based laser radars, and 8-μm to 12-μm passive, visible-passive, and 85-GHz millimeter-wave radar to evaluate target detection and identification in a tactical environment.

The advantages of multidomain information include enhanced target detection and identification as well as reduced false alarms from clutter. Information fusion can be accomplished at the pixel level or after processing the information in each channel. Multidomain ATR is a concomitant Army and Department of Defense (DOD) technology thrust using electronic, optoelectronic, and optical-processing techniques.

Figure 21-1 shows the current capabilities reflected by the sensor suite. This sensor suite can be expanded readily to include passive and active

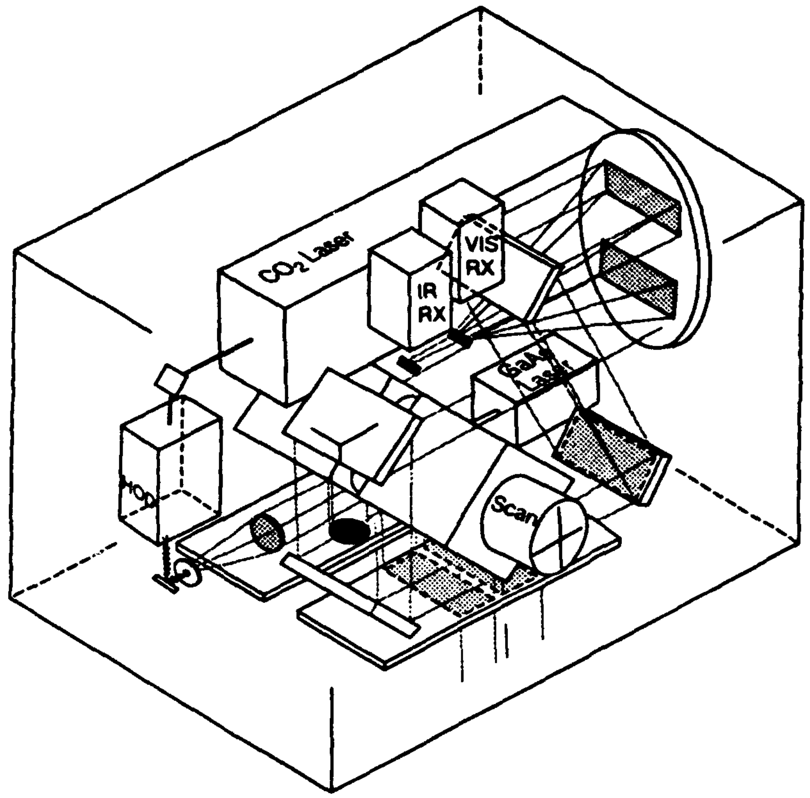


FIGURE 21-1 Multidomain sensor capabilities. Range = 1 to 3 km; absolute range resolution = 1 m (CO_2); Doppler resolution = 1 m/s (CO_2); relative range resolution = 1/3 m (GaAs); and NEΔT = 0° to 1° (8 to 12 μm).

camouflage detection wavebands (0.5 to 4.0 μm) and to provide higher resolution in range, relative range, and Doppler measurements. These systems also can be employed in satellites by using large apertures and high-power lasers. The resulting multidomain measurements make it extremely difficult for an enemy to use natural or manmade camouflage to conceal weapon systems.

IRST RANGING AND IDENTIFICATION

Passive infrared systems operating simultaneously in the regions at 3 to 5 μm and 8 to 12 μm can perform wide-area searches for low-flying stealth aircraft against terrain and cloud background. Spatial and temporal filters can be used to detect these targets and provide accurate angular pointing information to a laser radar, which in turn provides range and identification of the target.

One advantage of a passive IRST system is covertness. By operating in two bands simultaneously, the system presents the designer of stealth or camouflaged vehicles with additional difficulties. The IRST system is also useful for wide-area ground or sea surveillance.

The addition of a laser radar is highly compatible with the IRST design. For example, the coherent beam from a CO_2-based laser radar can use the same optics train as the IRST, which allows further clutter suppression and target identification (using range extent and Doppler characteristics), as well as providing range for a fire-control solution.

Current capabilities are demonstrated by an experimental, two-color, ground-based measurement system that was field-tested by Lincoln Laboratory in 1985 (Figure 21-2). This system has been used to gather large amounts of background data, as well as target signatures for a variety of air and ground targets. The target and background data have been used to develop detection algorithms and to evaluate the probability of detection and of false alarms. A simple CO_2-laser rangefinder is also attached to the system.

A passive IRST embodying the information gained over the past 6 years in detection and processing can be built in a military configuration. Further experience in operating a fully coherent laser in conjunction with the IRST and determining a packaging configuration is still required. If a first-generation system can be developed for field evaluation over the next 5 years, then full production of this system should be available within 15 years.

A passive wide-area search system with laser ranging and identification would have a major impact on low-altitude surveillance and defense against a variety of air targets. These targets include aircraft (conventional and tealth), cruise missiles, unmanned and remotely piloted vehicles, and tactical nissiles.

INTEGRATED SENSOR FUSION

The integrated sensor is a compact electronic device capable of "fusing" or integrating multiwavelength, multisensor data (Figure 21-3). The signal processing would be of the neural-network type, with optical-domain parallel processing in real time. A high-density focal plane would be achieved through the use of binary optical techniques with switchable detection capability in the infrared regions at 1 to 2 μm, 3 to 5 μm, and 8 to 12 μm, as required. A larger, more powerful sensor suite would include multicolor focal planes, visible-wavelength sensors, and microwave or millimeter-wave sensors, as well as laser radar and bistatic radar. The sensor-fusion device would integrate these sensor inputs to provide robust detection and identification capabilities.

The advantages of such a system are a complete all-weather, all-terrain, high-performance detection system for completely autonomous target

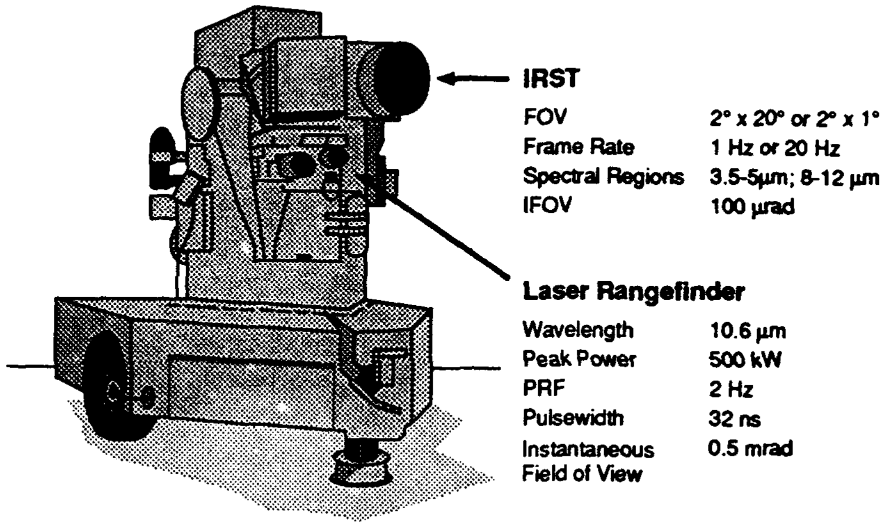


FIGURE 21-2 Massachusetts Institute of Technology/Lincoln Laboratory IRST Ranging and Identification testbed.

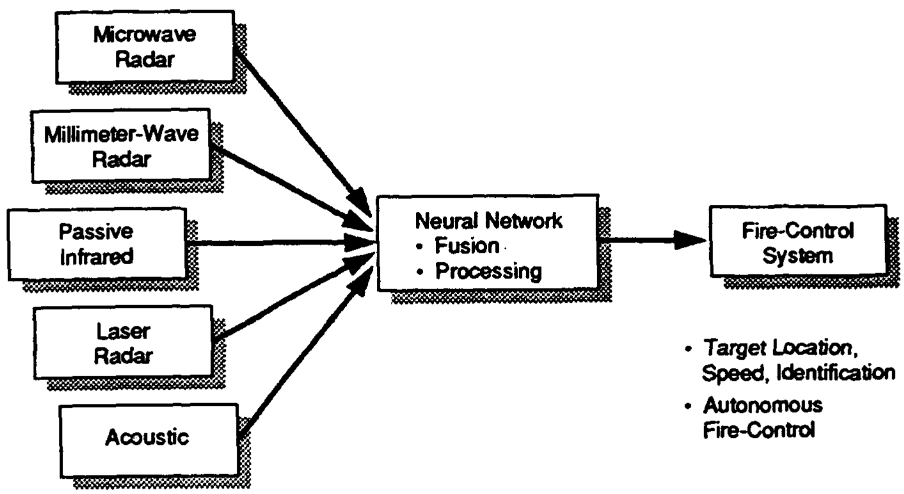


FIGURE 21-3 Integrated sensor-fusion device.

recognition and identification. This technology also would provide the extremely fast detection capability that will be necessary to counter smart weapons, stealth aircraft, and satellite weapons.

Focal-plane arrays are currently available in the infrared regions, but integration in one monolithic switchable structure has not yet been achieved. Developments are needed in three major areas: (1) optical parallel processing to emulate neural networks, (2) processing of signals from multiple acoustic receivers, and (3) channeling input to the fusion unit through a secure optical channel. The signal and information processing required will provide significant challenges; trade-offs between heuristic systems and neural-network emulation will become clearer as technology evolves. Hardening of nonlinear optical materials will pose a challenge for materials scientists.

Only integrated sensor fusion can satisfy the information demands of the future battlefield, which will require the rapid integration and interrogation of signals from a multisensor suite of detectors. This battlefield will require completely autonomous target detection, recognition, and acquisition, as well as an extremely rapid response to allow the fire control system to provide protection from satellite weapons, attack aircraft, and smart weapons. Under systems where the time element may not permit person-in-the-loop operation, the autonomous system must provide 100 percent target validation, a validation that will only be possible under a multisensor detection system. Future systems will necessarily be hardened against countermeasures.

SMART FOCAL PLANES

Focal planes with integrated processing of detected light waves will allow massively parallel processing of images with output at a reduced data rate for display or sequential processing by latter stages of ATR systems. Arrays of binary (diffractive) or refractive microlenses efficiently couple light into small-area detectors, thus providing space on the focal plane for processing circuitry (Figure 21-4). The backside of the focal plane would be read out in a massively parallel manner and imaged on sequential planes containing optoelectronic processing elements. Functions performed could include classical techniques such as correlation or could emulate the early stages of vision. Optical implementations of neural-network functions (e.g., learning and associative memory) in the subsequent planes would further advance the capability of these smart focal planes. The smart focal plane might include multicolor capability integrated with fusion of information at several wavelengths. Sophisticated focal planes will play an important role in aided target recognition, munitions sensing and fusing, and surveillance.

The incorporation of parallel-processing functions in the focal plane and massively parallel processing in closely integrated subsequent planes will yield major increases in processing speed in small imager systems. The limitations

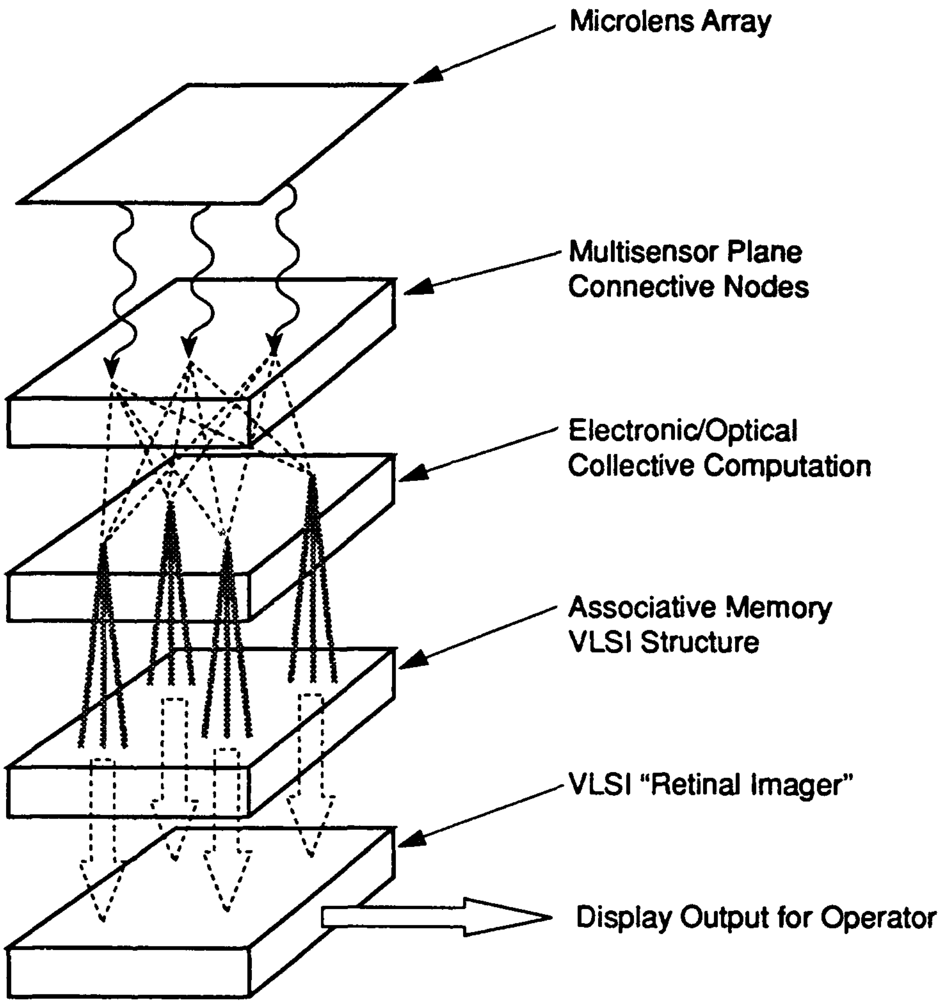


FIGURE 21-4 Future smart focal plane.

of serial readout and serial processing in conventional computers would be avoided. Advanced image-processing techniques that emulate neural processes associated with early vision are well matched to the parallel architecture.

Current focal planes are read out serially and processed by conventional serial digital computers. These computers employ simplistic but computationally intensive processing for functions such as time delay and integration, multiplexing, responsivity correction, and automatic gain control. Algorithms for ATR and similar image-processing and recognition functions are being explored, but no definitive approach has been identified. Optical techniques for classical two-dimensional cross-correlations and for Wigner transforms have been explored, but these, too, may not be the optimum processing techniques. Optical spatial light-modulators allow light incident on one side to modulate light on the other side. Today's devices are too insensitive to function as imagers, however, and the processing functions that they can perform are too primitive to implement a focal plane with significant processing capability.

Projected smart focal planes will incorporate matching microlens arrays to efficiently collect light and yield sensitive detection combined with processing capability in the initial focal plane. The number of pixels in the focal plane and the spatial resolution will be similar to today's focal planes. Optical processing planes will be implemented with advanced solid-state technology, especially advanced semiconductors and liquid crystals or other electro-optical materials. Highly parallel processing will yield image acquisition and processing rates of more than 5000 frames per second. Readout rates required for interfacing with subsequent digital-processing equipment will be minimized.

Smart focal planes with integrated imager and processor will be substantially smaller than today's systems, especially through a major reduction in processor size. Advanced capabilities in a small package will allow new smart missiles to find and track targets without the aide of a ground-based operator. ATR and tracking functions could improve terminal guidance and provide more accurate aim-point selection for man-in-the-loop systems. Imagers for surveillance and sensing could provide cueing for key image details such as motion or sharp edges.

SMART HELMETS

Future battlefields will require technologically assisted, enhanced awareness by the field soldier because of the increased use of camouflage or stealth techniques by both sides. In addition, the use of antipersonnel lasers, which are intended to blind or dazzle troops, will require that eye protection be worn. A potential solution to these dual requirements is the development of a "smart helmet" that incorporates advanced night-vision sensors, signal processing, and communications, as well as offering eye protection through indirect viewing.

The smart helmet would be designed as an integral system, as is now routine for fighter-pilot helmets. Visible-light and near-infrared viewing could be provided by a fourth-generation approach; infrared imaging in the 8- to 12-μm band can be provided by uncooled focal planes. The resulting multispectral images could be processed in the helmet, as they are in smart weapons, so that the soldier could be presented with visual cues from motion, heat, camouflage, and so on. For night fighting, especially, this approach would be invaluable. In addition to providing eye protection, the helmet would serve as a locator for laser sources.

Second-generation night-vision goggles have a narrow field of view (Figure 21-5). The Army is currently producing the third-generation night-vision goggle, which uses a GaAs/AlGaAs photocathode and a microchannel plate for electron avalanching onto a phosphor screen (Figure 21-6). The screen is then viewed through a fiber-optic image inverter. This device is effective over the 0.6- to 0.9-μm band; however, it is not designed to provide laser eye protection because of the open space between the eye and goggle unit. The field of view is 40 degrees.

An advanced integrated unit would allow coverage from 0.6 to 0.9 μm and 8 to 12 μm with the same or greater field of view. In addition to providing real-time image processing, the helmet could be equipped with a fiber-optic output/input capability—a soldier on night patrol could transmit his observations back to his unit. Additionally, tactical or directional information could be sent to him along the fiber and projected onto the viewing surface. As a result, the use of a smart helmet would greatly increase survivability on future battlefields. Also, it would provide a ready method of intercommunication among force elements.

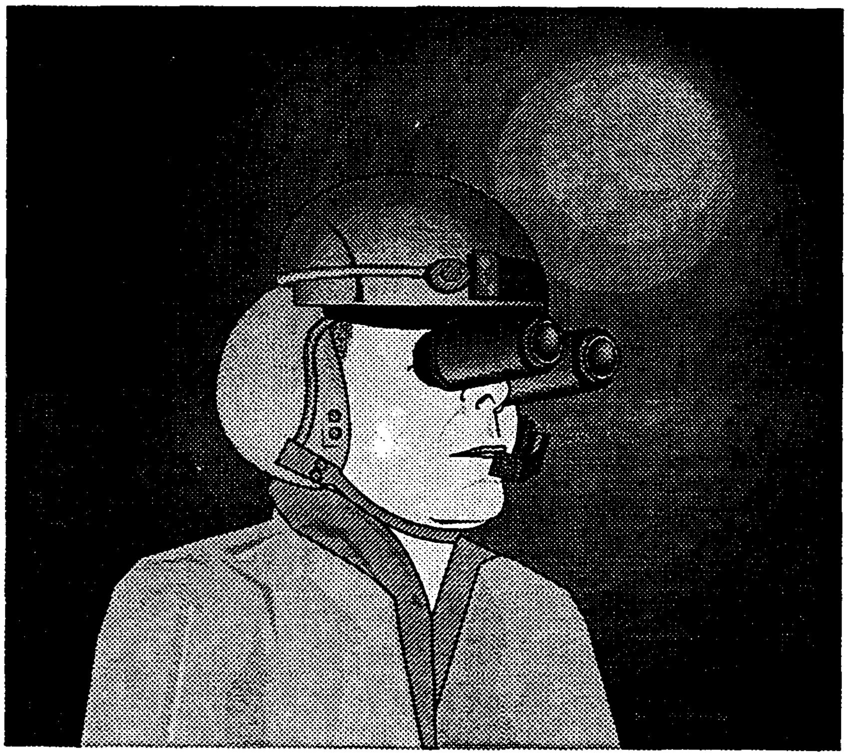


FIGURE 21-5 AN/AVS-6 night-vision goggles.

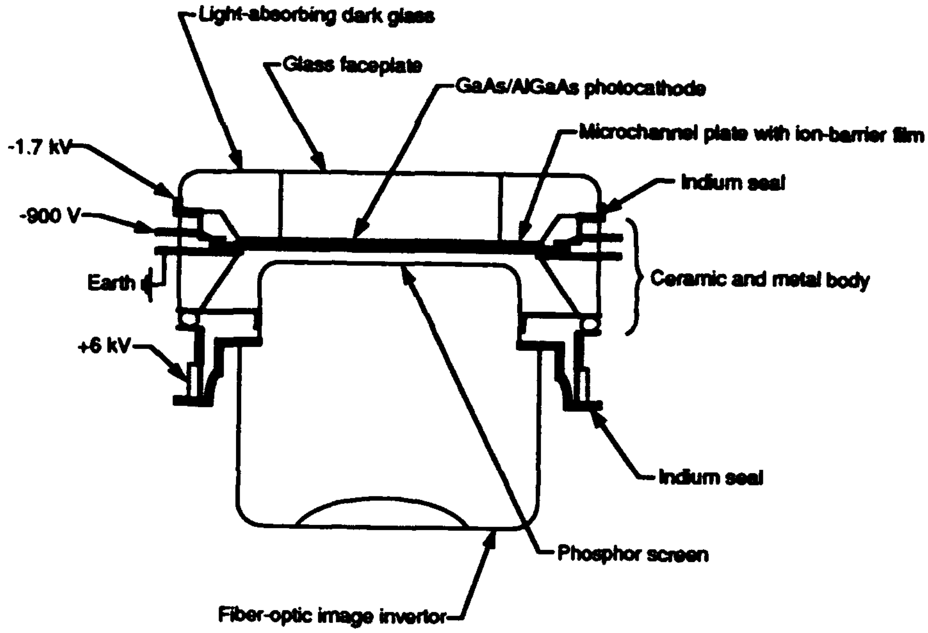


FIGURE 21-6 Third-generation image-intensifier assembly.

SMART DISPLAYS

Current display technology is relatively mature, and future developments in this area are likely to be modest improvements on what can be accomplished today. In future systems, information will be provided in the digital domain, and thin-film technology will be at the heart of any display system. The key developments will be the monolithic integration of drive circuitry with coupling to either a highly efficient light-emitting diode array or an electroluminescent array for low-power microminiature displays. Optical elements will provide for projection or direct-view displays. The optical design of the display will also resolve any problems associated with the directional emission properties of the appropriate technology.

The integration of the drive technology for monolithic displays will be compatible with digital information transfer, very low power and very high resolution (on the order of 2,000 television lines) and will be capable of three-dimensional color imagery with overlay symbology in a smart-array format. The smart displays also will be able to track both eye and head motion, be touch sensitive, and provide voice input and output to accomplish different mission objectives. These developments will be compatible with both desktop projection imagery (replacing current monitors) and major military applications that will use heads-up and helmet-mounted displays.

The present technology base includes cathode-ray tubes, liquid-crystal displays, light-emitting diode arrays, and electroluminescent displays. Each technology has different advantages and will be continuously developed. The battlefield environment will play a role in the ultimate technology of choice; for example, liquid crystals can provide very-low-power displays, but they are a poor choice for high-ambient-light conditions.

These projected capabilities are motivated by the need to interact faster and more effectively with an increasing amount of information and to direct and control information as well as the machines that acquire, transmit, and process that information through the combined actions of sight, sound, and touch. Large, full-color, high-definition, flat-panel displays will be an evolution of present technology. Real developments will be centered around more complete interface ensembles for smart displays. Displays will range from personal "eyepiece" viewers to direct-view screens to large multiviewer display screens. Interactive devices will be expanded to include touch screens, voice input and output, and head and eye trackers, self contained in the same smart display. The development of these advanced displays will have the ultimate goal of allowing personnel to operate (by true telepresence) in environments that are physically inaccessible or are too dangerous to enter.

The major impact on military systems will be the use of light panoramic systems, in which helmet-mounted or heads-up displays can be designed with a wide field of view using appropriate optics. Figure 21-7 shows an example of this potential of the new technology, illustrating a binocular heads-up display that uses an exponential toroidal optics system. This system is only possible with an extremely lightweight, high-intensity, thin-film display, and only if binocular vision is required in the central region. Total fields of view near 135° are possible,
permitting integration with sensors for piloting and sighting applications. Other displays will be used in a narrow field-of-view mode for individual weapon sights.

SMART FOCAL-PLANE ARRAYS

The smart focal-plane array (FPA) will be a monolithic structure operating as a staring imager in at least two different infrared bands, simultaneously and spatially equivalent. This multiwavelength feature will be

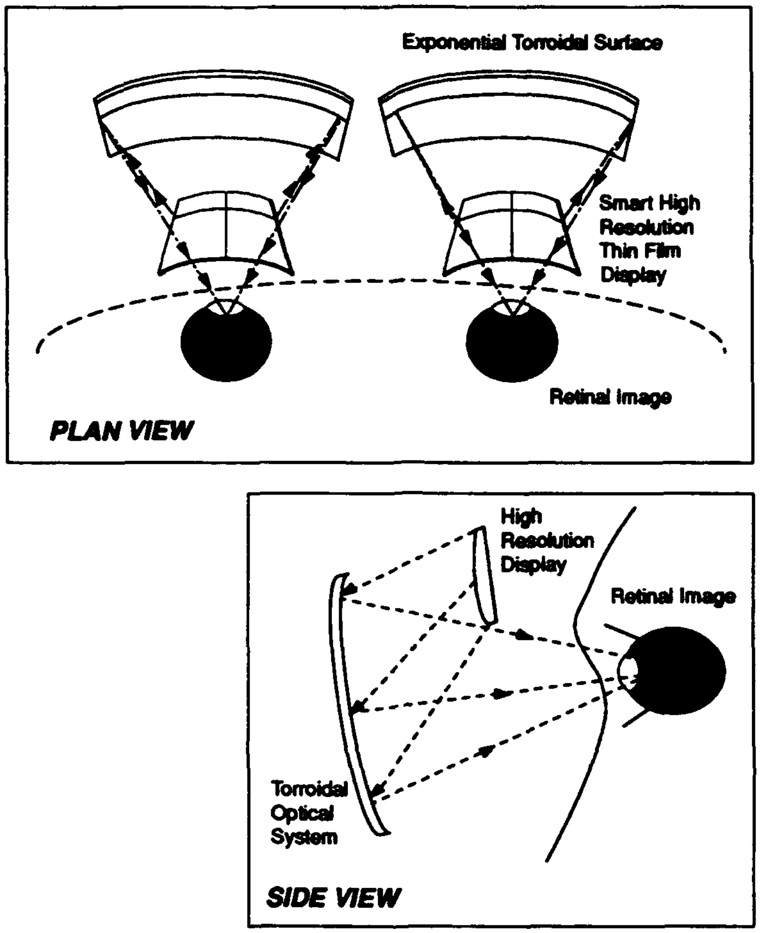


FIGURE 21-7 Binocular display system.

possible through advanced materials processing available through the next generation of microfactories. Infrared detectors with a high fill factor that are fabricated from multi-quantum-well structures with binary optical microlenses will permit signal preprocessing in the FPA. The signal information will be transformed, on chip, into the optical domain that will provide a neural-net emulation for target information-processing with direct access to the fire-control system. Countermeasure-hardening of the memory chip will be accomplished with nonlinear optical materials and diamond coatings.

The principal application for smart FPAs is in high-performance systems for autonomous fire control, to allow for immediate response to incoming smart weapons from missiles and attack aircraft. However, a low-power, smaller version of the array integrated into the smart helmet could render the individual soldier a serious threat to armor and aircraft attack (Figure 21-8).

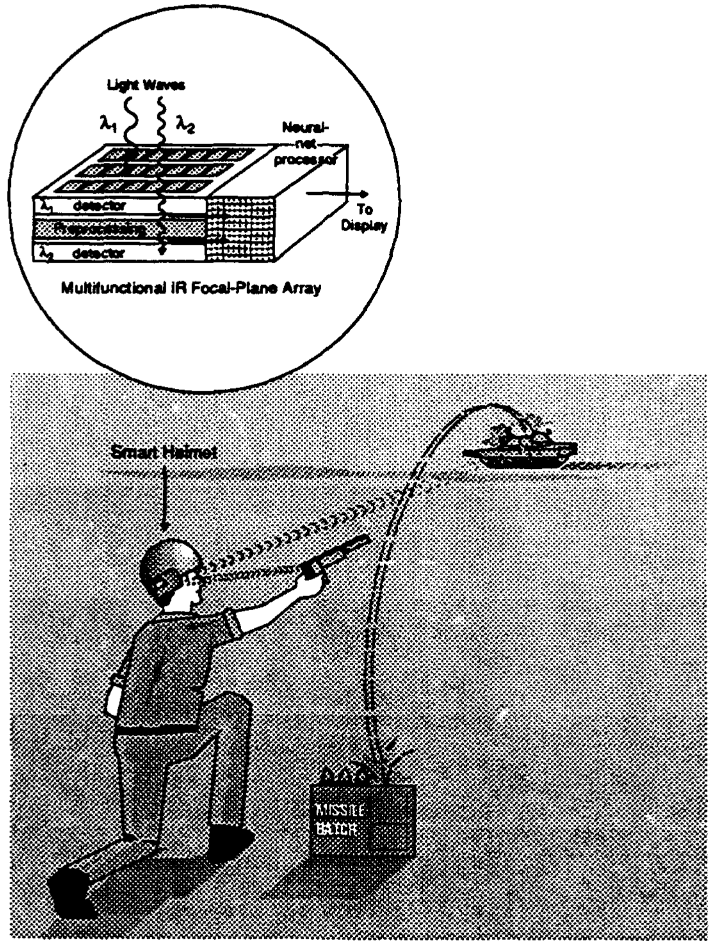


FIGURE 21-8 Smart focal plane arrays: technology and applications.

The present generation of Army FPAs employ a scanning system, with time delay and integration to improve sensitivity, in a 960- by 4-pixel format. The future materials developments under present production-feasibility programs for HgCdTe (mercury-cadmium-telluride) detector arrays will allow larger-area focal planes that can be used in staring systems for tactical applications. The practical limit of present hybrid technology is 256 by 256 pixels because of the problems of expansion match to silicon processors. Low noise is achieved by operating devices at a zero-bias condition. The limitations on resolution, sensitivity, and response time will be overcome with improved materials and the use of GaAs preprocessors. These devices, which still need some development, will send data to on-chip optical processors, that will emulate a neural-net processor to achieve a corresponding associative memory. The latter technologies also need considerable development, and autonomous target recognition and acquisition under field conditions will need to be validated.

Future generations of the smart FPA will provide an integrated target acquisition suite with smart processing to support autonomous fire control against any incoming threat. The similarly equipped smart helmet will give the individual soldier enough firepower to pose a real threat to armor and to oppose smart weapons. Implementation of the technology probably will evolve in two stages, initially (within 15 years) with the neural-net processor located off the focal plane and later (within 30 years), after concept validation, as a totally integrated package on the focal plane in a low-power version using parallel optical processing.

SCHOTTKY-BARRIER INFRARED FPAs

FPA sensors composed of Schottky-barrier detectors can be fabricated using near-standard silicon technology. (The Schottky barrier is a characteristic of the detector material, which gives it a very uniform response as well as high production yield, or lower cost to manufacture.) These sensors could improve sensor photon-collection efficiency by 10^4 over conventional infrared scanners. Although current platinum silicide (PtSi) devices have somewhat low quantum efficiency, they have demonstrated excellent thermal sensitivity in the mid-infrared region. The use of iridium silicide (IrSi) will permit coverage of the long-wave infrared region. Additionally, palladium silicide (PdSi) Schottky-barrier detectors may provide nighttime imaging in the 1- to 1.8-μm skyglow region (Figure 21-9).

The quantum efficiency of Schottky-barrier detectors is considerably lower than that of other solid-state detectors. This has inhibited their use in traditional infrared scanning-sensor designs. However, the use of a large number of detectors in a staring-imager format can compensate for lower quantum efficiency. Furthermore, Schottky-barrier FPAs have attained very low noise levels, yielding outstanding sensitivity.

PtSi arrays of 512- by 512-pixel detectors operating at 77 K are commercially available. Experimental IrSi and PdSi arrays of 128- by 128-pixel detectors have been fabricated and tested. Arrays of 1024- by 1024-pixel detectors should be available at all wavelength regions over the next decade, with 10,000- by 10,000-pixel detector arrays possible in the next two decades.

Schottky-barrier technology covers all wavelengths of interest to the tactical battlefield with a single technology. Target detection and acquisition, camouflage discrimination, and other functions can be accomplished using multispectral techniques employing a filter and a common focal plane. Alternatively, Schottky-barrier arrays tuned to particular regions of the spectrum can be registered spatially so that these functions can be accomplished in a staring-imager mode.

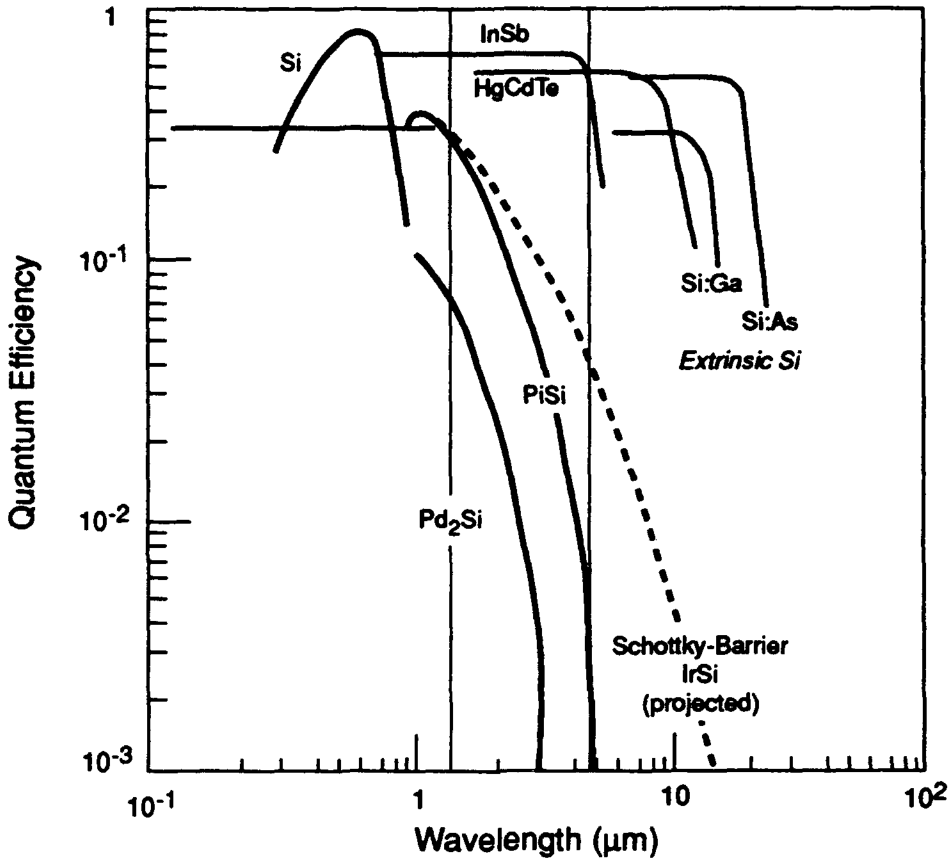


FIGURE 21-9 Quantum efficiency of commonly available detector materials.

NEAR-INFRARED SKYGLOW IMAGING

Schottky-barrier charge-coupled imaging arrays (SBAs) for the near-infrared can greatly enhance night-vision capability by taking advantage of the nighttime skyglow radiation in the 1- to 2-μm region. This persistent global source has an average brightness at ground level that is slightly greater than full moonlight, and it is not severely attenuated by complete cloud cover.

PdSi SBAs have the potential to achieve low-light-level imaging in a spectral region (1 to 3 μm) that has been inaccessible in the past because of a lack of good imaging sensors. From an operational point of view, this spectral region is unique because it provides a continuous source of illumination for imaging. In addition, this is the region where ambient-temperature blackbodies produce high-contrast thermal images. The correlation of skyglow and high-contrast thermal images in the same device should add a new dimension to target discrimination. Since PdSi SBAs operate at temperatures greater than 110 K, passive cooling is adequate for satellite installations.

The sensitivity, array size, and fabrication of PdSi SBAs is closely tied to the progress in visible-spectrum array technology. The first large arrays have video-rate imaging capability down to a scene brightness of approximately 100 nW/cm^2, which is marginal for night-vision applications. This limitation is primarily because of poor charge-transfer efficiency in the charge-coupled device portion of the array at low temperature.

The projected sensitivity of SBAs is of the order of 10 photoelectrons per pixel, which translates to video images of scene brightness of approximately 1.0 nW/cm^2. This improvement would yield high-quality images of skyglow-lit scenes and thermal images of objects that differ by roughly 1°C. To achieve this ultimate sensitivity, however, the readout charge-transfer efficiency of these devices at 100 K will have to be improved by 100-fold. Alternatively, it will be necessary to realize a noiseless "fat-zero" to negate the charge-transfer trapping. The existing final-stage readout amplifier will need to incorporate the latest low-noise techniques from related fields. With a dedicated effort, the sensitivities mentioned above could be realized in about a 4-year time frame.

The obvious impact on warfare of perfecting the PdSi SBA is unobstructed night vision for tactical forces and intelligence gathering. Less obvious are the capabilities that will ensue from opening up the 1- to 3-μm region to effective imaging. An imaging device that can see targets in scattered skyglow, and at the same time observe their thermal emission, will lead to new techniques for target discrimination.

22

Photonic, Optical, and Optoelectronic Technologies

Photonics is the use of photons to transmit, store, or process information. Fiber-optic telephone systems, compact-disc players, and checkout-counter scanners are examples of products using photonics. Military applications for photonics include:

- battle management;
- target recognition;
- low-observable target detection;
- electronic counter-countermeasures for radar and communications;
- fiber sensors for fuses, ordnance detection, and smart or covert surveillance devices; and
- fly-by-light systems and data buses for helicopters and other platforms that operate in environments with strong electromagnetic interference.

Photonic systems are more immune to unwanted interference than electronic systems, since the information is carried by a neutral particle along a nonconducting fiber. One important application of this feature is in flight control systems to provide greater protection against electromagnetic interference without the weight penalties associated with electromagnetic shielding. Photonic transmission systems operate at carrier frequencies on the order of 10^{14} Hz, or 100 terahertz (THz). These frequencies are around one million times higher than those for electronic systems and permit correspondingly large bandwidths of the order of 1 THz. Photonic systems are potentially more reliable and maintainable, since more can be done with fewer components. In computer applications, photonic systems have the potential to provide higher clock rates and parallel processing, thus dramatically increasing the throughput rate. Table 22-1 presents current and projected capabilities; specific applications and enabling technologies are discussed in the following sections.

GUIDED-OPTICAL-WAVE SENSORS

A variety of physical phenomena can cause changes in either the amplitude or the phase of optical waves traveling in fibers or in the optical waveguides of integrated optical devices. Phenomena that can be sensed in this way include vibration, temperature, pressure, rotation, magnetic field, and electrical field. Development of specialized optical fibers and waveguides for sensing applications will allow this technology to penetrate into many areas

TABLE 22-1 Current and Projected Capabilities of Photonic Systems

	Capabilities	
Parameter	Current	Projected
Local-area networks	100 MHz	10 THz (10,000 MHz)
Microwave-signal rejection	Coaxial, waveguide	Fiber optic (less weight and volume)
Narrowband-signal rejection	200-MHz passband, 1-MHz resolution, 40-dB rejection	1-GHz passband, 1-MHz resolution, 60-dB rejection
Target recognition	Slow, person-in-the-loop	Improved speed
Electronic digital signal processing	1 GOPS 100-megabit memory	1000 GOPS, 100-gigabit memory

NOTE: GPOS = billion operations per second.

of Army operations. The fact that fiber sensors can, with one technology, detect a variety of phenomena makes these sensors well suited for many types of fusing and surveillance applications.

Novel modes of operation of these optical sensors will be exploited to provide new capabilities. For some parameters, increased sensitivity relative to today's sensors will be achieved. For others, features such as compactness, passive operation, rapid deployment, and the ability to send sensed signals long distances over optical fibers will be of crucial importance.

Currently, many laboratories are developing fiber- and integrated-optical sensors for a variety of physical inputs. Considerable effort has been geared toward fiber-optic gyroscopes, which seem well matched to a number of missile applications (Figure 22-1). Compactness, robustness, and cost offset the somewhat lower sensitivity as compared to mechanical or laser gyroscopes. The Navy has taken the lead in developing acoustic sensors for sonar applications. A variety of thermal sensors also has been developed for industrial applications. Electromagnetic-field (DC, RF, and microwave) sensors generally have poor sensitivity as compared to conventional semiconductor receivers.

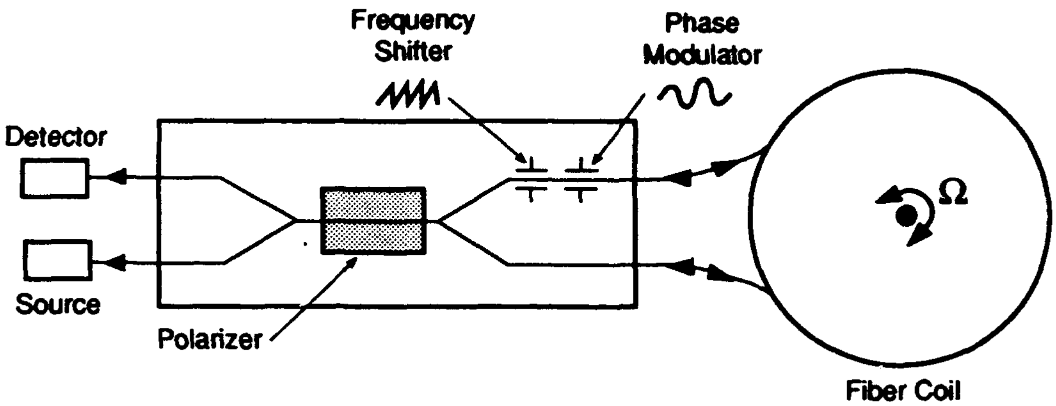


FIGURE 22-1 Fiber-optic gyroscope with integrated optical chip.

Smart structures with embedded optical sensors to detect strain can be used to construct critical systems, especially in the high-value parts of helicopters. Such sensors can provide improved diagnostics of important parts, such as rotor blades, for increased reliability and maintainability. This topic is treated further in Part VI: "Advanced Materials."

Projected increases in sensing capability and ease of deployment will be achieved through the development of specialized optical fibers, optical sensor-interfaced fibers, compact integrated optical circuits, and efficient high-power, high-stability lasers. The resulting guided-optical-wave sensors will be key elements for attaining advanced weapons control and the high level of situation awareness considered crucial for future ground operations. Possibilities include:

- advanced electromagnetic-field sensor in the form of low-noise passive, unpowered remote antennas/receivers (Figure 22-2);
- compact, inexpensive, and robust optical gyroscopes for enhanced missile guidance;
- optical fibers incorporated into structures (such as helicopter bodies) to monitor stress and structural integrity; and
- traffic and intrusion monitoring for both personnel and vehicles through a combination of pressure, vibration, and magnetic-field sensing.

FIBER-OPTIC NETWORKS

Advanced communications networks based on the proper mix of RF and fiber-optic links will provide the crucial information integration and

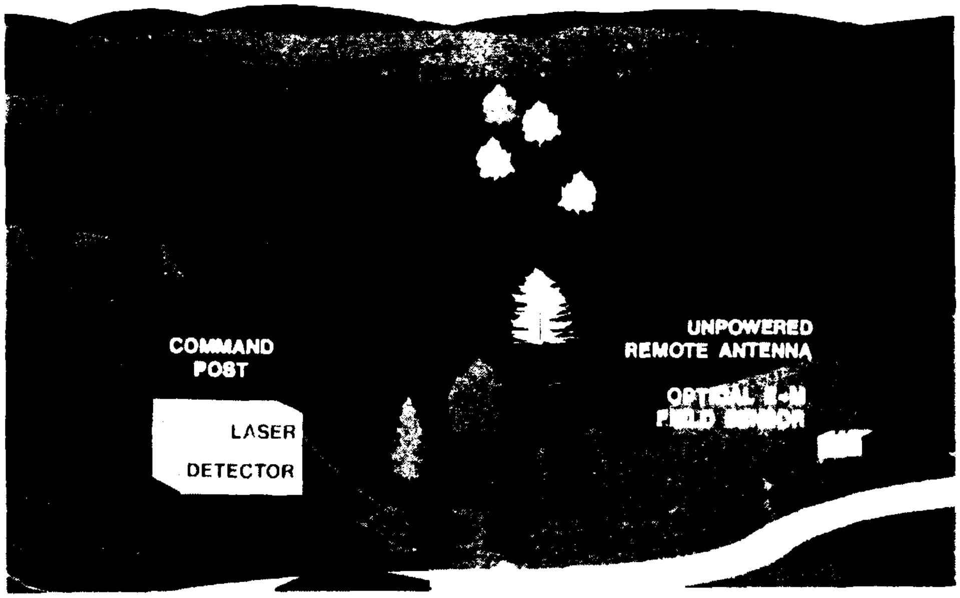


FIGURE 22-2 Guided-optical-wave sensor.

dissemination capability for C^3I. Flexible networking capability depends on advances in information routing in optical systems to accommodate a large number of users and to operate without centralized control. Techniques such as wavelength-multiplexed routing show promise for yielding this capability.

Wide-bandwidth optical fibers combined with advances in networking techniques will provide a jamming-, interference-, and intercept-resistant basis for a communications network that will be supplemented by more vulnerable RF links. Optical fibers can be rapidly deployed by both air and ground. Combined radio-transponder/optical-fiber links could service both fixed and highly mobile users. This capability will allow real-time access and distribution of battlefield information to a greatly expanded number of users.

Current commercial fiber-optic communications technology has focused on fixed-installation point-to-point links over long distances. Military adaptations of the technology are providing more rapidly deployable links for distances ranging from tens of meters to many kilometers (Figure 22-3). Networking capability generally is based on derivatives of the time-division-multiplexed techniques developed for telephone and local-area network systems. Such techniques often limit operational bandwidths and presently compromise the robustness and flexibility of the network.

In the future military system (Figure 22-4), an optimum combination of wavelength-division multiplexing and routing combined with time-division

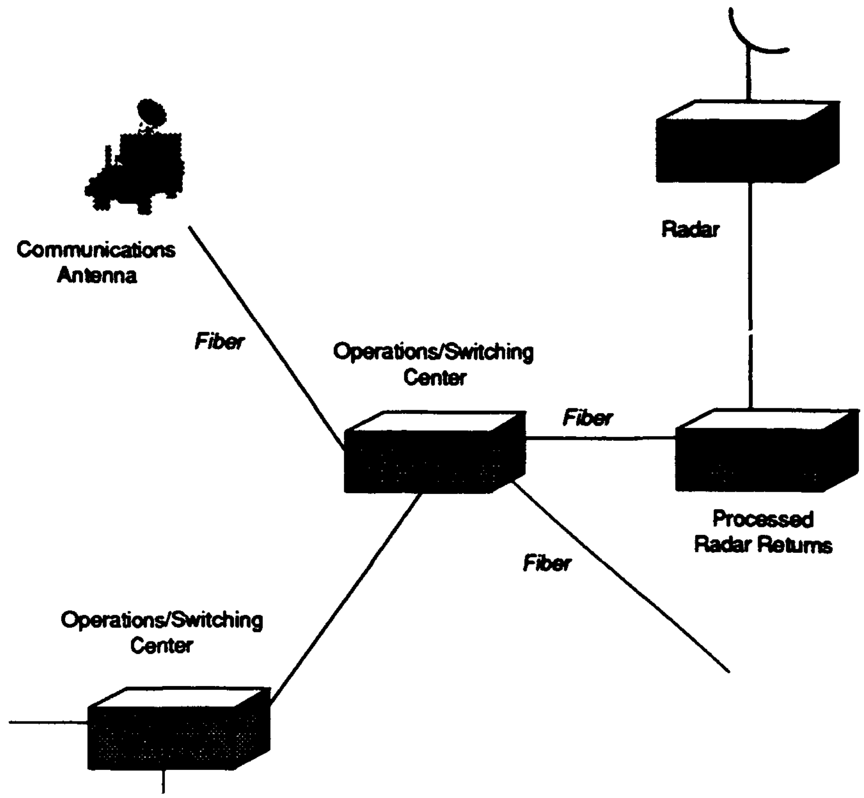


FIGURE 22-3 Present fiber-optic network.

techniques could provide tens to hundreds of megabits per second for hundreds of networked users. The combined peak network capacity would extend into the range of 10 gigabits per second or more. Shorter RF links to mobile users would provide increased resistance to jamming, terrain obscuration, and multipath resistance.

The networking capability provided by optical technologies will allow wide-bandwidth sensors to be more closely integrated with ground operations. Sensors and C^3I information will be distributed over the network to powerful data-fusion computers as well as to users. This will allow the Army to exploit these sensor inputs and the force-multiplier advantages of advanced C^3I.

FIBER-OPTIC TELEPRESENCE

Fiber optics also will provide the means for a very-wide-bandwidth link between an operator and a remote platform. The wide-bandwidth fiber allows the multisensory input (especially images) from the platform to be transmitted to the operator and the control signals to be transmitted back to the platform. This linking provides the essential elements of telepresence, the illusion to the operator that he is riding the platform. Applications would be to both

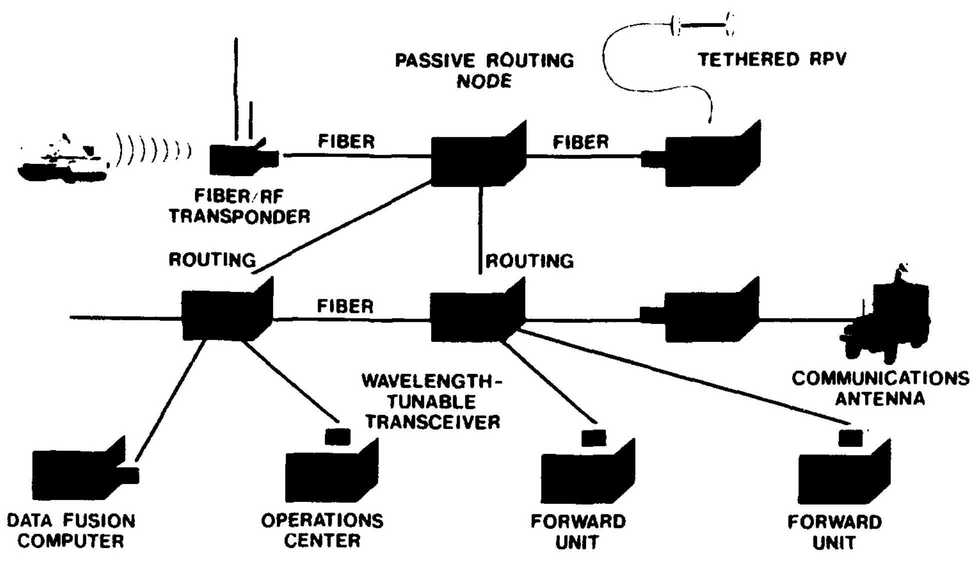


FIGURE 22-4 Future military fiber-optic network.

airborne and ground reconnaissance vehicles and weapons. Efforts to develop fully autonomous vehicles and smart weapons have been limited to relatively simple automatic target recognition and control strategies, because of limited on-board computer power and inability to exploit the sophisticated recognition and control capabilities of a human operator.

Optical fibers have the advantage of resistance to jamming, interference, and interception in a physical link that has long operating distances and is readily paid out from a moving platform. Exploitation of large computational capacity at the operator's site would allow the implementation of both "smart" systems and computer-assisted human control at higher levels than would be cost-effective or technically possible on the platform. The tele-operated platform could be expendable, yet have the advanced capability provided by a large computer working in concert with a human operator. Optical fibers provide the essential wideband link and remove the operator from hazardous environments.

The prototype of this new class of systems is the fiber-optic guided missile (FOG-M, Figure 22-5). The system limits its use of sophisticated robotics and telepresence technology. The primary sensory input to the remote operator is in the form of video images. Current low-loss fibers and spooling techniques provide ranges that extend beyond 10 km. Advances in ultra-low-loss optical fibers and spooling techniques will extend ranges to many tens of kilometers and bandwidths to several billion bits. Multisensory

FIGURE 22-5 Fiber-optic weapon guidance.

inputs will be processed at the operator's site and integrated with human functions to provide a "smart cockpit" remote from the platform.

Fiber-optic telepresence will yield mobile platforms that are small, cost-effective, and often expendable, yet possess an advanced capability by melding powerful computers and crucial human-operator control. Among the possibilities are the following:

- advanced FOG-M with increased range, target acquisition capability, and speed;
- airborne surveillance platforms with multidimensional sensors that require only minimal on-board processing capability to exploit the multisensory inputs in real time; and
- tele-operated ground vehicles for reconnaissance functions as well as weapons delivery, including miniature robotic tanks.

SOLID-STATE LASERS

Since the mid-1980s, DARPA, SDIO, and the Service laboratories have supported a renaissance in the development of solid-state laser technology. Among recent results are the rapid advances in the power and efficiency of semiconductor lasers and semiconductor laser arrays, their application to the pumping of solid-state lasers, the development of high-strength and low-optical-loss crystalline and glass laser materials, and the development of low-optical-loss and high-conversion-efficiency nonlinear crystals.

The advantages of these technologies are their high reliability and the low maintenance inherent in an all solid-state design. No high voltages are required, overall power efficiency is greater than 10 percent, and average power (100 to 1000 W) is available in a compact package. Multiband operation is practical, using advanced solid-state nonlinear materials to generate visible, near-infrared, or mid-infrared wavelengths. Mass-production techniques promise low cost for producing semiconductor laser-array pumps and solid-state materials.

At present, the highest efficiency comes from longitudinal pumping (where the pump and laser are collinear) of solid-state laser rods by stacks of diode-laser arrays with suitable microlens and mode-matching optics (see Figure 22-6a). Wall-plug efficiencies of 14 percent have been demonstrated, and efficiencies of 20 percent or higher are feasible. Efficiencies in this range have been demonstrated at the 1-W continuous-wave power level. Transverse pumping of solid-state laser slabs by two-dimensional diode-laser arrays (Figure 22-6b) is a better configuration for higher power generation at modest efficiencies. A Nd:YAG prototype device with 50-W average power (at 1 J and 50 Hz) and 8 percent efficiency was delivered for flight tests in FY 1990.

Projected capabilities include a Nd:YAG laser demonstrator with 300-W average power and an efficiency of about 10 percent and a lifetime greater than 10^9 shots, which will be developed by 1993. Efficient harmonic generation and use of a solid-state laser based on thulium-doped yttrium aluminum garnet crystal (Tm:YAG), as well as other wavelength conversion techniques, will enable this demonstrator or other devices to be wavelength-selectable from the visible region to the mid-infrared at greater than 100 W. This average power level exceeds the power-level requirements for many space and tactical applications.

One of the key technologies for extending solid-state lasers into new wavelength ranges is the use of nonlinear optical materials for harmonic generation and wavelength conversion. Recent advances in harmonic generation have been achieved by alternating period poling of waveguides and fibers. Optical nonlinearities are discussed further in the section on "Optical and Electro-Optical Materials Technology" and the section on "Applied Nonlinear Optics."

Recently, the yield of diode-laser arrays has improved dramatically (see below). A new DOD diode-laser-array producibility program is expected to reduce the cost of arrays to affordable levels for DOD and commercial applications. This technology will provide laser rangefinders and laser target designators that are more reliable and eye-safe than those available today. In addition, this technology will lead to new, compact, reliable, and efficient optical-image radars, and active optical countermeasures. It will also enable

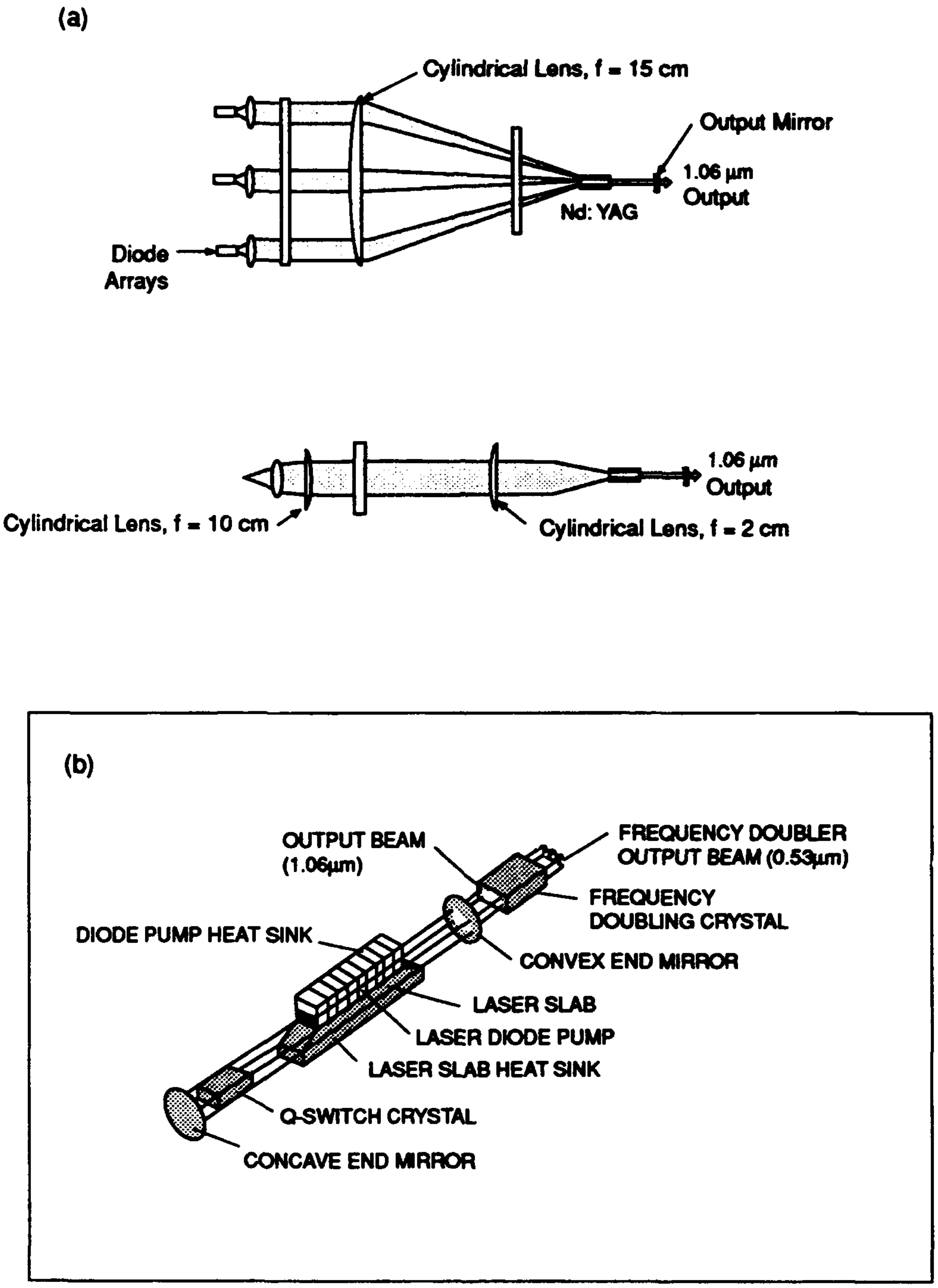


FIGURE 22-6 Longitudinal (a) and transverse (b) laser pumping.

high-bandwidth laser communication to commanders at theater, division, battalion, and perhaps company levels.

ADVANCED DIODE-LASER ARRAYS

Diode lasers are a highly efficient means for converting electrical energy to light and will form the basis for most future systems that use lasers. Although significant progress is being made in increasing the diffraction-limited power levels from individual diode lasers and amplifiers, the power from an individual laser is ultimately limited by mode breakup and thermal effects. Scaling to high power levels will therefore depend on the development of diode-laser arrays.

The most extensive current use of diode-laser arrays is for pumping solid-state lasers (described above). Arrays delivering several kilowatts of peak power have been assembled for this purpose. The solid-state laser converts the incoherent output from the array into a spatially coherent output beam. Currently, two-dimensional arrays are assembled from stacks of bars containing linear arrays of lasers. The cost will be reduced and thermal performance improved through the development of monolithic two-dimensional arrays of surface-emitting diode lasers. Two types of surface-emitting lasers are being developed, vertical-cavity lasers and horizontal-cavity lasers with integrated beam deflectors. Currently, the horizontal-cavity devices lead in performance. Two-dimensional diode-laser arrays will be especially useful for pumping two-dimensional microchip laser arrays. These monolithic diode-laser arrays also have the advantage of being readily mated to lithographically defined two-dimensional micro-optic lenslet arrays (either binary/diffractive or refractive) to achieve power concentration.

Small efficient optical sources will provide a number of new capabilities for warfare systems, including:

- lightweight optical avoidance-sensors for aircraft;
- eye-safe and covert rangefinders and other sensors;
- small laser radars for special applications, such as motion and vibration sensing;
- identification-of-friend-or-foe (IFF) sensing; and
- line-of-sight wideband communications.

LONG-WAVELENGTH DIODE LASERS

Diode lasers emitting in the 2- to 3-μm region are required for proximity fusing applications. Required technical characteristics of the lasers depend on the specific application; power requirements, for instance, change as applications are extended from very-short-range (~1 meter) systems for shaped charges to 100 meter or more for sensor-fused munitions. Other short-range radar and seeker systems also could benefit from this technology.[1]

Backscatter from foliage clutter and water aerosols (fog, cloud, and some military smokescreens) is greatly reduced in certain frequency bands in this spectral region. Considerable advantages in target/clutter discrimination could therefore be realized. Figure 22-7 shows a plot of the backscatter-to-extinction ratio for a water droplet distribution characteristic of natural clouds and fog. This figure shows a minimum in this ratio that is over two orders of magnitude lower than in most of the visible-light and near-infrared range. Although transmission at the minimum is quite low, adequate transmission for fusing ranges can be obtained near the minimum. In fact, for short-range systems, absorption can be an advantage by reducing the distance at which the system's signals can be detected, thereby improving covertness, and also by

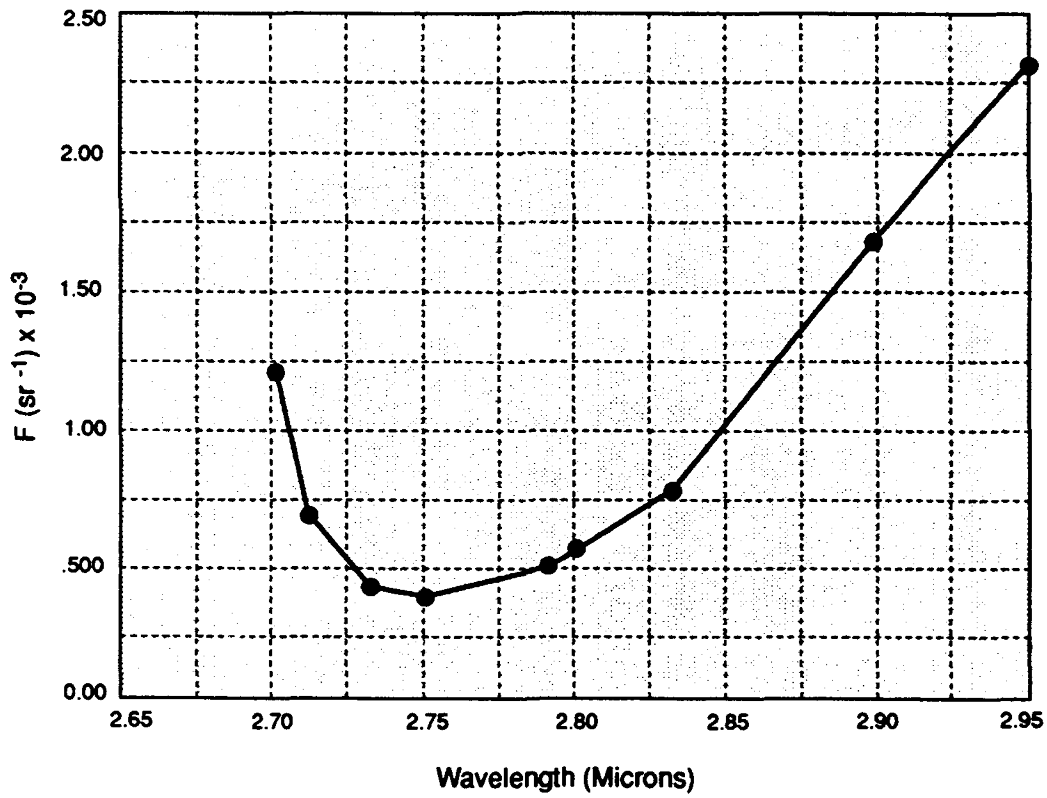


FIGURE 22-7 Backscatter-to-extinction ratio for clouds and fog.

[1] References for this section are Casey, 1986; Toda et al., 1987; Sztankay, 1987; and Gupta, 1989.

making interception or jamming of its signals more difficult. Similar minima occur for foliage clutter returns.

Diode lasers are now generally available from the visible spectrum to ~1.5 μm in the infrared. Current proximity-fuse systems utilize 0.9-μm laser diodes and are susceptible to prefiring in clouds, smoke, and foliage. Within 15 years, however, wavelengths as high as 3 μm should be available, along with coherent sources and processing in integrated optical systems. Within 30 years, arrays for higher power and beam steering should be available, along with optoelectronic integrated circuits (OEICs) for increased integration of optical and electronic functions.

OPTOELECTRONIC INTEGRATED CIRCUITS

Electronic integrated circuit technology makes possible the fabrication of many electronic devices on a single semiconductor chip. Integrated optics technology combines optical waveguide components on a single chip. Likewise, OEIC technology unites both of these individually powerful technologies on a single semiconductor chip (NRC, 1988). An OEIC device can function either as an interface between the two technologies (converting electronic signals to optical signals or vice-versa, as lasers or detectors) or as a functional hybrid of the individual technologies (e.g., as a signal processor). Figure 22-8 shows a generic optoelectronic chip; see also the discussion in the preceding section.

The key advantages of this hybrid technology include the following:

- integration of electronic processing with optical sensors;
- compact and inexpensive signal and information processing;
- greater ruggedness and reliability of optical technology; and
- development of practical ultra-wide-bandwidth data and communication links.

OEICs will be key to developing optical interconnections, which will eventually replace many of the conventional electromagnetic interconnections in computer systems. Optical technology promises increased density, speed, parallelism, and freedom from electromagnetic interference. Advances in packaging technology for integration of optical elements in advanced optoelectronic multichip modules will be important for the future uses of OEICs.

Electronic integrated circuit technology, already mature, is still advancing. Integrated optics is demonstrating promising capabilities and is beginning to be incorporated into important systems. The two technologies are just beginning to be combined, but this integration is moving rapidly, driven largely by commercial applications. Within 15 years, optoelectronics will be

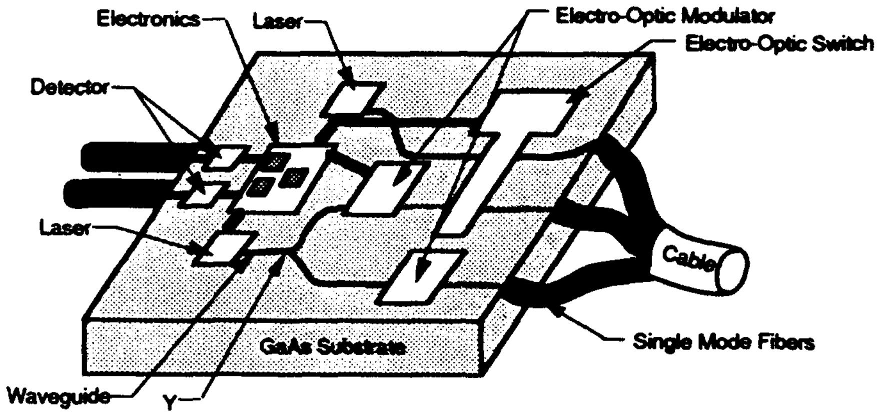


FIGURE 22-8 Optoelectronic integrated circuit.

mature enough to yield communication and computer interconnect applications; rapid progress also will occur in signal and information processing. Within 30 years, optoelectronics will be functional in a wide range of applications that will make use of the benefits of massively parallel optical processing and wavelength multiplexing.

OPTICAL AND ELECTRO-OPTICAL MATERIALS TECHNOLOGY

A variety of materials support the role of optics in passive and active sensing, information processing and storage, and high-speed optical communication. Several types of passive optical materials are crucial to Army missions. These include infrared-transmitting materials for windows and domes in passive or active optical sensors. Special fibers will be needed for operation in new wavelength bands and for fiber sensors. (The latter use was discussed earlier, in the section on "Guided-Optical-Wave Sensors.")

Nonlinear optical materials are critical for a large number of applications of optics. Optical limiters are needed for eye protection and for optical detectors. Better nonlinear materials with high efficiencies and operation over a wider range of temperatures and wavelengths will be important for converting the output of solid-state lasers into wavelength bands that cannot be efficiently generated directly by these lasers.

For communications, nonlinear materials offer the possibility of switching and routing optical signals without the need for high-speed electronic control. For information processing, the same materials offer ultra-high-speed optical logic gates. Nonlinear and electro-optical materials offer the possibility of fabricating arrays of optical logic gates or optical neurons, thereby achieving high computational throughput by taking advantage of the parallelism of optics. Some of these materials can be used to build integrated optical devices and electrically addressed spatial light modulators. A particular class of nonlinear materials, the photorefractive crystals, perform storage of holograms, thus facilitating optical memory and programmable optical interconnects. Some of these materials are also used for phase-conjugate mirrors, an important element in many optical-processing architectures.

At present, the most mature and well-characterized materials for optoelectronic applications are GaAs and, to a lesser extent, the other III-V semiconductors. GaAs supports high-speed (subnanosecond) circuitry as well as sources, detectors, modulators, and waveguide devices, all integrated in monolithic form. These devices will benefit from the new structures that can be fabricated through modern epitaxial-growth techniques. These new structures include faster and higher-power transistors and heterojunction devices, as well as quantum-well layers, superlattices, quantum wires, and other quantum-confined structures. Advanced epitaxial technology also will provide semiconductor materials for expanded wavelength coverage by diode lasers (see section above on "Long-Wavelength Diode Lasers").

The ability to fabricate quantum-well structures has provided a new detector technology with significant potential. AT&T Bell Laboratories has pioneered GaAs/GaAlAs quantum-well detectors. The present devices have poor quantum efficiency and high dark currents, and they require cooling to below 100 K. But a combination of band-gap engineering with the use of III-V materials with narrower gaps should yield better performance at long wavelengths. Improved control, reproducibility, and uniformity are significant potential advantages of this technology over the current state of the art.

Ferroelectric liquid crystals can be integrated with silicon VLSI circuits to form an integrated electro-optic device with potentially important applications in smart focal-plane arrays and information processing. Spatial light modulators and smart pixels have been demonstrated that can switch voltages of tens of volts at high contrast (greater than 1,000) and submicrosecond switching speeds.

Lithium niobate is the most mature material for volume holographic storage and interconnects. With a single exposure process, one billion interconnections can be stored in a 1-cm^3 crystal, and holographic associative memory has been demonstrated in research laboratories. The interconnect capacity may be much more limited, however, if the gratings are written sequentially, because of erasure effects and recording nonlinearities. In addition, lithium niobate is commonly used in integrated optical devices. Light can then be controlled to yield an information bandwidth of 20 GHz and an extinction ratio of 25 dB with 5 to 10 volts.

The nonlinear optical interactions of certain organic materials show promise. Polyacetylene, for example, displays a nonlinear refractive index change of nearly 10^{11} cm^2/W and a response time of well under 100 fs. For communication applications, silica fibers have been used for switching of femtosecond optical pulses.

Most of the above capabilities, however, have been demonstrated only in small-scale research devices. With adequate support for materials research and device development, maturation can take place, especially with the III-V semiconductors. In the short run, optical processing applications will be dominated by arrays in which the logic function (or other nonlinear computation) is performed electronically and the optics serve as a highly parallel mechanism for interconnection. Fast, nonlinear switching devices will continue to evolve, but there still is a question as to whether their switching energies can be reduced enough to permit them to be fabricated in dense two-dimensional arrays. Such arrays would achieve parallelism as well as switching speed with acceptable power dissipation.

The computational throughput, measured in terms of the product of speed-power and spatial-density, for optoelectronic arrays based on III-V semiconductors will be difficult to surpass for some time. One promising technology over the long term is III-V integrated optics at 10-μm wavelength, using quantum-well optical nonlinearities mediated by intraband transitions with very large dipoles. By using an infrared wavelength, the energy-per-photon is lower than that for visible light; with appropriate input and output couplers, two-dimensional arrays are then possible.

The above materials will have a significant impact on all military missions that utilize optics. What should be stressed here is that technologies for these materials, even in III-V semiconductors, are poorly developed compared to silicon technology. Nonsilicon technologies will require a substantial and sustained investment in basic and applied research to achieve the required maturation.

Currently, DOD appears to be heavily dependent on photonics vendors who mainly address commercial markets and consequently have little interest in developing technology to address the Army's requirements for high reliability and operation over a wide range of operational extremes. Operation of optical devices and systems over a wide range of temperatures is especially important. An example of the development needed is the recent advance in strained-layer quantum-well diode lasers that can operate over a much wider temperature range (-60°C to 100°C) than previous diode lasers. Another special concern is the radiation-hardened aspects associated with fiber-optic links and optoelectronic devices and circuits. Advanced photonic materials and devices are essential to the future of optical sensing, communication, signal processing, and computing, but lead times of a decade may be required before development of advanced systems can begin.

OPTICAL NEURAL NETWORKS

Neural networks are made of two types of processing elements. By analogy with components in biological networks, these are often called neurons and synapses. A synapse performs an operation on its single input. The operation is typically a multiplicative weighting; in some cases, it may be a difference calculation or other operation. A neuron receives inputs from many synapses, combines them in a particular way, and then performs a generally nonlinear operation on the result.

Two technologies offer particular promise for advanced network implementations: electronics and optics (Figure 22-9). Electronics, even

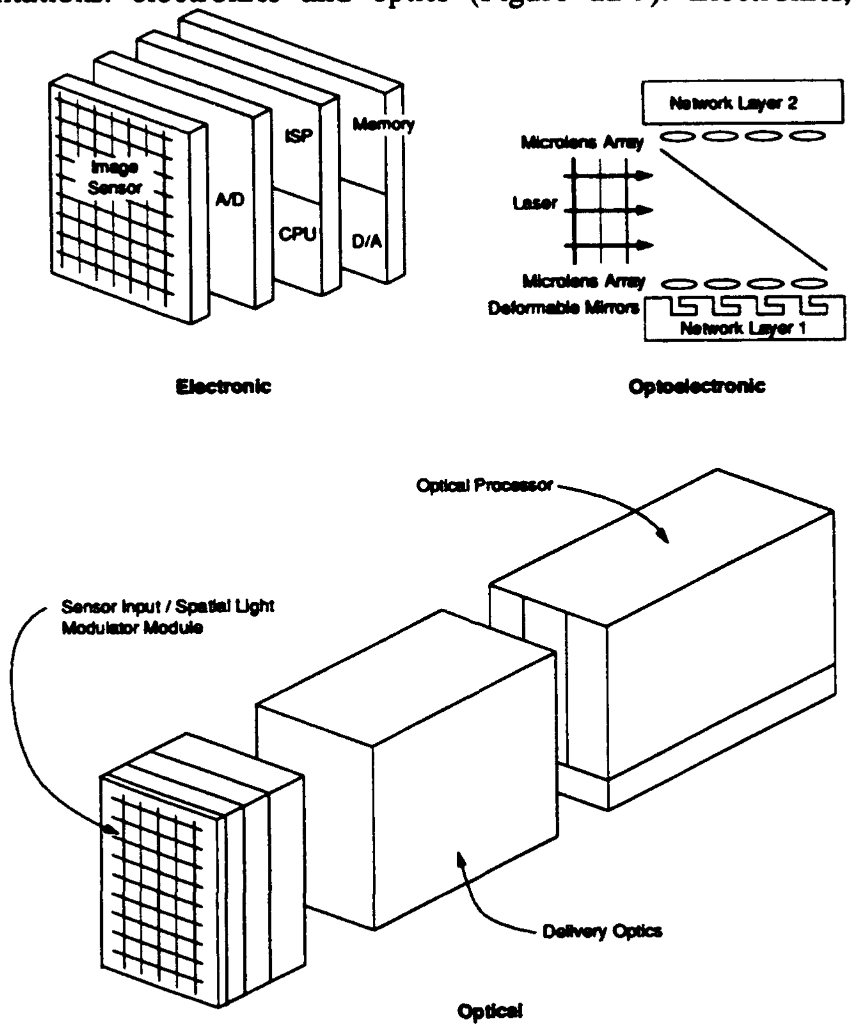


FIGURE 22-9 Electronic, optical, and optoelectronic neural-network implementations. The electronic implementation includes functional modules for analog-to-digital conversion (A/D), a central processing unit (CPU), integrated signal processing (ISP), and conversion of processing results from digital back to analog (D/A).

analog electronics, is relatively well developed and can readily provide flexible, well-controlled nonlinear characteristics. On the other hand, electronic circuits, which are confined to a plane, can support only a relatively small number (less than a million) of neurons and synapses in a single component. They also are constrained in the types of connectivity that can be achieved. The two extremes of fully connected networks and nearest-neighbor-connected networks can be implemented efficiently in integrated circuits; intermediate connectivity patterns, however, pose a problem.

Optical and optoelectronic devices for networks are considerably less well developed than electronic devices but offer potentially much larger numbers of neurons and synapses per component (perhaps as high as 10 billion). Optical systems can support more flexible connectivity patterns and can provide long-distance interconnects without capacitive or inductive crosstalk and loading. Optical designs are particularly well suited to space-invariant connectivity, where the connection weight between any pair of neurons depends only on their relative geometric positions. Many vision and image-processing network architectures require precisely this kind of connectivity. Figure 22-9 shows three implementations of neural networks.

There are two generic approaches to using optics to support the connectivity of a neural network. One is to store synaptic weights in a planar *transmissive (or reflective)* device, such as a spatial light modulator (SLM), and to use lenses and fixed holograms to provide interconnection topology. The maximum number of independent synapses that can be provided is N^2, where N is the linear dimension of the SLM array divided by the optical wavelength. Thus, N neurons can be fully interconnected with N neurons. This optical connectivity is no greater than that available from electronic implementation within a chip. However, there is a significant advantage to having long-distance interconnects free from capacitive and inductive crosstalk and loading. Optics can be used to supplement nearest-neighbor electronic interconnects on a chip of optoelectronic neurons. Also, many neural network problems do not require full connectivity between planes of N^2 neurons. Numerous feature-extraction tasks performed by the early visual system, for example, rely on intermediate or even nearest-neighbor connectivity.

The second generic approach is to use volume holograms stored in photorefractive crystals. This approach appears to offer connectivity between two area arrays of $N \times N = N^2$ neurons, for a total connectivity of N^4. However, the number of independent connections (i.e., gratings) that can be stored in an ideal medium is limited by diffraction to N^3 (i.e., the volume of the hologram divided by the cube of the wavelength). In actuality, each of these N^3 gratings provides roughly N connections of identical weight lying on the surface of a cone (the so-called "Bragg cone degeneracy"). This gives the appearance of N^4 connections, but only one connection from each grating is useful. Nevertheless, this approach does in principle provide richer connectivity: $N^{3/2}$ neurons can be fully interconnected with $N^{3/2}$ neurons. Furthermore, a volume hologram provides for space-variant interconnects. Because of the Bragg conditions, each angle of incidence can be made to address a separate pattern of connections.

Table 22-2 summarizes a survey of existing U.S. technology in this important field. Current technology can support about 10^3 neurons and 10^6 synapses. Advanced technology should support 10^6 neurons and 10^9 synapses, with a throughput of 10^{12} connections per second.

Optical neural-networks will provide real-time automatic target recognition using a variety of sensor data, including passive visible and infrared, laser-radar, and millimeter-wave data. In addition, neural networks can be used for speech understanding and complex signal processing. The adaptive-learning capability provided by neural networks will radically improve information processing and distribution on the battlefield.

ACOUSTO-OPTICAL SIGNAL PROCESSING

Optical processing of information uses light as an information carrier, and the light (along with the information it carries) is manipulated using some of the more common tools of optics: lenses, mirrors, and prisms. Information is typically encoded into light using one or more of three means: amplitude modulation, frequency modulation, or phase modulation. One of the following interaction mechanisms is used to perform the modulation: acousto-optic, electro-optic, or magneto-optic. In this way, large amounts of data can be simultaneously encoded on light and processed in parallel. Information-carrying light beams can pass through one another without influencing the information on the beams, further increasing data-handling capacity (see generally Berg and Lee, 1983). These characteristics contribute to the capacity of current versions of optical processors such as the acousto-optical (AO) correlator to perform the equivalent of 10^{13} operations per second.

Information throughput for optical processor architectures is two to three orders of magnitude greater than that for digital electronic processors. Smaller and lighter than digital processors, optical processors also require considerably less power to operate. A typical application might be the calculation, to a resolution of 25 kHz, of the power spectral density and 15-μs time-of-arrival measurement of an input signal having 60 MHz of instantaneous bandwidth. Table 22-3 lists the requirements for three technologies: digital electronic, analog optical, and analog acoustic (surface acoustic wave or SAW).

Table 22-2 Summary of Research and Development on Optical Neural Networks

Name and Type	Implementation	Features
BDM/NRL Attentive Associative Memory Network*	Prototype neural network based on light-emitting diode (LED) and P-type intrinsic N-type (PIN) photodiode components and electronic amplifiers that employs attentive associative memory. Ultimately the implementation of this compact architecture will use electro-optic materials in the spatial light modulators (SLMs) with an inherently nonlinear transfer function, obviating the need for electronic amplifiers.	Distinctive features include: • storage of vectors individually; and • lenseless design (two-dimensional SLMs), a compact system that is both light-efficient and permanently aligned.
NRL Adaptive Real-Time Holographic Network	Optical implementations of artificial neural networks, using real-time holographic implementations and five distinct optical architectures employing SLMs; the latter enable the required nonlinear operations. Most of these architectures are also optically cascadable modules, with all input and output information patterns in optical form. These cascadable modules have been designed to be optically interconnected and cascaded to construct more sophisticated multilayer artificial neural-network architectures for solving particular problems.	Powerful adaptive learning capabilities. This is an essentially, all-optical architecture, with both learning and recall operations accomplished optically, without the aid of adjunct electronic computations. In the optically addressed SLM architectures, the requisite additions, subtractions, multiplications for inner and outer matrix products, and actual updating and storage of the synaptic-weight matrix are accomplished by the SLMs.
CalTech/JPL GaAs Optoelectronic Neural Chip*	Prototype neural network based on a GaAs monolithic, two-dimensional array of optoelectronic neurons operating in conjunction with a volume hologram. The optoelectronic integrated circuit (OEIC) is under development.	This prototype is the first optoelectronic implementation of a neural network based on monolithic integrated OEICs, rather than on discrete devices. Since all the neuron elements on the OEIC are not connected electrically, and the interconnects are specified optically, the OEIC can be a basic building block for several types of neural networks.
Northrop All-Optical Network	An all-optical, continuous-time recurrent neural network. The network is a ring resonator, which contains a saturable, two-beam amplifier, two-volume holograms, and a linear, two-beam amplifier.	Novel features that distinguish this network from other all-optical architectures include fully adaptive bipolar, and (potentially) asymmetric, interconnects; low-noise recall of stored attractors; and enhanced algorithmic flexibility.

Hughes Opto-Electronic Resonator Network	Employs all-optical and hybrid electro-optical nonlinear holographic associative memories (NHAMs). A NHAM consists of a hologram situated in an optical cavity that provides gain and feedback. The hologram defines the stable modes of the resonator. Several angularly multiplexed optical reference beams are used to record numerous images in the hologram. When the hologram is subsequently addressed by a partial or distorted version of one of the stored images, the system settles into the stable state "closest" to the input image. The system thus performs as an error-correcting, fully parallel associative memory.	The optical associative memories, with their full parallelism and large number of interconnects, are extendable to high-speed implementations of large multilayer neural network models.
Rockwell/ CalTech Holographic Networks*	Optical implementations of associative-memory networks using quadratic or higher-order interconnections.	The unique feature of many of these optical systems is that the realization of the interconnections is not confined to the plane, as would be the case in electronic systems. The interconnections are implemented in a volume, which offers more degrees of freedom in a more compact form than a plane.
University of Pennsylvania Optical Networks	Bimodal, optoelectronic neural network that can be used in two distinct modes, depending on the noise level (temperature) of the network.	Distinctive features of the network include: • stochastic learning; • full programmability; and • potential for compact packaging. The absence of capacitive or inductive loading inherent in optical interconnects means that the time response of the entire cluster is that of the individual modules; this suggests that massive neural networks might be feasible with this clustering approach.

*BDM = BDM Corporation; CalTech = California Institute of Technology; NRL = Naval Research Laboratory; JPL = Jet Propulsion Laboratory.

TABLE 22-3 Comparison of Technologies for a Spectrum Analysis Problem

Technology	Chips (no.)	Volume (in^3)	Dynamic Range (dB)	Power (W)
VHSIC Phase I	2000	3000	60	3200
VHSIC Phase II (goal)	350	1000	80	2000
Acousto-Optics (current)		400	35	75
Acousto-Optics (goal)		200	80	50
SAW (current)	10 RACs	2000	50	200
SAW (goal)	5 RACs	1000	60	100

NOTE: VHSIC = very-high-speed integrated circuit; SAW = surface acoustic wave; RACs = reflective array compressor.

AO signal processing is already a viable area with demonstrated potential in many applications of signal-analysis. AO devices provide key elements for functions such as spectral analysis, radiometers, time-integrating correlators, ambiguity-function generators, high-speed spatial light modulators for optical information processors, and synthetic-aperture-radar processing.

One current example of an analog AO information-processing device is the time-integrating AO correlator. This device uses the AO interaction to evaluate the similarity of electrical signals by encoding these electrical signals on light and then performing mathematical operations with the light. This device performs a specific mathematical function (the correlation transform) useful in signal processing at a rate several orders of magnitude greater than the fastest digital computers. The optical correlator has a variable integration time that allows signals of low signal-to-noise ratio to be integrated up out of the noise. The construction of the optical correlator uses optical minibench fabrication techniques, which allow the construction of a light, stable, and rugged optical system that can operate over wide ranges of temperature with a high degree of vibration immunity.

The correlation function is a flexible signal-processing operation that can be used to determine many characteristics of electrical signals, such as spectral content and phase with respect to a reference. With these characteristics, it is possible to identify specific signal types and determine the location or velocity of emitter platforms. There is no limitation on the source of the electrical signals that can be processed other than that their electrical bandwidth must be less than or equal to the electrical bandwidth of the correlator for the correlator's total processing gain to be used. This implies that signals from medical sensors (such as electroencephalogram or electrocardiogram) or signals from ultrasonic sensors are as "correlatable" as radio signals detected by an antenna.

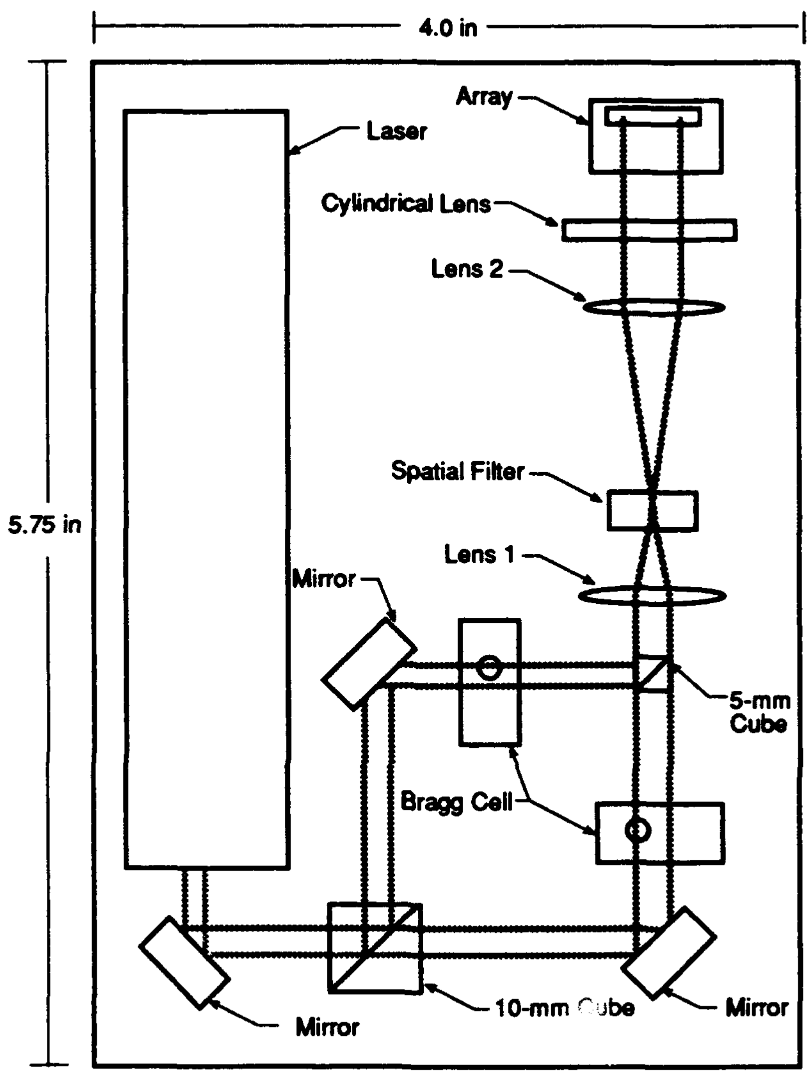
The environmental ruggedness of minibench optical processors such as the AO correlator currently allow their operation under field conditions. The device shown in Figure 22-10 has been tested in operation on random three-axis vibration-testing equipment by subjecting it to acceleration/deceleration shocks of 2 *g* from 2 to 5000 Hz. The minibench correlator pictured has also been thermally stressed from -30°C to 50°C. The correlator operated within nominal specifications for all tests.

Because of developments in materials and manufacturing technologies, it is probable that the existing minibench techniques will be superseded in 5 to 10 years by integrated-optics structures for use in most types of one-dimensional processing architectures. Any structures requiring two-dimensional detectors (two-dimensional arrays or video cameras) will still require discrete optical systems. Within 15 years, analog optical architectures should be capable of solving complex pattern recognition problems in real time. The optical architectures should be capable of being flown in or out of the atmosphere to perform on-board signal processing and target recognition.

Within 30 years, discrete optical components should no longer be necessary for most optical processing architectures; integrated-optics materials and manufacturing technologies will have solved the problems that currently limit us to hybrid source-modulator-detector optical systems. The size, weight, and power advantages of optical processing as an alternative to digital electronics for tasks such as guidance and tracking should ensure that optics has a niche in expendable systems (e.g., munitions, throwaway jammers, and man-pack systems).

OPTICAL GENERATION, CONTROL, AND DISTRIBUTION OF MICROWAVES

Optical techniques will play an important role in future RF and microwave systems because of the unique capabilities of optics for generation, control, and distribution of microwave signals (see generally Bhasin and Hendrickson, 1988). For generating microwave signals, the mixing of two lasers can provide signals modulated at frequencies that are orders of magnitude beyond the current capability (Figure 22-11). External modulators capable of phase modulation, amplitude modulation, or both have been demonstrated at frequencies beyond 40 GHz. Optical fibers are excellent waveguides for the distribution of microwave signals on optical carriers, with available bandwidths of hundreds of gigahertz. This technology is promising for use in phased arrays, in operation and control of remote antennas, in high-data-rate microwave communications, and in secure communications.



BRAGG CELL (from Crystal Technology)
2-GHZ BANDWIDTH
600-NS TIME APERTURE

DIODE LASER (from Spectra Diode Labs)
100-MW CONTINUOUS-WAVE LASER
TE COOLER CONTROL
OUTPUT POWER CONTROL

DETECTOR (from Fairchild Weston)
1,024-ELEMENT CCD
HIGH DYNAMIC RANGE (>50 dB)

PROCESSOR SIZE, 70 IN^3

FIGURE 22-10 Acousto-optical time-integrated correlator.

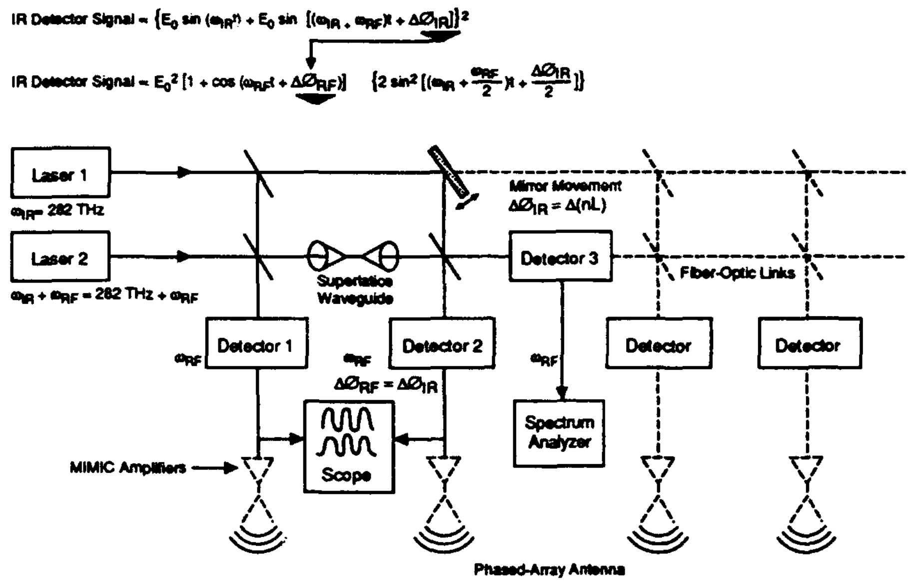


FIGURE 22-11 Optical control of microwaves.

Optoelectronic technology is maturing very rapidly, driven primarily by commercial applications. Fiber-optic communication links have been demonstrated at ranges of 100 km, and military spinoffs of the commercial market are under development. Within 15 years, fiber-optic components will be well integrated with circuitry to handle microwave frequencies; microwave and optical circuitry will be integrated on a single chip. Within 30 years, sophisticated optical computing of control signals will be incorporated for antenna-beam shaping, null steering, sidelobe suppression, and other adaptive antenna functions. Optical techniques will provide nanosecond frequency chirping, phase shifting, and beam steering. Many microwave frequencies will be multiplexed over one network.

ADAPTIVE OPTICS

Adaptive optics are designed to compensate for optical aberrations that would otherwise limit the performance of optical and optoelectronic systems. The principle of operation utilizes a wavefront sensor to measure the aberrations, which then sends electronic signals to a deformable optical element (mirror or transmissive device), which then does the compensation. The wavefront sensor obtains its signal from the target or receiver, or the signal is generated synthetically. More advanced approaches under study use nonlinear optical materials that can sense and perform the compensation in a single component.

Aberrations due to optical-system imperfections and atmospheric turbulence cause substantial signal degradation or loss of coherence in virtually all of today's optical systems. These loss factors limit performance because few systems currently use adaptive optics. Future systems, including ground-based lasers for antisatellite applications, will not perform without adaptive optics. These optics substantially increase the operating range (path length) and improve the resolution of optical systems, especially those utilizing lasers. At present the two principal approaches employ (1) discrete components and (2) nonlinear phase conjugation, as shown in Figure 22-12.

The state of the art for discrete components is

- number of channels (control elements), 2000 uncooled or 241 cooled;
- precision of wavelength and compensation, 1/20 wavelength in visible light; and
- measurement efficiency, near the photon noise limit.

Similarly, demonstrated capability for nonlinear phase conjugation is

- spatial resolution of 50 × 50 pixels;
- temporal bandwidth of 10 Hz; and
- reflectivity of >50 percent.

These numbers represent a substantial technical base, but there are few such components in use. Present systems are more suitable for laboratory and field-experiment operation; they hardly represent operational capability. In particular, the practicality of nonlinear phase conjugation, except for a few select applications, is still in doubt. New techniques are required to deal with uncooperative targets, where there may be insufficient signal to activate the wavefront sensor.

By the end of the next decade, it is anticipated that cooled adaptive-optics components, such as those required for high-power lasers, might grow to the many-thousand-channel level. It will likely take 5 to 7 years

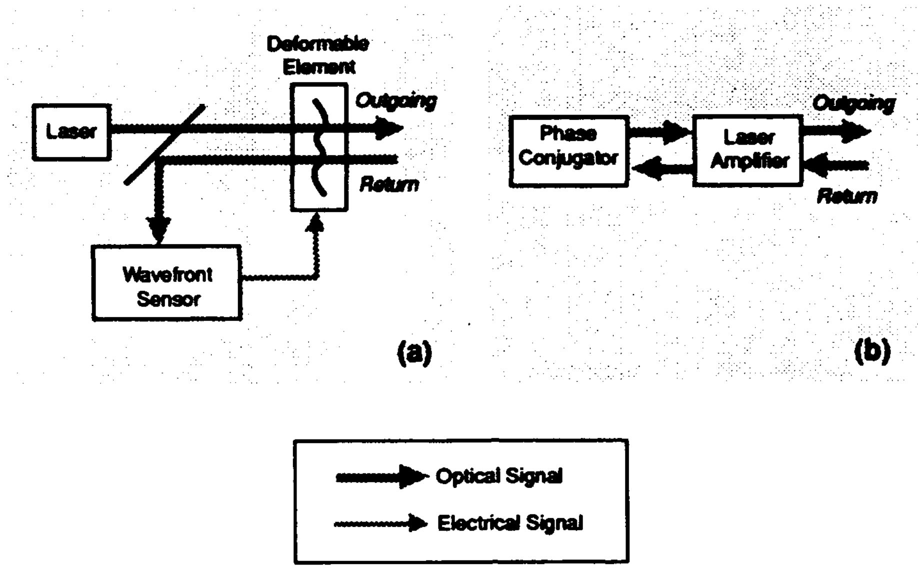


FIGURE 22-12 Adaptive-optics systems employing (a) discrete components and (b) nonlinear phase conjugation.

to demonstrate the practicality of nonlinear phase conjugation. This might be the breakthrough needed to greatly simplify and possibly "ruggedize" the approach.

The impact of adaptive optics on warfare systems will come through improvements in the performance of tactical optoelectronic systems, including:

- antisensor laser systems;
- battlefield imaging (passive);
- space-object imaging (active or passive);
- autotracking; and
- optical jammers.

Additionally, adaptive optics make possible the projection of substantial amounts of laser power through the atmosphere, for applications such as:

- ASAT (antisatellite) lasers;
- ballistic-missile defense (SDI boost- to midcourse-phase missile kill/discrimination, using relay mirrors);
- ground-to-space laser communication; and
- antitactical missile defense.

APPLIED NONLINEAR OPTICS

Second- and third-order optical nonlinearities are used to control and manipulate coherent optical beams for the protection of multifunction focal planes against lasers and for components needed to realize all-optical processing (Figure 22-13). (See generally Shurtz et al., 1989.) The degree of control and function desired can be achieved passively (derived from the beam intensity or coherence properties) or actively (through applied fields, thermal changes, etc.). Passive laser protection will be available in the 15-year time frame; advanced optical processing components, in the 30-year time frame.

The key advantages of the control afforded by nonlinear optics include:

- multifunction sensors that can operate in hostile laser environments;
- optical processing and computing components;
- very-high-density optical storage;
- high-speed image processing; and
- decisive battlefield command and control.

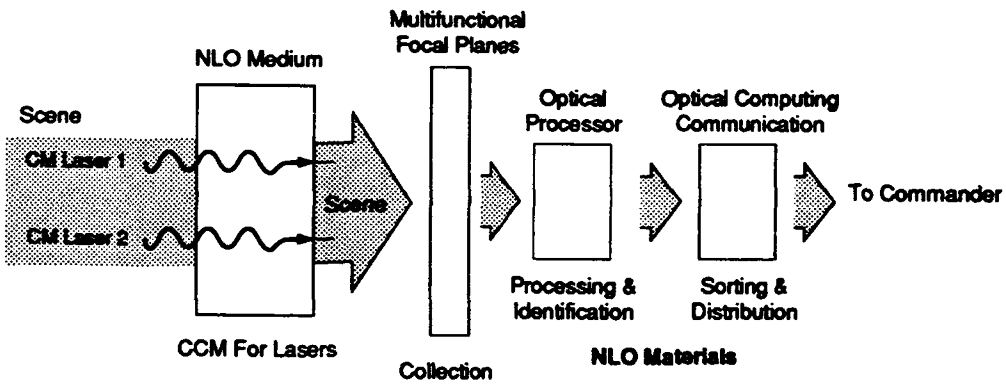


FIGURE 22-13 Nonlinear-optical controls.

The field of nonlinear optics continues to expand at a healthy rate. Organic materials are being explored for many applications formerly reserved for inorganic crystals or semiconductors. Short-pulse spectroscopic techniques are used to probe and identify new materials with superior nonlinear properties suitable for all optical applications. Photorefractive materials and phenomena have been used for many first-time demonstrations of all-optical components for processing and computing.

Passive protection against lasers, for sensors or eyes, is expected to be available in 15 years. Protection will be provided for advanced multifunction focal planes against a multiplicity of incident laser beams over a broad spectral bandwidth. Complete protection will be provided against continuous-wave- and pulsed-laser systems.

Advanced optical-processing and computer components should be available in about 30 years. The development of all-optical reconfigurable interconnects, incoherent-to-coherent converters, and spatial light modulators will allow the manipulation of imagery and permit full utilization of multifunctional focal planes. Useful realizations will include image enhancement, amplification, restoration, addition and subtraction, and storage.

BINARY OPTICS

Binary optics is a broad-based diffractive optics technology that uses lithography and micromachining to create novel optical devices and to provide design freedom and new choices of materials for conventional refractive optical elements. This optics piggybacks on advanced VLSI circuit technology and is complemented by computerized optical-design procedures.

In general, binary optics will reduce the number of elements in complex optical designs by half. It thus permits the increased use of integral optics, in which temperature-compensated seats and keys on the elements of a system are placed by the same lithography and the same precision with which the surface is shaped. This permits computer-integrated assembly of systems that require virtually no alignment.

Mass production of binary optics through replication, embossing, or molding of optical subassemblies gives it great potential for low cost. It increases the productivity and quality of broadband optical elements and pushes optical system designs further into the deep infrared and ultraviolet through diffractively compensated materials. Binary optics allows optics designers—for the first time ever—to create novel components and complex optical sensor front-ends with integrated processing (amacronics), as shown in Figure 22-14.

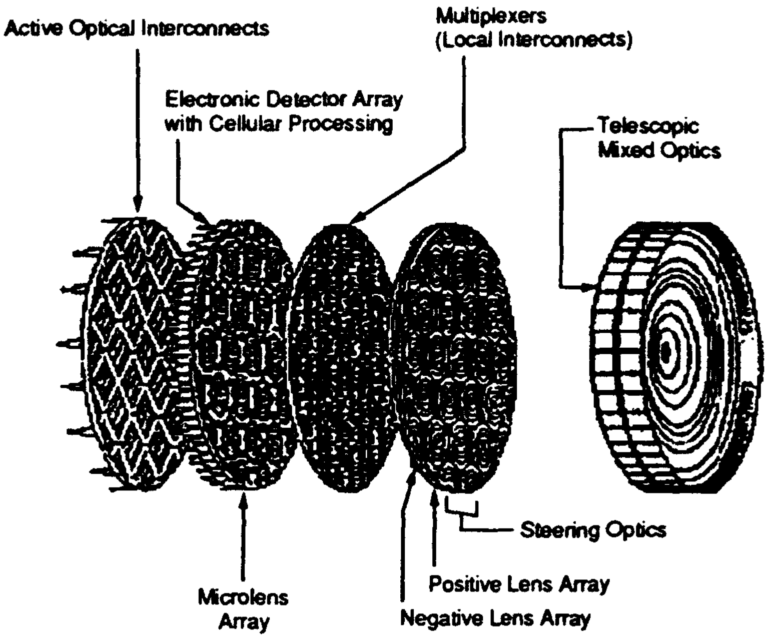


FIGURE 22-14 Amacronic-sensor technology.

Technology transfer of binary optics to U.S. industry started in 1988. Since then, over 30 optics and aerospace companies have acquired the knowledge and capability to produce binary optics. Various devices have been or are under development, such as:

- laser-beam multiplexers and beam-profile shapers;
- arrays of microlenses (with densities of 20,000/cm^2);
- arrays of coupled-laser microcavities;
- aspheric- and chromatic-corrected telescope optics; and
- agile scanners and radiation-hardened focal planes.

Since detectors, lasers, electronics, and optics can now be made using the same manufacturing techniques, future systems can be designed with a monolithic approach. For example, as shown in Figure 22-15, starting with the detector array of an infrared sensor, microlenses can be used to focus energy into subelements. This frees focal-plane area for local processing. Additionally, optical processors, optical interconnects, and steering elements can be designed integrally. This monolithic approach may not be optimal in all cases, but the use of binary optics permits ready exploration and trade-off of hybrid and monolithic approaches.

Binary optics has the potential to simplify the production of optical systems for military application. Moreover, through integration of various functions, the resulting system should be cheaper and lighter and should consume less power. Since optical systems are widespread in the Army and promise to become increasingly deployed in various smart systems, the impact of this technology will be significant.

WIDE-FIELD-OF-VIEW OPTICS TECHNOLOGY

The Army is developing the technology for optical sensor packages in support of advanced ballistic missile defense applications. These packages will be large-aperture, lightweight, radiation-hardened, staring arrays operating in the low infrared, with high resolution and a large field of view (up to 40 degrees). These technologies will include on-array signal processing and beryllium-mirror fabrication.

The advantages of sensor arrays such as these are primarily reduction of size and weight, but performance can also be increased. On-array processing accomplishes some of this and also reduces sensor noise and data-rate requirements. Analog-to-digital conversion can be performed on the sensor array as well. Survivability in a nuclear environment is enhanced, and fabrication is simplified since some beryllium optical components can be replicated without requiring additional coatings. Sensors with one or more of these desired characteristics already exist, but none combine all characteristics in a single package. Sensors with these characteristics will be applicable to several sensor missions, including exoatmospheric surveillance, exoatmospheric homing weapons, and airborne surveillance.

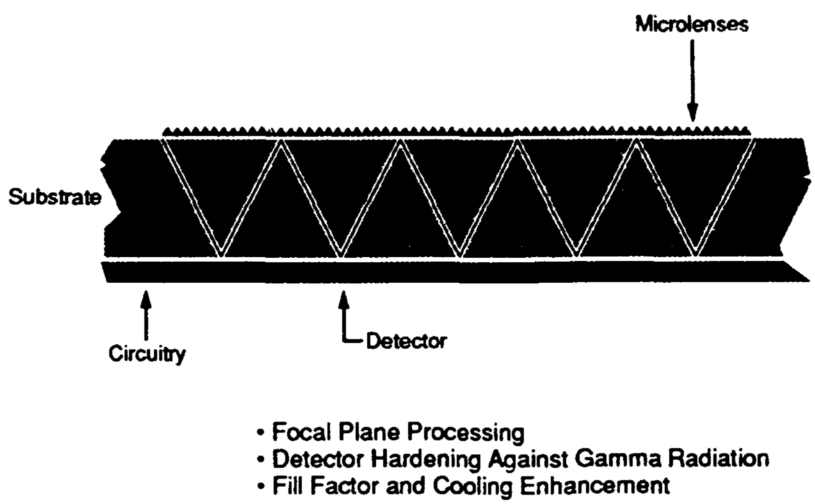


FIGURE 22-15 Optics and electronics integration.

Design work is in progress for a wide-field-of-view optics train. Hot isostatically pressed beryllium blanks have been formed at diameters of 16 cm. A 1-meter fabrication chamber has been completed. Vapor deposition of beryllium-on-beryllium has been demonstrated. Replication by physical vapor deposition on polished molds has been demonstrated, as has a subscale focal-plane array with on-array processing.

By 2020, full performance arrays will be available. These will be up to 1 meter in diameter, with a field of view greater than 40 degrees. By this time, full on-array processing will be implemented, and the entire device will be hardened to nuclear radiation, and out-of-field noise rejection will be improved over existing devices. Certainly costs will be substantially reduced by replicating optics in mass quantities.

23

Directed Energy Technologies

DIRECTED ENERGY WEAPONS

Directed energy weapon (DEW) is a generic term for a number of emerging technologies that produce concentrated electromagnetic energy or particles (atomic or subatomic) to perform offensive and defensive warfare tasks.[1] DEW technology includes:

- medium- to high-power lasers that can be used for antisensor, antimissile, antisatellite, and anti-smart-weapon applications;
- RF directed energy sources—either narrowband, high-power microwave (HPM) or wideband (video pulse)—for similar applications for jamming and/or damaging electronic equipment; and
- charged-particle-beam (CPB) devices for mine detection, mine clearing, and anti-smart-weapon and anti-nuclear-weapon applications.

Weapons based on directed energy technologies have interesting potential. DEW effects are delivered at the speed of light. This is dramatically demonstrated for high-pulse energy weapons, where damage is achieved in a single pulse. Even for thermal damage effects, the equivalent Mach number for DEWs is large. DEWs are highly directive and can achieve highly accurate "surgical" kills. DEWs potentially have a high rate of fire and a rapid "reload" capability, giving them the ability to overcome saturation attacks. DEWs have new modes of lethality, including (1) intense laser light that could blind soldiers and create a possible psychological impact on troops; (2) burnout or permanent upset of equipment over large areas behind enemy lines caused by HPM energy; and (3) defeat of salvage fusing in nuclear weapons through CPB.

Low-power directed energy devices have already been deployed in quantities in the form of laser rangefinders, laser target designators, microwave radars, and electronic-warfare devices. High-energy laser experimental systems have been developed and tested to illustrate the potential advantage of DEWs. They are exemplified by the Army mobile test unit (circa mid-1970s), the Air Force Laser Laboratory (circa 1980s), and the

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[1] High-power DEWs were also assessed by the Propulsion, Power, and High-Power Directed Energy Technology Group. Their assessments and forecasts are in Chapter 44.

Navy SEALITE program (circa mid-1980s). These service efforts and resources are subsumed in the ongoing high-energy laser programs of the Strategic Defense Initiative Organization (SDIO).

Advanced-engineered optoelectronic countermeasure systems have also been developed and field tested. Recent and continuing advances in solid-state laser technology (see "Solid-State Lasers" in Chapter 22) support the possibility for full-scale engineering decisions by DOD in the early 1990s.

The recent development of high-voltage (200 kV to 2 MV), high-current (1–100 kA), short-pulse (20 ns to 5 μs) electron-beam accelerators as microwave-tube drivers (magnetrons, backward-wave oscillators, free-electron microwave amplifiers) has made possible the production of peak powers (several gigawatts) and high energies per pulse (nearly 200 J). The recent stable outdoor propagation of relativistic electron beams (20–40 MeV, 8 kA) confirms the theoretical predictions of electron beam control to achieve stable lead-pulse propagation, one of the key issues of charged-particle-beam weapons.

Under sustained funding by SDIO, DARPA, the Department of Energy, and the DOD, DEW technologies will evolve until they have the performance required for Army missions and fit the size constraints of Army platforms. More detailed discussions of projected technology capabilities are provided elsewhere in this report. See "Solid-State Lasers" and HPM technology under "Directed Energy Weapons" in Chapter 22, and "Free-Electron Lasers," "Laser Antisatellite Systems," and "Compact Accelerators" in this chapter.

In the future, maturing DEW technologies will enable the Army users to obtain hands-on experience with DEW prototypes and to develop better operational concepts. As DARPA and the Army continue to incorporate models and effects of DEWs into the Simulation Network (SIMNET), the Army user will be able to safely evaluate DEW doctrine, tactics, and training issues in simulated combined-arms warfighting.

Current DEW warfare systems primarily threaten unprotected sensors and electronics. Weapon systems therefore need to be retrofitted with sensors and electronics hardened against existing and future DEW threats. The impact of the increased cost and the degradation of performance involved in this retrofitting has not been fully assessed. The logistic impact, the enhanced survivability impact (especially in compressed engagements), and the force-multiplier impact of employing DEW adjuncts and dedicated DEW platforms in combined-arms warfighting have not been fully assessed.

LASER ANTISATELLITE SYSTEMS

A laser ASAT system, sketched in Figure 23-1, consists of the following critical technologies:

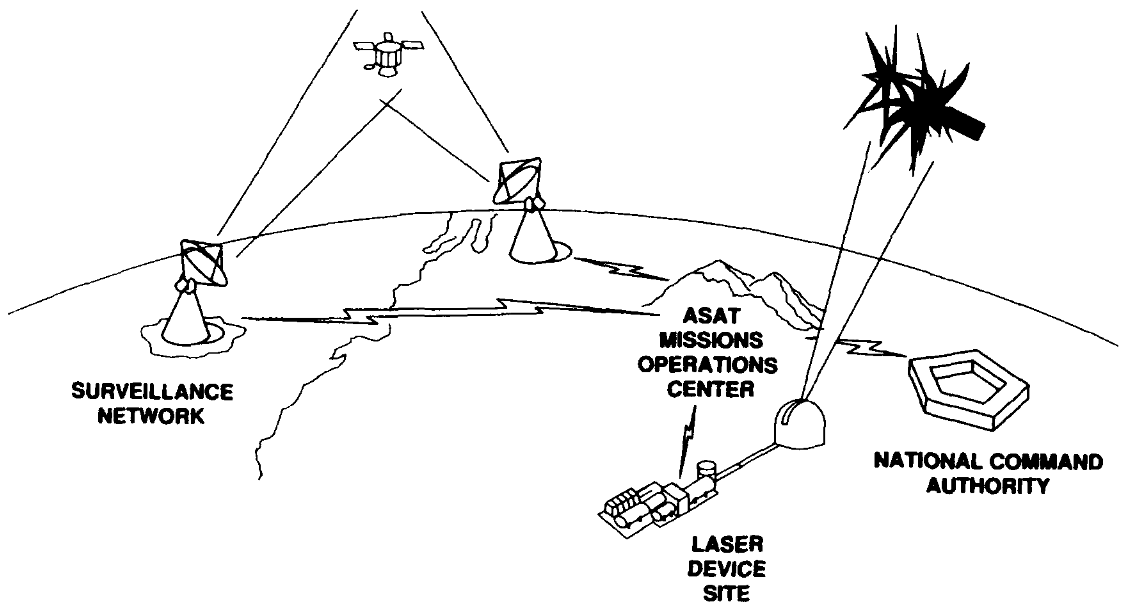


FIGURE 23-1 Laser antisatellite (ASAT) system.

- satellite surveillance network;
- target-acquisition and precision-tracking subsystem;
- high-power laser; and
- adaptive-optics and precision-beam-control subsystem.

The satellite surveillance network consists of microwave radars and communication subsystems, two technologies that are well developed. Laser radar technology is sufficiently mature to provide the required precision target tracking (see Chapter 21, "Optical Sensor and Display Technologies"). The major high-power laser technology candidates are chemical lasers and free-electron lasers (FELs; see next section). Both the high-power laser technology and adaptive-optics technology are under development by SDIO. More specifically, the Army is developing a ground-based FEL at the White Sands Missile Range as part of the SDI program. This system, when completed and augmented by advanced adaptive-optics technology, can be used to evaluate the potentials of a ground-based laser ASAT system.

Increasingly, armies will depend on space assets to support ground commanders. The objective of the ground-based ASAT system is to achieve space control, a warfighting mission of the U.S. Space Command and its components. Such a system would provide capability that complements the ground-based kinetic-energy ASAT. The laser ASAT is likely to be more effective than other ASAT systems against satellites at high altitudes that have maneuverability. The other advantage of a ground-based laser ASAT is a large, nearly unlimited magazine (reduced logistic burden and increased "shoot-look-shoot" capability). In addition to reducing, perhaps eliminating, enemy space surveillance, targeting, and command and control capability, a laser ASAT system could be used to perform other missions such as fixed-site theater missile defense and long-range air defense.

No operational ground-based laser ASAT has yet been deployed. An experimental system at White Sands consists of a chemical laser operating at 3.8 μm and the SEALITE beam director. This system can be upgraded to evaluate some of the thermal-blooming, defocusing, and atmospheric-compensation issues associated with a ground-based laser ASAT. In the laboratory, FELs have produced kilowatts of power (over short bursts) at visible wavelengths. The beam-control components are in various stages of development. Although the basic physics of FELs and advanced adaptive optics have been proven, substantial engineering efforts still remain.

Construction of the ground-based FEL test at White Sands has begun. The laser device design and construction began in FY 1990. By 2020, sufficient laser power is expected to be available in a package small enough to allow fixed sites to be deployed in a theater of operations, each with the capability to produce a destructive, line-of-sight hard kill of any satellite in low or medium earth orbit (up to an altitude of several thousand kilometers). These fixed sites would also have an adjunct capability against tactical ballistic missiles. Mobile devices would be available at lower power, sufficient to jam or destroy satellite sensors; they would be capable of moving with the units they support. In addition, if space-relay optics are available (as part of a deployed Strategic Defense System, for example), a hard-kill capability against targets in geosynchronous orbit would also be provided, working in conjunction with the high-power fixed sites.

FREE-ELECTRON LASERS

High-energy lasers have been of interest to the military since lasers were first invented in 1960. One of the newest varieties to be developed is the FEL. This device uses a high-energy accelerator to create an intense stream of electrons. The stream is directed through a series of alternating magnetic fields (a "wiggler"), causing the electrons to emit coherent electromagnetic radiation of a wavelength determined by the speed of the electrons (their energy) and the strength of the magnetic fields (wiggler period). Since these parameters are continuously variable, an FEL is theoretically tunable anywhere on the electromagnetic spectrum, from long-wavelength microwaves to short-wavelength x-rays. Because the entire process takes place in a vacuum, the output power and beam quality are not limited by self-distortion mechanisms common to conventional crystal or gas lasers. The pulse format is easily controllable, since it is determined by the shape of the electron pulses produced by the accelerator.

The unusual characteristics of the FEL give it some distinct advantages over conventional lasers. These include:

- efficient (>25 percent) production of very high output powers;
- broad continuous tunability;
- excellent beam quality; and
- straightforward logistic support, because they are electrically powered.

Two approaches to the FEL are under development by the Army through funding from SDIO (Figure 23-2). One approach uses an RF accelerator to produce the electron beam, and thus is called an RF FEL. The other uses a linear induction accelerator to produce the beam, and so is termed an induction linear accelerator FEL. Both have demonstrated sufficient electron-beam brightness for operation at high power, and both have been operated at a variety of wavelengths with reasonably high efficiency. Peak output powers in excess of 10 MW have been demonstrated, and average powers in tens of kilowatts have been achieved for short durations. Construction of a major test facility has begun at White Sands Missile Range. Many of the high-power components (such as electron photoinjectors, pulsed and RF power supplies, high-power accelerator cavities, and automated controls) have been demonstrated in prototype form.

By 2020 (assuming the SDI support), the Technology Group expects that multiple FEL ground sites will be deployed, with a corresponding constellation of space-relay optics capable of handling the substantial optical power produced by the devices. These will be capable of intercepting and destroying missiles during the initial boost phase of their flight. Accelerator and wiggler components will be small enough to consider an operational

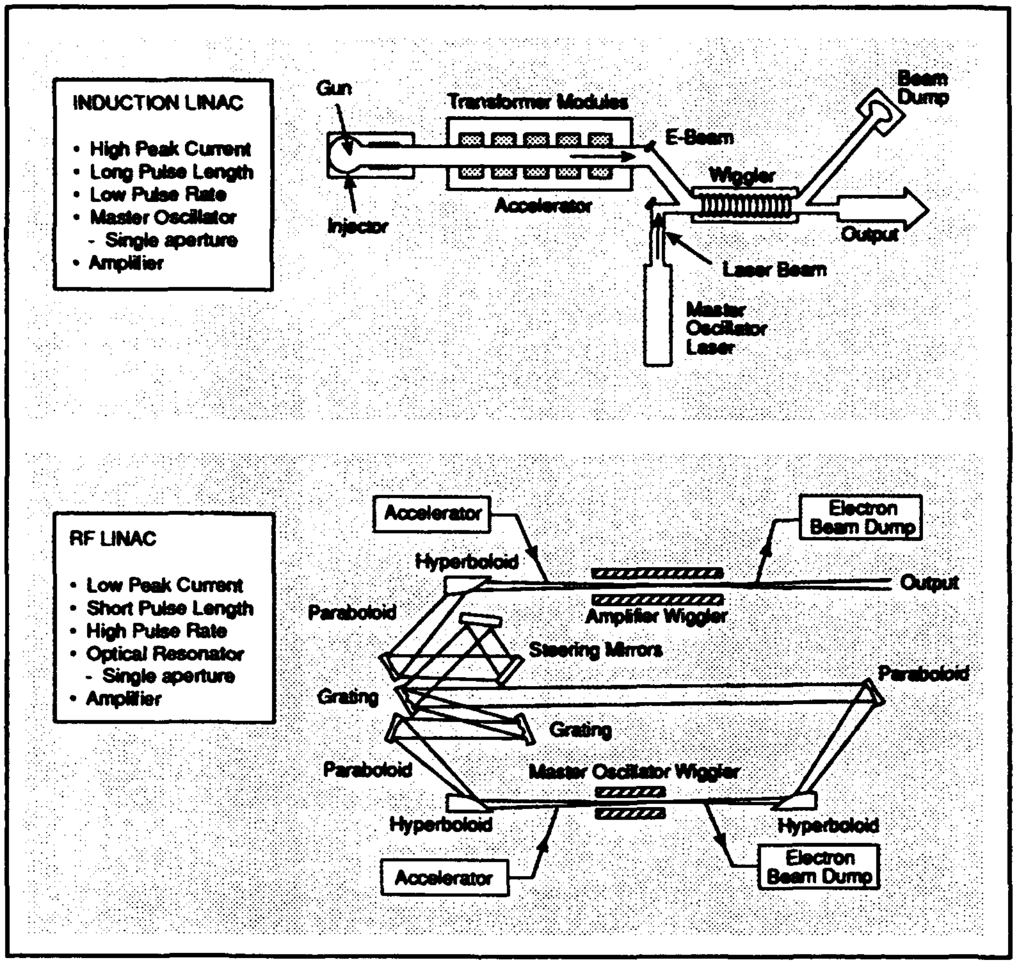


FIGURE 23-2 Free-electron laser concepts.

space-based platform, as well as mobile surface or airborne basing. In the tactical arena, coherent high-power microwave beams based on an FEL will be available in the multimegawatt class. A deployable laser ASAT system based upon FEL technology and advanced adaptive-optics technology could provide a theater commander with means to jam or destroy an enemy's space surveillance, targeting, and command and control assets. Extended air defense or fixed-point defense in rear areas can include a line-of-sight laser weapon. Wavelength agility will be built in to overcome sensor-hardening countermeasures.

RADIO-FREQUENCY DIRECTED ENERGY TECHNOLOGY

Electron-beam accelerators have been developed that are capable of high-voltages (200 KV to several MV), high currents (1–100 kA), and short pulses (10–1000 ns). Their use as microwave tube drivers has facilitated the evolution of conventional microwave sources, such as magnetrons, klystrons, and backward-wave oscillators into more powerful sources. The result has been the production of HPM tubes that use intense, relativistic electron beams to produce narrowband, RF output power levels of several gigawatts and output energies per pulse as high as 200 J.

The former USSR produced pulses with power and energies two to three times higher. Their microwave tubes functioned in the frequency regime between 1 GHz and 35 GHz and, for the most part, operated in single-pulse mode. A newer development in this country is the solid-state switch that produces high-power wideband RF (video pulse) and can operate in the repetitive pulse mode (10–100 Hz) in the frequency regime of 100 MHz to 1 GHz. Power-conditioning and antenna technologies are also under development. All phases of RF DEW technology require increased effort to reduce size and weight and to increase efficiency, power or energy, and power-handling capability.

High-power and high-energy RF sources will allow the development of a new class of DEWs in which adiabatic burnout of electronic components and, in some cases, detonation of electroexplosive devices, will cause permanent damage to critical electronic and optoelectronic subsystems. There is also the opportunity to produce effects less severe than burnout, such as permanent upset or degradation of analog and digital circuits, which would also result in a mission kill. These effects have been observed and measured in U.S. laboratories for several years; a national data base of effects has been assembled and is maintained by the interagency RF DEW community.

Figure 23-3 shows the current capabilities of both U.S. and Soviet narrowband (HPM) sources. Projected capabilities under development include:

- efficient, injection-locked, modular, magnetron microwave sources (200 MW, 3 GHz, 1 μs) under development for incorporation into fixed antenna arrays capable of tens of gigawatts and tens of kilojoules of output per pulse;
- efficient multiwave (overmoded) Cherenkov microwave sources (15 GW, 6 GHz, 1 μs) in single devices capable of generating several kilojoules of RF energy per pulse;
- several other narrowband (HPM) sources with kilojoule capability and with repetition rates of several tens of hertz;
- power supplies and modulators for these devices designed to weigh under 1000 lbs;

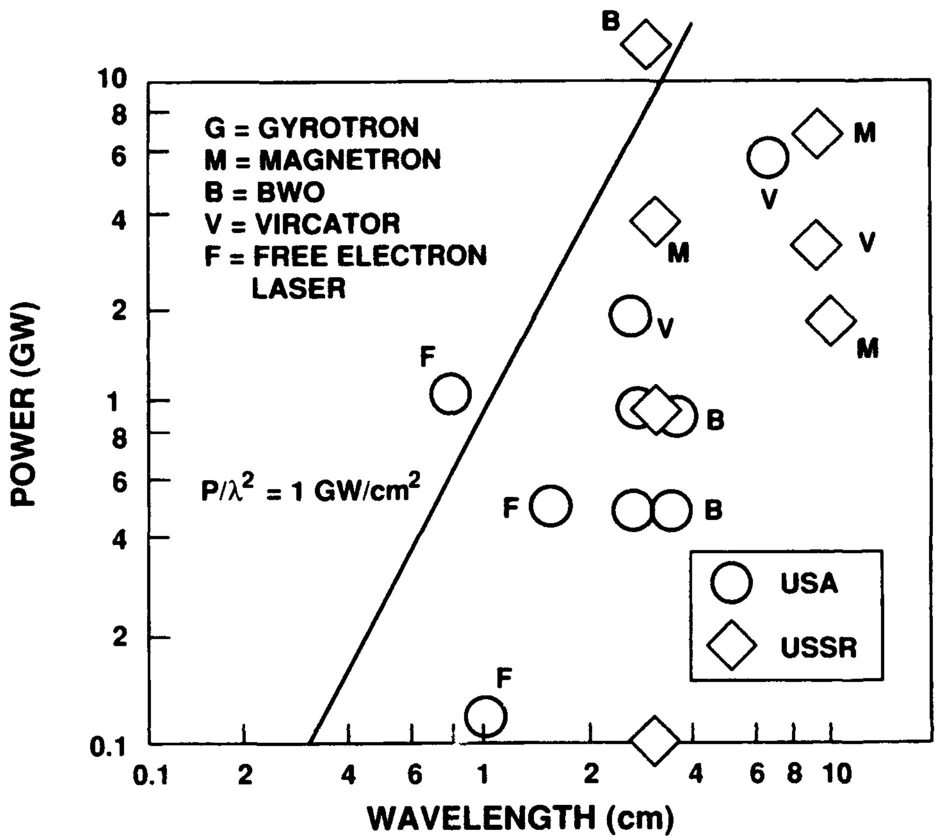


FIGURE 23-3 Radio-frequency directed energy weapon capabilities of the United States and the former USSR.

- antenna sidelobe control of up to 40 dB; and
- solid-state devices coupled to wideband radiators, allowing high-power systems with kilohertz repetition rate capability and steerable beams.

HPM sources possibly will be used as electronic countermeasures (causing burnout, permanent upset, or premature detonation) against the following targets:

- smart munitions;
- antiradiation missiles;
- scatterable mines;

- fixed- and rotary-wing aircraft;
- radar-guided and infrared-guided missiles;
- communication nodes; and
- remotely piloted vehicles.

COMPACT ACCELERATORS

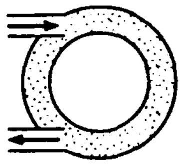
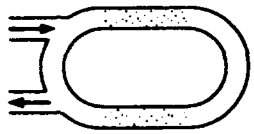
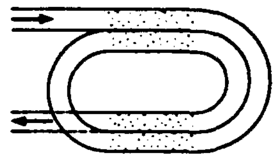
Accelerating charged particles is a recent scientific pursuit that had its beginnings in the early 1930s. Use of accelerators in roles other than scientific (e.g., high-energy physics) experiments did not begin until the 1960s. In the 1970s, the DOD (led by the Navy in its CHAIR HERITAGE Program) started to investigate the usefulness of these devices as charged-particle-beam (CPB) weapons for point defense applications. In the 1980s, first DARPA and then SDIO funded the development of linear induction accelerator technology at the Lawrence Livermore National Laboratory and RF accelerator technology at the Los Alamos National Laboratory, as well as at Boeing Company Laboratories.

The basic concept underlying the compact accelerator is to bend the linear transport section of a linear induction accelerator into a spiral or circular geometry, so that the same accelerator module can be used to accelerate the same swarm of particles repeatedly (see Table 23-1). Implementing this concept requires new developments in technologies for beam transport, pulse power, and fast switching. Without compact accelerators, however, CPB weapons, HPM devices, and FEL sources will not be practical.

The Naval Research Laboratory (NRL) is currently developing the modified Betatron with Navy 6.1 and 6.2 R&D funds. Recently, researchers at NRL showed that it is feasible to inject the beam: the beam-trapping efficiency is as high as 75 percent, and the approximately 0.4- to 0.5-kA trapped beam has been accelerated from 0.5 MeV to more than 10 MeV. Injection and extraction at higher currents and voltages remain critical issues.

DARPA is supporting the development of two future compact accelerator designs: the spiral line induction accelerator and the ion-focused recirculating racetrack (IFRR) options. Assuming steady funding, a critical milestone for both designs will be to achieve 8 MeV and 10 kA with a pulse width of 35 ns by the end of FY 1992. A second benchmark is the achievement of a multipulse, 50-MeV, 10-kA compact accelerator by FY 1994-95.

TABLE 23-1 Compact-Accelerator Options

	 Modified Betatron	 Ion-Focused Recirculating Racetrack	 Spiral Line Induction Accelerator
Accelerating section	Circular	Straight	Straight
Transport mechanism	Magnetic	Ion-focused recirculation	Magnetic
Type of accelerating field	Continuously ramped (slow pulses)	Pulsed to reset cavities	Pulsed to reset cavities
Core type	Air core	Dielectric cavity	Ferrite cavity
Injection/ extraction	Issue	Issue	No issue
Repetition rate (multi-pulse)	Issue	Minor issue	No issue
Number of passes	100 to 1000 (limit is time to accelerate versus interpulse spacing)	6 to 8 (limit is deterioration of pulse shape)	3 to 19 (limit is complexity and number of beam lines)

Defense applications of compact accelerators, at increasingly higher accelerator currents and voltages, include:

- radiation processing of food;
- mine detection;
- mine negation;
- efficient, high-power microwave generation (HPM weapon);
- efficient, high-power FELs (ASAT, BMD); and
- CPB weapon (terminal defense).

References

Berg, J.J., and J.N. Lee. 1983. Acousto-Optic Signal Processing: Theory and Implementation. New York: Marcel Dekker, Inc.

Bhasin, K.B., and B.M. Hendrickson, eds. 1988. Optoelectronic Signal Processing for Phased-Array Antennas. Proceedings of the Society of Photo-Optical Instrumentation Engineers, vol. 886

Casey, H.C., Jr. 1986. Semiconductor Laser Sources and Detectors at Wavelengths of 0.67, 1.77, 1.93, and 2.50 μm. Report HDL-CR-86-100-1. Adelphi, Md.: U.S. Department of the Army, Harry Diamond Laboratory, September.

Gupta, N. 1989. Diffuse Reflectance Measurements of Foliage and Target Samples. Report HDL-TR-2155. Adelphi, Md.: U.S. Department of the Army, Harry Diamond Laboratory, January.

Keller, J.J. 1986. Central office equipment makers preparing for big push. Communications Week. 24 February:C2.

Kelly, J.J. 1986. Central office equipment makers preparing for big push. Communications Week. 24 February:C2.

Killinger, D.K. and N. Menyuk. 1981. Remote probing of the atmosphere using a CO_2 DIAL system. IEEE Journal of Quantum Electronics. QE-17(9):1917-1929.

NRC. 1988. Photonics: Maintaining Competitiveness in the Information Age. Board on Physics and Astronomy, National Research Council. Washington, D.C.: National Academy Press.

Shurtz, R.R., II, E.J. Sharp, G.L. Wood, and M.J. Miller. 1989. Advanced Optical Hardening Concepts: A Technology Assessment. 23rd IRIS-IRCM III:237 (1985). DARPA Optics Review 1989. Warrenton, VA. August 22–25.

Smith, P.W. 1982. On the physical limits of digital optical switching and logic elements. Bell System Technical Journal (subsequently changed to AT&T Technical Journal). 61(8):1975–1993.

Sztankay, Z.G. 1987. Backscatter from Clouds and Aerosols at 0.9 μm and Its Effects on Active Sensors. Report HDL-TR-2114. Adelphi, Md.: U.S. Department of the Army, Harry Diamond Laboratory, January.

Toda, M., T.J. Zamerowski, I. Ladany, R.U. Martinelli. 1987. Laser Materials for the 0.67-μm to 2.5-μm Range. Report HDL-CR-86-351-1. NASA Contractor Report 4050. Adelphi, Md.: U.S. Department of the Army, Harry Diamond Laboratory, March.

PART V

BIOTECHNOLOGY AND BIOCHEMISTRY

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Summary of Findings for Biotechnology and Biochemistry

Discoveries, inventions, and breakthroughs in the field of biotechnology are occurring at an ever-increasing rate. The application of biotechnology for military purposes in the next 30 years will be driven by the choices made when allocating research and development (R&D) resources, rather than by accidents of discovery. The potential exists for the Army to revolutionize its capabilities by exploiting major advances in biology, chemistry, physics, mathematics, and engineering as they converge to support the maturation of biotechnology.

Relative to other technologies with military application, biotechnology can be characterized as:

- the newest and most immature;
- the most rapidly expanding in terms of discoveries, inventions, and applications;
- the most rapidly changing in terms of perceptions about its importance; and
- the technology based on the widest number of scientific disciplines (physical and life sciences, mathematics and engineering, and manufacturing technologies).

Biotechnology presents both unusual opportunities and problems for the Army. The opportunities, which could revolutionize U.S. military capabilities, will also be exploited by hostile forces to develop new threats. A number of factors will contribute to the development of military capabilities that employ biotechnology:

1. The information on discoveries and applications (i.e., publications, patents, or other indicators) is more widely dispersed than in other areas of militarily relevant science.
2. The physical scale of laboratories and specific equipment required to develop weapons or countermeasures from these technologies is smaller than for conventional technologies.
3. The capital investment and sophistication required to construct research facilities are low. The field is scientist-intensive rather than equipment-intensive.
4. The production and process technologies involved in the manufacture of biomaterials will become highly automated, which will increase access to biomaterials by developing countries who will be able to purchase subsystems requiring less technical competence to manage and maintain. The requirement

for highly trained technicians in this field will diminish in the next 30 years as it has in other fields following several decades of rapid technological growth.

The Army cannot afford to ignore either the increased capabilities, or the increased threat, that will result from advances in biotechnology. The products of the biotechnology explosion in the next decade will serve the Army well. Numerous studies of biotechnology futures have been sponsored or initiated by Arr commands with centralized biotechnology program management, but these studies have had a tactical focus. This report on technology forecast assessments (TFAs) is the first strategic biotechnology study to outline choices of resources and outcomes for the Army in view of the likely research developments over the next 30 years.

The purposes of this report are to provide policy-makers with adequate information and to serve as a guide for the Army biotechnologists. The report is arranged in a series of TFA papers, each of which can be read individually. The Army decision-maker will have to use these papers as the basis for understanding the section entitled "Opportunity Road Maps: How to Get There." The road maps lead to the most important products for each of seven high-payoff opportunities that biotechnology can offer the Army.

A section preceding the road maps ("Where to Go: The Seven Highest-Payoff Biotechnology Applications") is intended for research planners; for each of the seven areas, technical reasons are given for why research investment now and across the next 20 years will lead, within 30 years, to the development of extremely important products. An eighth opportunity—certain to have high payoff—is handled as a separate chapter, "Biotechnology and Countermeasures Against Chemical and Biological Warfare."

The 1972 Biological Warfare Convention[1] was consulted and adhered to during this Technology Group's deliberations and in this report. The convention prohibits the development of microbial or biological agents for use in weapons or equipment for hostile use. This prohibition encompasses the production, acquisition, and retention of such agents. The convention also prohibits similar uses of toxins. A toxin is generally understood to be a

[1] The formal title is the *Convention on the Prohibition of the Development, Production, and Stockpiling of Bacteriological (Biological) and Toxin Weapons and Their Destruction*. The United States is a signatory to both this convention and the June 17, 1925, *Protocol for the Prohibition of the Use in War of Asphyxiating, Poisonous or Other Gases, and of Bacteriological Methods of Warfare* signed in Geneva, Switzerland, on June 17, 1925. The United States also participates in the five-year reviews of the 1972 convention, the last of which was held in 1991.

naturally produced product of an organism that is poisonous when present in the tissues of another organism. The convention does not prohibit the use of organism-produced materials that are not toxins.

In its forecasts of potential military uses of biotechnology, the Technology Group has used the term "antimateriel product" to mean a product of living organisms that does not fall within the categories prohibited by the 1972 convention. Thus, microbes or other living organisms and toxins produced by organisms are specifically outside the bounds of antimateriel products.

The legal issues of adherence to the 1972 convention and other treaty obligations become more complex when one considers applications for biotechnology products where the intended use is not harmful but harm might occur as an accidental side effect. Another dimension of complexity arises when a product can be produced by either conventional chemical processes or by bioproduction (possibly involving bioengineered organisms). Would the chemically produced material be allowed in applications that might cause harmful effects through accidental exposure, although the same material from a bioproduction process is prohibited?

Some of the more interesting and novel applications for antimateriel products are sometimes described by the research community as having "soft kill" capabilities when used against vehicles or other systems. This term implies that the application renders the targeted system inoperable or ineffective without breaching it structurally, as an explosive charge or ballistic round might. The term, which is also applied to uses of lasers as antisensor weapons, is in contrast to "vehicle hard kill." As used in this report, "soft kill" refers only to vehicles or systems and not to killing or harming human beings or any other organism.

For the reader with limited knowledge of life sciences, this Part includes a "Biotechnology Tutorial" (Chapter 31), a "Biotechnology Glossary" (Chapter 32), and a "Biotechnology Human Resource Forecast" (Chapter 33).

The tutorial and glossary were extracted with permission from *Biotechnology: Opportunities to Enhance Army Capabilities* (Army Materiel Command, 1989). The manpower forecast was written by David W. Morris, a contributor to the STAR Study. Biographical sketches of the authors and contributors to this Group are in Appendix B of this volume. In addition to these sources, the Technology Group also recommends several other general sources on the field of biotechnology generally and Army applications of biotechnology: the *Army Technology Base Master Plan* (U.S. Department of the Army, 1990), *Biotechnology: An Industry Comes of Age* (Olsen, 1986), *Biotechnology: Bridging Research and Applications* (Kamely et al., 1990), and *Opportunities in Biology* (NRC, 1989).

These TFAs were written for the technically oriented reader and concentrate on scientific advances in biotechnology and biochemistry needed to reach the 30-year targets. The report was originally intended to serve as guidance to the STAR Systems Panels, and the language used is related to their mission orientation. The report also identifies nonbiological technologies that are synergistic or even, in instances, required to develop the full potential of the technologies under discussion.

To identify candidates for the selection of the highest-payoff applications and opportunities, this Technology Group made extensive use of the terms of reference and early drafts of working papers from the STAR Systems Panels. A separate section entitled "Systems Panels Matrix" describes the evaluation process used to make the selection.

This Group decided to use a modified Quality Function Deployment (QFD) process to reconcile and balance the scientific *technology push* possibilities with the Army's *requirements pull* to meet its future needs. The Group chose not to evaluate current programs, either U.S. or foreign, but to assume that the Army choices can and should include both, as argued below, in the section on "Foreign Cooperative Research Efforts."

The Group first concentrated on biotechnology and biochemistry areas *not* being pursued in the Army or at *university-level* research centers if they were found to satisfy both of the following conditions: (1) identified with specific high-payoff opportunity that was Army intensive, and (2) required at least one "leapfrog" research discovery. The Technology Group's specific recommended high-payoff opportunities had to be characterized as *technology push* and not evolutionary. Thus, it was necessary to find either a new subtechnology that needed to be invented or some synergism with potential technological inventions identified by other STAR Technology Groups—or Systems Panels.

The QFD method was used to create a matrix linking the outlines of the specific mission-oriented study reports from the Systems Panels with this Group's TFAs. The Group created a matrix for each systems area, extracted all biotechnology and biochemical possibilities applicable to them, and matched these potential applications against its technology forecast selections. The Group selected the seven highest-priority Army-intensive applications, as well as one or two key products possible from three supporting technology areas for each. A *road map* was then created for each of those seven areas, covering the next 30 years.

Each road map shows time points and decision requirements for the Army (as opposed to the private sector) to commit resources needed to accomplish the application's goals. The Group also consulted an independent expert in biotechnology manpower, David W. Morris, to assess the educational requirements for the science, to assess the sources of scientific talent, and to assess the anticipated times in the next 30 years when the human resources will be available to the Army. This contribution, which is included here as Chapter 33, "Biotechnology Manpower Forecast: The Science, the Talent—Concerns for 2020," concludes that the lack of trained academically oriented scientific manpower will be as much a rate-limiter to progress as technology itself.

The road maps at the end of this report are not meant to be the end points of this effort. Although they respond to the STAR terms of reference, they do not include the costing and manpower resource requirements an Army decision-maker would obviously need prior to funding a research initiative.

EXPLOITATION OF CAPABILITIES

The chances for success in achieving biotechnology goals require a fundamental appreciation of the basic sciences and engineering, including molecular biology, nucleic acid and protein chemistry, immunology, infectious diseases, and process engineering. Thus, program management best resides in technical domains such as the U.S. Army Materiel Command and the Medical Research and Development Command. In-house technical expertise will be necessary to leverage technology developments in foreign as well as domestic private sectors. Furthermore, some foreign military biotechnology programs currently lead U.S. military and private-sector programs and can be targeted for leveraging. With proper interface between the Army and outside resources, the possibilities for amplification of results based upon relatively small investments are high.

The Army has the seed capability for these interfaces. The Medical Research and Development Command directs approximately 10 percent of its grants and contracts to about two dozen academic institutes and also manages research in nine overseas laboratories. All of these programs are highly mission-oriented, mostly in areas that relate to defenses against the two key medical threats identified by the history of warfighting and by all projections of future needs: infectious disease and chemical, toxin, and biological (CTB) agents. The existing programs are healthy, and their strength offers unique opportunities to acquire needed additional technology from growing or leading-edge medical research facilities overseas. Most of this research is in biotechnology as we define it.[2]

Other, larger efforts in biotechnology materials and processing research in a number of Army and Department of Defense (DOD) components are described in the *Critical Technologies Plan* (DOD, 1991). Subprograms in the fields of biosensors (e.g., chemical/biological warfare detection), bioprocesses (e.g., chemical warfare decontamination and hazardous waste remediation), biomaterials (e.g., bioadhesives, radionuclide separation systems, room-temperature explosives, low-cost manufacturing, and

[2] An explication of primarily medical projects and foreign biotechnology acquisition opportunities can be found in the Army Science Board Summer Study of 1989 (not repeated here, but accepted by reference; see Army Science Board, 1989).

microencapsulation), and bioelectronics (real-time fermentation and biological process control) were specifically reviewed for this study.

ESTABLISHMENT OF WORKING GROUPS

The Army should consider the establishment of more joint military technical working groups. The membership could include foreign military or civilian liaisons or staff as jointly selected by military services and other government agencies. Membership of such joint research teams should include working-level scientists as well as program managers or eminent senior scientists. It is the Technology Group's contention that the future can be seen better by including the perspectives of those at the research bench in technology projections.

FOREIGN COOPERATIVE RESEARCH EFFORTS

Although numerous studies within DOD have identified England, France, Japan, and Israel as countries in which militarily significant biotechnology projects often lead U.S. laboratory research, less than 2 percent of Army biotechnology resources are currently being spent in international cooperative research.

While preparing this report, the Group evaluated programs in most important foreign biotechnology academic and private-sector laboratories and concentrated on nonpharmaceutical efforts. The Group identified two generic barriers to serious cooperative research in biotechnology. These are barriers that are often used as excuses to avoid foreign relationships: (1) the fierce control of foreign military authorities over free exchange of personnel and project data in biotechnology, usually in biocomposites (synthetic fabrics, explosives, radionuclide separation technology, and stealthy materials produced by biologicals); and (2) a primary interest in turning discoveries into licensing and profit-oriented opportunities. But the Group also identified some advantages in leveraging foreign biotechnology research efforts:

- Certain defensive military applications of biotechnology are more advanced in foreign countries, due, primarily, to the closer cooperation that exists between academic and military communities. The dichotomy between technology push and requirements pull is better addressed by foreign countries through a closer association between academic and private laboratory researchers and their military requirements community.
- Certain other critical areas in which the United States does not lead in biotechnology development can benefit from specialized biotechnology developments. For example, Japan is generally considered to be a leader in

the development of algorithms for real-time microenvironmental control of bioreactor process technology. Nonetheless, some U.S. corporations are rapidly increasing scale-up capabilities for large-quantity batch processing.

The Army cannot afford to duplicate expenditures and efforts in all areas of Army interest. A strategy must be developed to leverage biotechnology programs, such as the above, to maximize return on U.S. R&D investment dollars.

CHEMICAL, TOXIN, AND BIOLOGICAL WARFARE DEFENSE CAPABILITIES

The Group believes that chemical, toxin, and biological warfare (CTBW) will grow as a threat. CTBW can provide a significant advantage to an aggressor, and deterrence is best achieved by a system of countermeasures that eliminate the efficacy of CBT agents. These countermeasures include (1) detection and identification, (2) physical protection, (3) medical prophylaxis and therapy, and (4) decontamination. Biotechnology will prove pivotal in developing all four categories of countermeasures, greatly enhancing the Army's ability to deter and defend against CTBW threats.

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Biotechnology Attributes and Applications

The realm of biotechnology stands today where the realm of electronics stood when solid-state devices began to replace tubes. Biotechnology will change nearly every aspect of our lives; and it will change the way war is waged. Today, biotechnological successes are most prevalent in the areas of medicine and pharmaceuticals, agriculture, and the bioproduction of unique "natural" chemicals such as sweeteners and solvents. In the future, our capabilities will include large-scale bioproduction from generic, nonspecial feedstocks (beyond the pharmaceutical and fermentation capabilities we now have); the design and synthesis of novel biomaterials; the capability to functionally link biological molecules with electrical, optical, or mechanical systems; the ability to selectively improve or change life forms; and the ability to decontaminate the environment.

Today we work reactively on better treatments and prophylaxes for new diseases as they are discovered and for old ones as they mutate and develop resistance. In the future, we could be able to fortify the human immunological shield, perhaps through genome manipulation, to categorically and preemptively protect against all potential disease variants and CTBW threats in all global areas. Today we reproduce or modify things we find in nature. In the future, we will be able to design completely unique new substances and altered organisms of varying complexity. The boundaries of achievements will be determined primarily by the natural laws of physics, chemistry, and biology, and, in some countries, by human laws. The rate of achievement will be determined by the laws of funding and the availability of bright, highly trained young scientists.

If these things are to be considered possible, it is proper to question just what distinguishes biotechnology from other technologies and provides the basis for these ambitious expectations. Some of the unique characteristics of biotechnology are reliable complexity, available conditions, specific activity, compact systems, and improved performance.

RELIABLE COMPLEXITY

Biological systems perform complex, repetitive syntheses—such as transcription of deoxyribonucleic acid (DNA) to ribonucleic acid (RNA) and synthesis of biomolecules on RNA templates—with few errors and no appreciable side products compared with "chemical" synthesis. This permits the routine and reliable production of complex substances, with few contaminants and fewer requirements for purification. These features are important for the production of substances ranging from medicine to fuel to food to biopolymers. Moreover, biological systems can detect errors and generally correct them automatically for critical systems.

AVAILABLE CONDITIONS

For the Army applications discussed in these reports, biochemical reactions (e.g., biochemical bond formation, scission, and rearrangement) take place under relatively mild conditions of temperature, pressure, pH, and so on, compared with most chemical industry processes. This means that biosynthesis or bioproduction processes can be safer and cheaper, and require lower energy inputs, much lower temperatures, less critical operating conditions, and a less complex apparatus.

SPECIFIC ACTIVITY

Biomolecules typically have highly complex and sophisticated structures, which impart capabilities for very precise and sensitive recognition of other compounds. This complex structure can also be a weakness if functioning in a harsh environment is required. However, if properly harnessed, these recognition capabilities can provide highly selective detection of target compounds. The complex structures of biomolecules can also impart a capability to act specifically (e.g., to seek out, attach, or bind; to make or break a chemical bond; and to alter target compounds). Regarding the application of biosensors outside of biological systems (that is, to detect molecules in the environment instead of within a living pathogen), their role may be an intermediate one. However, this limitation may be overcome within 20 years by better physical methods. For example, biosensor detection of a toxin or organism (bacteria, virus, or rickettsia) is actually recognition of specific identifier molecules or patterns of molecules on the surface of cells and organisms. Using biomolecules (e.g., antibodies) exploits the information regarding the specific nature of these identifier codes. If these codes were known, more conventional and robust techniques, such as mass spectrometry or electron microscopy, might be more usable. However, for use within organisms, including humans, biosensor applications have no competition.

COMPACT SYSTEMS

Biosystems, such as a leukocyte (white blood cell), an eyeball, or a brain, are compact compared with a manufactured electrical/optical/mechanical system with equivalent capability. In effect, biology offers a complete package of codes, templates, manufacturing machinery, and packaging machinery—all sized at the biomolecular level, which is significantly smaller than any man-made manufacturing system. We can, with difficulty, make a motor device barely visible to the middle-aged eye. Protozoa incorporate motor-like devices a thousand times smaller. If simple biosystems can be harnessed, substantial size and power reductions are possible. Also, when a biosystem is reproduced based on a design found in nature, part of the initial research costs have been offset.

IMPROVED PERFORMANCE

Biotechnology deals with the molecules, reactions, and systems that form the basis for life and nature. It therefore provides a unique potential for effecting changes in the soldier, who is not only the most sophisticated organism in nature, but also the most critical, complex, and costly of all the Army's weapon systems. Biotechnology, coupled with medicine, will provide the understanding and capability to combat disease and CTBW threats on completely new fronts, perhaps even to improve and correct the human genome to alleviate flaws in metabolism, to generate disease resistance, or to enhance mental and physical performance.

If all of the above capabilities of biotechnology were to be realized and exploited, what could they mean to the twenty-first century Army, and what military applications can be envisioned? This following list represents the Group's assessment of the possibilities:

- *Deployable bioproduction* used in the theater of battle, with indigenous feedstocks and low energy, will provide a broad range of product capabilities (i.e., food, fuel, and materiel) and shorten the logistics tail that would otherwise limit certain extended operations for special forces in remote areas.
- *Enhanced immunocompetence* will alter the white-cell genome, provide immunological responsiveness to a global roster of diseases, and produce broad disease resistance in situ, which will increase the number of effective personnel in a battle theater.
- *Biosensor systems* will be deployable by drones or troops to survey deployment sites, perimeters, and flanks, to detect disease and CTBW threats, to detect troops and equipment, and to assess environmental parameters, all of which will increase intelligence and provide earlier warning.
- *In-field diagnosis and production of countermeasures* will permit rapid diagnosis of disease or CTBW threat and will provide therapeutics and prophylaxis. This will increase the number of effective personnel on the battlefield.
- *Novel materials* will unveil unique new capabilities such as biocamouflage and bioantifreeze and will improve current capabilities

(i.e., antiflak fibers, adhesives, and lubricants). The use of these cost-effective methods will provide portability (in-theater production will be possible), enhance novel properties (i.e., lighter, stronger, regenerative, and adaptive), and shorten tails, lighten loads, lower signatures, and heighten mobility.

- *Extended human performance* will be possible by coupling human beings to machines neuroelectrically. This will enhance the individual's capability for increasing task loads and efficiency, thereby reducing manpower requirements and promoting the use of unmanned platforms that can support remotely manned, equipment-intensive battles.
- *Antimateriel products* will be used for antipropulsion materials (i.e., fuel, lubricant, airway), in antiterrain materials (soil, vegetation), and to discretely target and ensure highly accurate delivery. These products will allow commanders to choose where and what to fight.

What technology areas must be pursued by the Army in order to realize these warfighting capabilities? The following list of primary technology areas began as a mix of technologies and applications. The Technology Group then honed the list to separate applications and products from technologies. For example, gene manipulation is a set of technologies (something one does to produce a product), whereas devices for enzymatic decontamination or detection of CTBW agents are products or applications. This list of critical technologies resulted:

- *Gene technologies.* The most familiar of the biotechnologies and perhaps the foundation of biotechnology as we know it today, gene technologies include the set of methods and procedures used to "touch the genomes" of nature: to identify, change, and exploit the genome and to create materials and life forms. This set includes gene replication, splicing, modification, regulation, transportation, and expression—the technologies to identify, copy, modify, and use the blueprints for biotechnology products.
- *Biomolecular engineering.* This technology allows for the design and production of molecular or composite biotechnology products with specific, tailored capabilities. Today we can produce small biomolecules *dc novo* and modify or reproduce naturally occurring molecules in biological systems. We also have some understanding of why and how biomolecules function. Over the next 30 years, we can acquire the knowledge base necessary to understand and predict the structure–function of large-molecule relationships. We will also be able to predict the physical, chemical, and biological properties of such molecules. We can apply this knowledge to the design, construction, and mass production of completely new molecules and materials to meet specific requirements. Molecular engineering, more than any other biotechnology, can provide the capability to advance biotechnology from adaptation to innovation.

• *Bioproduction technologies*. These techniques and procedures are needed to exploit the creations and applications of the technologies above by producing quantities of materiel required for Army needs. Generally, bioproduction technologies will have lower energy requirements, utilize milder reaction conditions, and have the flexibility for using simple, variable feedstocks. These technologies today include fermentation; solid-phase molecular synthesis; and bioreactors with sequenced stages of biosynthesis, scale-up, and downstream processing. Other techniques are yet to be realized. Ultimately, production capabilities may be transportable to remote theaters. If one considers that plants can essentially construct themselves from a blueprint (DNA) and a small startup package in the seed—plus air, water, sunlight, and a few minerals—then the possibilities for remotely deployed bioproduction seem more realistic.

• *Targeted delivery systems*. Composites will allow products to be discretely targeted and maximally effective. These technologies include special packaging technologies for safe transport to target areas, special recognition technologies for the release of products at target sites, and the coupling of these two. Medicine will be the initial beneficiary of these technologies and will dominate their development. Two near-term applications will be targeted therapeutics and diagnostic compounds. In later phases of development, other adaptations, such as encapsulated products with specific battlefield applications (incapacitation of hardware or sensors) and dormant/recognition/activation operational capabilities, are considered quite feasible.

• *Biocoupling*. These technologies will be necessary to apply the recognition capabilities of biotechnology to sensors, detectors, and diagnostics. This technology area must blend special subsets of physics, chemistry, biology, and engineering. It represents a formidable challenge: to couple the sensitive and selective but fragile detector biomolecules—primarily suited for aqueous environments—to electronic, optical, or mechanical systems.

• *Bionics*. This final set of technologies enables the connection of the human organism to machines and systems without the conventional mechanical man–machine interfaces, such as fingers, hands, or toes. These technologies will extract data from and feed data into the neural domain of humans, using noninvasive or mildly invasive connections, and greatly expand the performance boundaries of the individual. The performance of multiple overlapping tasks with rapid switching, the elimination of rate-limiting visual and aural information screening and processing steps for information accrual, and the enhancement of training and learning processes—all will transform the soldier of the twenty-first century. These advances will accommodate the ongoing transition from a manpower-intensive to a technology-intensive warfighting capability.

What must the Army do to exploit these technologies and realize these warfighting capabilities? All of these technologies will receive attention outside the Army—from the private sector, from U.S. government agencies, and from foreign, commercial, and government interests. However, as history shows, none of these entities will work on the Army's specific problems. And, of course, the Army cannot afford to duplicate efforts being performed in these other sectors. The Army must maintain viable R&D biotechnology programs and capabilities to adapt the output of biotechnology at large to its specific needs. Historically, the Army has maintained laboratory facilities and staff, research contract programs, and cooperative foreign information exchange programs to leverage and adapt technology to its use. These mechanisms must be maintained and not starved to the point of inadequacy as the budget shrinks. Three specific steps seem appropriate:

1. Assemble research teams with a mix of disciplines including physics, chemistry, biology, medicine, and engineering, instead of the more common segregation of staff members by their technical disciplines. Biotechnology is the most interdisciplinary of all fields.
2. Stabilize funding for technology to provide continuity of research and adaptation efforts. Buying research and biotechnological innovations is not like procuring materiel or manpower, where the quantities needed may be reevaluated from time to time. Without a clearly defined funding line for biotechnology, including a commitment for separate program development within the DOD system, this emerging discipline will not be fully exploited for the military.
3. Establish stronger foreign ties for data exchange. The exploitation of biotechnology may be the first technology area in which the United States will not lead the way. Western European and Japanese investments in biotechnology at the equivalent of $6 billion to $8 billion from private and governmental sources, leads the U.S. domestic investment in biotechnology by $2 billion to $4 billion total. The Army will need to increase its access to these communities, including R&D investment in them.

In summary, biotechnology will offer some unique and revolutionary capabilities to the twenty-first century Army. It will change the way we fight. It will also change the way our adversaries fight, and some potential adversaries may be ahead of us in this technological area. The United States did not keep the secrets of atomic warfare for long, even in the secretive atmosphere of the 1940s and 1950s. In the communicative, mobile, commercial world of the next 30 years, the data for both defensive and offensive biotechnological breakthroughs will be uncontainable and, essentially, public information. Almost any country will be able to possess the data. Witness the rumored chemical warfare and pharmaceutical manufacturing capability in Libya, which is not a technology leader. The

United States must compete; the Army cannot relegate biotechnology to anything less than a *must-have* priority.

26

Technology Forecast Assessments

GENE TECHNOLOGIES

Description and Attributes

Gene technologies are a group of technologies involved in the transfer and expression of new genetic material into the genes of organisms. Technologies concerned with recombinant DNA and cell fusion (or hybridoma) are the major techniques for gene transfer. Technologies dealing with recombinant DNA, genetic engineering, or gene-splicing technologies permit the production of new or modified biomolecules and organisms. The subtechnologies include:

- sequencing of nucleic acids and proteins;
- synthesis of peptides and nucleic acids;
- identification, selection, and cloning of genetic material;
- manipulation and control of gene expression;
- gene vectors;
- promoter sequences;
- amplification of gene materials (polymerization chain reaction technique);
- restriction enzymes;
- abzymes;
- ribozyme technology; and
- knowledge of the genome.

Together, these technologies allow for the rapid, efficient insertion and expression of specific, new genetic materials into cells and organisms. The sources of these new genetic materials are synthesized DNA, naturally occurring DNA, and altered DNA. The transfer of specific genetic material into organisms makes possible the production of new substances encoded by that genetic material, as well as the creation of new organisms with new properties and characteristics. Knowledge of specific genes and the mechanisms by which they interact will permit the transfer of multigene, complex characteristics into cells and organisms.

Knowledge and understanding obtained from molecular engineering, protein engineering, protein conformation, and molecular structure–function relationships will allow the production of new and modified biological materials and substances. Techniques for the translation of structural information on proteins into genetic *instructions* and for the rapid, efficient insertion and expression of this genetic material will permit the automated and rapid production of new biological molecules and substances.

Cell fusion, or hybridoma, technology involve the fusion of two cells, for example, a specific antibody-producing cell and a cell that can be readily grown in culture. The resultant hybrid cell, called a hybridoma, maintains the ability to produce specific antibodies and to thrive in cell cultures. Hybridoma cells secreting specific classes, types, isotypes, and idiotypes of monoclonal antibodies can be selected and cloned. Monoclonal antibodies represent a class of biomolecules with unique, specific recognition and binding capabilities. Hybridoma technology can produce monoclonal antibodies with distinct biological functions; different affinities; additional molecular adducts, such as enzymes or abzymes, toxins, or markers; or antibody fragments and single-chain antibodies of smaller molecular weight. Antibody fragments and single-chain antibodies—all can be produced through hybridoma technology.

The hybridoma field is advancing rapidly. A new technique produces, clones, and selects genes for both mouse and human monoclonal antibodies. This technique produces new monoclonal antibodies in days instead of months. Whole repertoires, or libraries, of binding substances can be created and studied in days. Such revolutionary (as opposed to evolutionary) advances will continue to occur over the next three decades. The time from discovery to application of biotechnology techniques and information is decreasing; it is now months instead of years. New scientific instrumentation can be expected to incorporate advances in technology within a year-long product cycle.

The gene technologies make it possible to produce new substances and organisms with many applications in medical and nonmedical areas:

- discrete recognition substances (DNA probes, receptors, and antibodies);
- biomaterials (structural, functional, and renewable);
- therapeutics and drugs;
- vaccines and multivalent vaccine delivery systems;
- biological response modifiers (physiologically active compounds);
- artificial body fluids and materials;
- bioelectronic materials (signal trapping and amplification);
- new foods and production processes;
- decontamination, detoxification, and bioremediation processes;
- diagnostics for disease and CTBW threat detection; and
- materials for adsorption or neutralization of hazards and for purification.

Projections

Genetic technologies will be employed to develop and produce systems for the following uses:

- deployable biosensor/telemetry systems for the detection of a spectrum of CTBW agents, the diagnosis of diseases, and the collection of field intelligence;
- globally keyed enhanced immunocompetence for rapidly deployed forces;
- novel and advanced materials for foods, fuels, and explosives; lightweight and high-tensile-strength materials for ballistic and antiballistic applications, extreme-environment lubricants, antifreezes, surfactants, and solvents; and enzymatic/catalytic materials for decontamination and detoxification of CTBW agents;
- rapid regional medical diagnosis and therapeutics for disease and CTBW agent prophylaxis and therapy;
- biocamouflage materiels and systems using adaptive, regenerative, low-radar reflectance, and signature-suppressing properties; and
- antimateriel systems, such as biological fogs and coagulants for fuel or lubricant degradation.

Impact on the Twenty-First Century Army

Gene technologies will be essential to biotechnology applications for the twenty-first century Army. As the Technology Group has described them, gene technologies lie at the core of the field of biotechnology. They will be required at some stage for nearly every biotechnology product, whether information or materiel. Thus, gene technologies will help to reduce costs, shorten the logistics tail, and lighten the load of operating forces. They will enhance mobility and deployability and improve the health and performance of personnel. New weapons and intelligence-gathering capabilities for U.S. defensive purposes (by nonsignatories to the Biological Weapons Convention) can be developed through biotechnological applications that specifically require gene technologies.

BIOMOLECULAR ENGINEERING—DESIGN, CONSTRUCTION, AND PRODUCTION

Description and Attributes

Biomolecular engineering will enable the design and production of molecular (or composite) biotechnology products with specific, tailored capabilities. Today we can produce completely new molecules and materials to meet changing requirements. Molecular engineering, more than any other area of biotechnology, can advance biotechnology from invention to application.

The *subtechnologies* or disciplines underlying molecular engineering include (1) those needed to relate details of biomolecular structure to function, a necessary step to predict the structures required to achieve a desired function; and (2) those needed to design, construct, and produce molecules or composites for specific functional goals. At this level, the disciplines include:

- structure–function physical chemistry (e.g., quantum-chemical, ab-initio stereographic electronic mapping);
- physical biochemistry (e.g., active-site molecular mechanisms correlated with structure; complex tertiary and quaternary structure determinants including phasing of biosynthesis, solvent, and counter-ion effects);
- computational capabilities for the calculation, simulation, and display of models and for the design of biomolecules;
- physical sciences that produce structural details of biomolecules (e.g., x-ray crystallography, nuclear magnetic resonance, electron microscopy at the *large-molecule* level of resolution);
- molecular synthesis biophysics and chemistry (e.g., solid-phase and mixed-phase synthesis of complex molecules);
- physics and biochemistry of biopolymer synthesis (for complex, nonrandom, multiple species or nonhomogeneous polymeric materials); and
- biochemistry and molecular genetics of genome design (for bioproduction of novel molecules and biopolymers not occurring in nature).

This incomplete list of subtechnologies illustrates the multidisciplinary nature of the problems to be addressed. If a molecular engineering capability is deemed to be of sufficient value, the Army will need to establish a unit of in-house research and science management capability equally broad in disciplinary scope.

Current Capabilities

The ability to relate structure to function and behavior is limited for all but the smallest biomolecules. In the most advanced predictive systems, such as those employed in predictive toxicology, there are many surprises and failures of prediction. The ability to design *de novo* a biomolecule for any complex goal (e.g., radar nonreflectivity) is essentially nonexistent. At best, one can look at naturally occurring examples and try to mimic nature. However, no new biophysical principles need be discovered; the sophisticated scientific disciplines needed to pursue a molecular capability already exist. Unfortunately, the efforts that ultimately will contribute to molecular engineering are scattered among various disciplines and are aimed at diverse goals. Examples include protein engineering conducted in biophysical-biochemical laboratories; molecular imaging with design and graphics features developed by computer systems experts and mathematicians; and bioprocess research found often in chemical engineering laboratories with little molecular biology or microbiology staff.

Projections

Biomolecules differ from other chemicals by virtue of their complexity of structure and their subtlety and specificity of function. Moreover, nature can manufacture these complex molecules from simple feedstocks. (Plants basically make themselves from air, water, specific light frequencies, and a few minerals). The ability to design and produce specialized biomolecules and materials for Army missions could provide such capabilities as:

- deployable bioproduction from indigenous feedstocks;
- enhanced personnel health, prophylaxis, and performance;
- novel materials for a wide range of missions (e.g., biocamouflage and signature reduction of troops and equipment);
- rapid field response to battlefield hazards, (including CTBW), conventional trauma, and environmental extremes;
- expanded human performance; and
- antimateriel techniques and weapons, including soft kills.

Impacts on the Twenty-First Century Army

Molecular engineering can produce information and materials that will significantly lighten the logistics tail, improve intelligence gathering, improve personnel health and performance, and provide novel materiel for a highly mobile, low-signature force. The costs of routine production of these materials are expected to be lower than for nonbiologically produced substitutes. Also, in most cases, nonbiologically produced substitutes will not be comparable in purity. Molecular engineering offers unique capabilities that could in some instances shape, as well as accommodate, the tactics and force structure of the Army in the twenty-first century.

BIOPRODUCTION TECHNOLOGIES

Description and Attributes

Bioproduction technologies are the key to the commercial availability of new biological molecules and engineered organisms. The following are some of the bioproduction technologies that support the growth of cells and organisms that produce natural materials or genetically engineered biomaterials:

- bioreactors;
- cell culture and fermentation techniques;
- cell growth media and factors;
- cell lines (mammalian, insect, bacterial, yeast, algal);
- cell processing and harvesting techniques;
- chemical coupling techniques and processes for the immobilization of cells and proteins; and
- purification/isolation techniques.

Cell fermentation and culture techniques, cell lines, and—particularly—bioreactors must be developed to create efficient processes for large-scale production. New surfaces and materials are being discovered that permit the efficient culture of cells and the culture of primary cells that previously were difficult or impossible to culture. Significant new capabilities will result from these advances.

Organisms or enzyme systems can perform chemical reactions and biotransformations with low energy inputs at ambient temperatures and pressures. This ability gives bioproduction technologies inherent advantages over conventional or chemically based synthetic technologies. High-temperature stable enzymes that can rapidly break down complex cellulose (wood fiber) materials to simpler sugars have been identified. These simpler sugars can be used as intermediates to create new materials. By elucidating the sequence and structure of these enzymes, scientists could identify the backbone that confers the thermoresistant property. The information on and characteristics of thermoresistance obtained through protein engineering, biomolecular engineering, and gene technologies could be transferred to a number of other enzymes or biomolecules.

Genetically modified organisms will provide the capability for producing new materials and materials that are otherwise difficult to obtain. Covalent coupling to inert, solid support materials of affinity ligands, enzymes, and other specific-recognition biomolecules with the proper conformation and orientation will form the basis of new purification and processing technologies for rapid, efficient, ultrapure large-scale processing. Downstream processing and purification of biomolecules that was costly, slow, and wasteful can now be done quickly, efficiently, and cost-effectively. Recent advances in membrane-affinity separation technologies permit this rapid purification of monoclonal antibodies at large scales, as shown in Table 26-1. Bioproduction technologies are less costly and less environmentally damaging, and they occur with greater speed, specificity, and selectivity. These technologies need to be scalable from laboratory to industrial production. Advances in bioproduction technologies continue to occur rapidly; they are expected to be significant over the next three decades.

TABLE 26-1 Process Comparison for the Purification of 1 Gram of Monoclonal Antibodies

	Column Chromatography	Membrane Affinity Separation
Process time	2 to 3 days	1 hour
Process yield	40 to 60 percent	90 to 95 percent
Purity	95 percent	99 percent

Source: Nigro, 1989.

Projections

Developments in bioproduction technologies will permit the following:

- bioproduction of foods, fuel, and explosives from variable, indigenous, renewable feedstocks;
- production of novel and advanced materials for ballistic and antiballistic applications, lightweight, high-tensile-strength fibers, solvents,

enzymatic decontamination and detoxification systems, extreme environment lubricants, antifreezes, and surfactants;

- production of materials for rapid, regional medical diagnostics, drugs, and vaccines for disease, CTBW prophylaxis, and therapy;
- production of biocamouflage materials; and
- production of antimateriel systems.

Impacts on the Twenty-First Century Army

Bioproduction technologies will contribute unique capabilities to the twenty-first century Army in two critical areas: logistics support and materiel cost control. In these two areas, biotechnology can help shape warfighting capability in the next century. Deployable bioproduction of food, fuel, and other supplies from renewable and indigenous feedstocks will represent a major new capability. In general, bioproduction of certain types of materiel will typically be less costly after initial R&D investments are recovered.

TARGETED DELIVERY SYSTEMS

Description and Attributes

Targeted delivery systems use chemicals, biomolecules, and microencapsulation systems. Active biosubstances and chemicals are encapsulated in membranes or matrices that permit controlled release, such as by diffusion or triggered release, through the dissolution of capsule material. Future microencapsulation systems using new biocompatible, biodegradable, and advanced biomaterials, will protect sensitive active compounds from degradation or inactivation by light, environmental, chemical, or biological stresses. Field-deployable, stable systems can be useful for intelligent biosensors, decontamination and detoxification systems, detection, and biocamouflage systems for signal suppression (low observability).

Oral, nasal, and transdermal administration of drugs, peptides, proteins, and vaccines through microencapsulation systems also are being developed. Drugs can be delivered to specific sites within the body to provide for more efficient therapy with less toxicity and fewer side effects. Antibodies, specific receptor/ligand systems, and microencapsulation systems will form the basis of targeted delivery systems. Microencapsulation processes are being developed to protect sensitive biomolecules from inactivation and to deliver to specific sites. They will also be used to control—or trigger, depending on mechanical, physical, or physiochemical changes—the release of bioactive substances at the sites of action.

Systems and processes for special-purpose applications in agricultural biopesticide and toxin delivery are being developed and evaluated for their ability to protect sensitive biopesticides and toxins from environmental and ultraviolet light degradation. Microcapsules that float on the water surface are being developed for mosquito control. New systems for controlled and triggered release of encapsulated components, such as release triggered by specific electromagnetic radiation frequencies, would permit the development of many new capabilities for the Army.

These microencapsulation systems will permit the use of biological substances that otherwise would be inactivated or degraded. Immobilization, covalent coupling, and crosslinking technologies will be important in the processing and orienting of biomaterials. Knowledge of the construction of microcapsule systems and proper coupling of biological components is needed to develop targeted delivery systems that are stable and functional. Advances in these techniques are occurring rapidly and will continue to do so during the next three decades.

Targeted delivery systems have many applications for medical and nonmedical uses, such as drug and vaccine delivery, prophylaxis, CTBW decontamination and detoxification, purification and specific adsorption systems, agricultural biopesticide and toxin delivery, cell therapy, tissue or organ regeneration and replacement, artificial cell development, and energy-rich and performance-enhancing foods.

Projections

Advances in the development of targeted delivery systems will produce intelligent, self-regulating microencapsulation delivery systems. Such systems will be composed of advanced materials and bioengineered polymers, enzymes, abzymes, antibodies, or new therapeutics. Specific triggering mechanisms for release of encapsulated substances will be developed (e.g., pH, ionic strength, specific receptor/ligand binding, preselected frequencies of electromagnetic radiation).

Targeted delivery systems will have many military applications:

- globally keyed enhanced immunocompetence systems for rapidly deployed forces;
- systems that use novel and advanced materials for foods, fuels, explosives, and enzymatic decontamination and detoxification;
- rapid regional medical diagnosis, therapeutics, and vaccines for disease, CTBW prophylaxis, and therapy;
- biocamouflage systems using adaptive, regenerative, low radar reflectivity, and signature-suppressing materials;

- antimateriel systems such as biological fogs, foaming air passage restrictors, and coagulants for fuel or lubricant degradation; and,
- terrain control systems, such as soil-degradation systems using remotely triggered or delayed-release microencapsulated compounds.

Impacts on the Twenty-First Century Army

Biotechnologies that will produce targeted deliveries of drugs, chemicals, or biochemical compounds (i.e., the highly specific delivery, target recognition, and release of a designated compound) will carry appropriate biotechnology products in the direction that smart weapon systems now pursue. These capabilities can significantly improve the health, survivability, and performance of personnel through medical products and materiel. They also can provide improvements in such areas as antimateriel, camouflage, and intelligence gathering. These biotechnologies can play a major role in providing greater flexibility in the deployment of troops for the twenty-first century Army.

BIOCOUPLING—BIOCAPTURE, RECOGNITION, AND SIGNAL TRANSDUCTION

Description and Attributes

Biocoupling is used here as a term to describe the techniques needed to couple biosensors and biomolecules to electronic, optical, or mechanical signal processing. For near-term biosensor applications and for more distant bioelectronics applications, this technology must develop quantifiable, stable, environmentally rugged, low-error techniques for coupling biocapture and recognition events with some means of signal amplification, transduction, and interfacing with electronic, optical, or mechanical equipment. The biosensor (e.g., antibody and bioreceptor) development phase of these systems is proceeding apace. The coupling of biosensors—particularly while maintaining stability and specificity—will be much more difficult. Without coupling technologies, biosensor technology may very well stagnate or develop along inappropriate paths because system applications for biosensors and bioelectronics will require sophisticated and reliable interfaces (Figure 26-1).

The component technologies or disciplines of biocoupling include:

- biochemistry, molecular genetics, receptor physiology, and pharmacology, to identify, design, and develop biosensors with the required specificity and sensitivity;

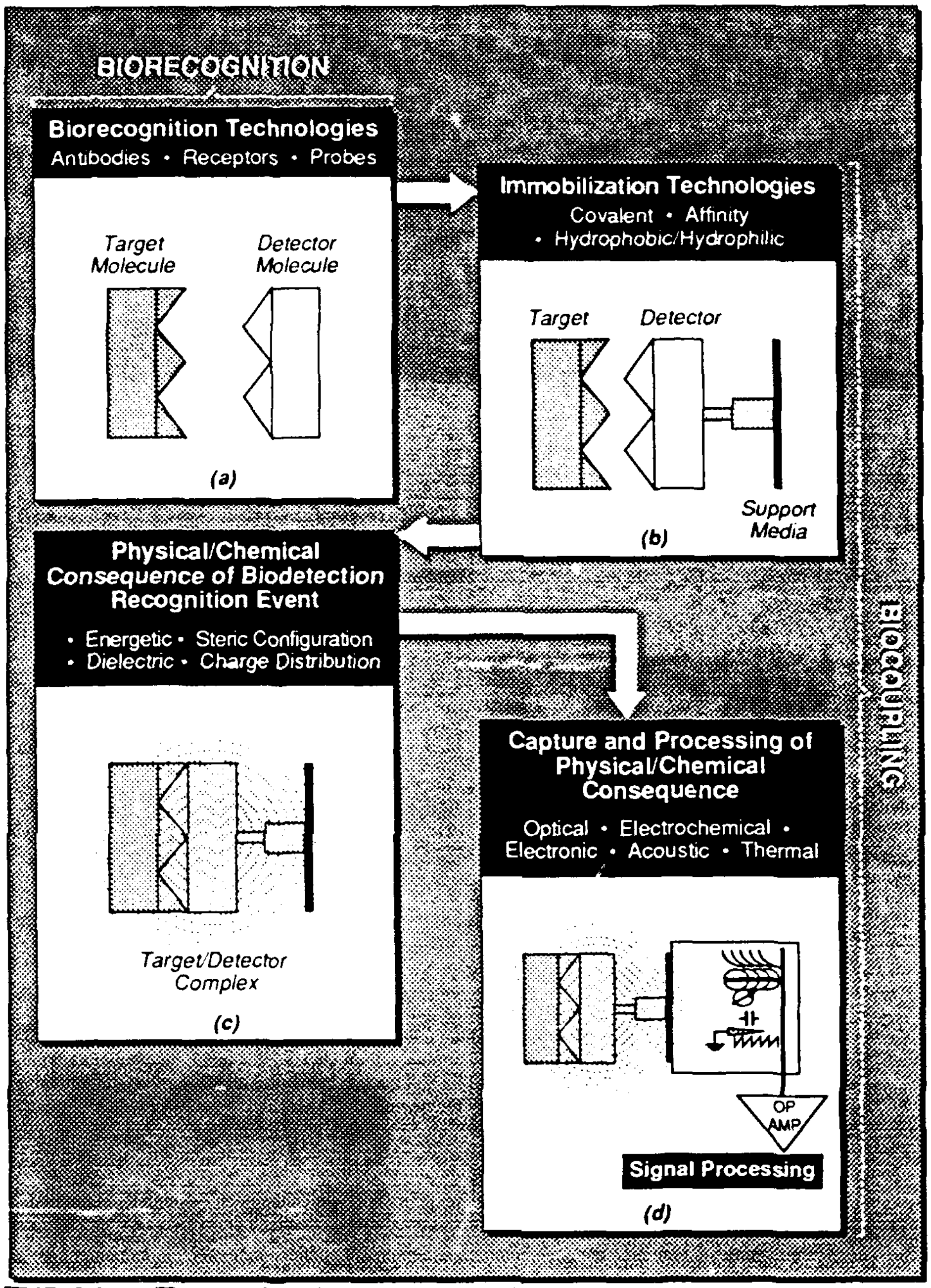

FIGURE 26-1 Events in biodetection: biorecognition and biocoupling. (a) The biologically derived "detector" molecule is capable of a highly specific "recognition" interaction with a target molecule. (b) In the device's configuration, detector molecules are typically immobilized so recognition events can be monitored. (c) When a detector molecule combines with a target molecule, a unique physical/chemical change occurs in the detector-target complex. (d) This recognition-specific change is measured by an appropriate technique, whose output is fed to the signal-amplification portion of the device. Biocoupling comprises the measurement of the physical/chemical change and the subsequent signal amplification.

- physical chemistry of macromolecules, to assess the structural, spectral electromagnetic, electronic, and optical parameters that are quantitatively altered by a biosensor's recognition of its specific target molecule(s), as contrasted to nonspecific changes due to biosensor degradation;
- the physics and chemistry of signal trapping and recognition, including membrane matrices, crystalline structures, covalent or adhesive bonding to surfaces, and electronic, magnetic, or optical field perturbations;
- engineering adaptation of unit-event signals into systems with integrated outputs; and
- engineering adaptation of the sensor environment to the sampled environment, including quantitative transport of sampled environment from either air or nonaqueous media to the aqueous media typical of the biosensor environment.

Bioelectronics, which encompasses such concepts as computer biochips for great size reductions in memory storage devices, is significantly further away than functional biosensors. However, bioelectronics will require biocoupling as well as binary biomolecular structures (biomolecules with two stable configurations). Biocoupling may limit or determine which types of biosensors or biomemory molecules are usable, so development of both technologies may be impeded by failure to develop biocoupling technologies at the same time as, or even in advance of, biosensor and binary-mode biomolecules.

Current Status

Biocoupling is significantly less advanced and receives less attention than sensor molecule technologies. Techniques now employed for arraying biosensors include (1) suspension in aqueous media and (2) adhesive, covalent, or nonspecific bonding to various surfaces. Techniques for detecting molecular capture and recognition events include alterations in capacitance, gas flow resistance, conductance, and optic field perturbations. These array and detection techniques have not yet produced the quantitative, specific, and robust devices needed for coupling biosensors to detection and integration systems. This situation is to be expected because of the need to first establish biosensors as a viable concept apart from a system. However, as noted, biocoupling methods may determine which molecular types are feasible as system biosensors. Biocoupling should, therefore, be pursued parallel to the development of individual biosensors.

Projections

Biosensors offer sensitive and highly specific detection and identification capabilities. When coupled with an integrating system, biosensors could provide greatly improved intelligence-gathering, diagnostic, and monitoring capabilities. Potential military applications include:

- deployable detection and analysis systems (with telemetry), to assess remotely the presence and even the status of hostile troops and equipment, disease and CTBW threats, and environmental parameters;
- rapid diagnosis and identification of disease and CTBW threats in the field;
- terrain and perimeter monitoring;
- monitoring of critical personnel performance and performance modification (see also "Bionics" below); and
- bioelectronics, a more distant possibility that could provide the miniaturization technologies to take biosensor systems to the next stage of sophistication.

Impacts on the Twenty-First Century Army

The development of biocoupling technologies will be critical to the overall level of intelligence and information available to deployed forces and to their health and performance. Increased requirements for mobility will demand faster and more detailed assessments of the threats. Manpower constraints (including training costs) will demand better prophylaxis and treatments to maintain the force strength, methods to speed return to duty of casualties from disease and CTBW, and methods to enhance self-treatment and self-evacuation capabilities on the battlefield. The capabilities offered by biosensors will significantly increase our warfighting capabilities in all these areas.

BIONICS (EXTENDED MODELED HUMAN PERFORMANCE)

Description and Attributes

A bionic technology results from the purposeful mimicry of a living physiological system. It is considered successful when a device is produced that replicates the function of the system both semiquantitatively and qualitatively. For bionic systems that mimic radar, sonar, or optical technology, the living model is typically neurophysiological, neuromuscular, and neurochemical whereas the corresponding devices are electromagnetic, electromechanical, or electrochemical, respectively.

The living nervous system has a unique capability for coupling environmental signals to receptor systems that act as high-gain analog-to-digital converters and signal processing "black boxes." As a result, neural systems are being copied more rapidly than those that are purely biochemical, enzymatic/catalytic, or humeral (based on protein conformation or tertiary structures). There are a few important exceptions of military interest, such as olfactory models for battlefield detectors of very low concentrations (femtograms/m^3, or 10^{-15} g/m^3) of simple organic molecules.

Bionic technologies have three major components:

1. bioelectronics;
2. biochemistry, upon which current fielded systems depend; and
3. biomechanics, which will assume increasing importance as other disciplines mature and create new (nonneural) concepts based on physical structures.

The principal subtechnologies are

- biocomposite analysis and process technology for batch production;
- biopolymer analysis, especially for long-chain fatty acid characterization of rheological (electromagnetically modified dynamic flow) properties, enzymatic/catalytic biochemical production, and static-flow property models for electromagnetic stealth; and
- biocompatible material development, in which substances are found or invented *de novo* that do not trigger immune-system rejection when injected or implanted in humans.

Of the above, biocomposite analysis and process technologies are the least mature. Full development will especially require the parallel development of nonlinear modeling capabilities—e.g., finite-element analysis of tissues that (1) change their elastic or tensile properties as functions of loading directions and rates, (2) change their surface reflective and refractive properties as functions of electrical stimulation or charge, and (3) possess exceptionally unusual but militarily useful properties, such as decoupling direct-stress (i.e., blast) overpressure from viscous (thoracic or abdominal) tissues with high acoustic-impedance layers.

Current Status

Passive bionics, a technology in which the Army seeks to emulate properties of living materials for single-purpose objectives, is mature and will progress steadily in the next 10 to 15 years, producing some striking successes but no surprises. Potential developments include animal fibers for personal armor, biomimetic optical polymers with nonlinear conducting properties for eye protection from lasers, artificial sense organs for robotic applications (based on force-deflection accelerometry), and bioelastomers. A multicomponent, cybernetic, or systems-analytical approach is on the horizon; it would involve modeling the animal system's neurally modulated performance in a smart or "brilliant" artificial system.

Projections

Passive bionics will assuredly produce single-property, short-term, useful aids that provide current systems with protection, mobility, and surface-property modification. Multiproperty, complex materials and smart systems could be invented in 30 years. The probabilities absolutely depend on the concomitant development of high-density neural cubes with expert-system properties and on the biocoupling devices described above. If a program (supported by either intramural or extramural funding) is initiated to enhance the analysis of specific animal systems, the invention of new bionic applications is possible. These include lightweight foam-fiber body armor, selected organisms with chameleon properties, small articulated surveillance units (1.0 m × 0.5 m × 0.5 m) coupled to headsets, preternatural (non-human-detectable wavelengths) optical (night-vision) devices, acoustic devices using active cancellation (which lessens noise rather than enhance signals), homing perceptrons, and artificial membranes with biological properties (sensors for contractile protein activity, solute-solvent purification, or electromagnetic *extended-touch* skin).

Impacts on the Twenty-First Century Army

The central theme of passive bionics is to extend human performance and protection. R&D in active bionics, as with radar and sonar, also can serve to replace current protective systems (body armor, thermal, and electromagnetic) with better systems (less costly, lightweight) for the individual soldier. Fine neuromuscular discriminability and control (remote manipulation), when coupled to robotic systems, can extend individual performance at a distance. In short, bionic mimicry of any human capability (except abstract judgment) is possible to the extent that a human neuroelectromechanical attribute can be defined. A battlefield scenario is possible in which human beings, in locations remote from the battlefield, manage unmanned fighting systems.

27

Where to Go: The Seven Highest-Payoff Biotechnology Applications

DEPLOYABLE BIOPRODUCTION OF MILITARY SUPPLIES

As previously indicated, this concept involves the generation of food, fuel, potable water, explosives, and, perhaps, ammunition components from indigenous feedstocks—potentially even from air, water, and either sunlight or other simple energy sources.

Currently, technologies such as fermentation and hydroponics produce biomass and foodstuffs without soil and attendant cultivation. Deployable bioproduction pushes the bioreactor, or bioproduction, concept out 30 years, when feedstocks from locally available vegetable matter, water, crude fossil fuels, or any organic feedstock—ultimately to include air (CO_2, N_2, H_2) and water, with sunlight as an energy source—can supply compounds composed of carbon, nitrogen, hydrogen, and oxygen. These theater-based production units would significantly shorten the logistics tail of deployed forces. When adapted to produce food and fuel for mobile-unit missions, they would greatly decrease the resupply requirements of mobile forces.

BIOSENSOR SYSTEMS FOR DETECTION, MONITORING, DIAGNOSIS, AND INTELLIGENCE GATHERING

These notional systems involve various types of biosensors integrated into systems that will require biocoupling technologies. The systems, not the sensors themselves, are the novel concepts. Biosensor systems will vary as to composition and mission. One possible system, for deployment by drones into potential troop deployment areas, includes sensor elements for detecting endemic disease organisms, the presence and strength of hostile forces, environmental factors, and CTBW threats. This system would transmit intelligence for deployment decisions and strategies. Another system would provide rapid detection and diagnosis of disease or CTBW threat as well as prophylactic or therapeutic information. Still another would be designed to monitor perimeters or terrain for encroachment by hostile personnel or CTBW threats. This system would provide more certainty and greater information-gathering potential than presently conceived CTBW detectors or listening devices.

ENHANCED IMMUNOCOMPETENCE FOR PERSONNEL

This concept consists of developing techniques to manipulate the genome of white blood cells (lymphocytes) so as to confer rapid immunocompetence against diseases and CTBW agents. The development of rapid immunocompetence could be accomplished by in-situ manipulation or by extraction, manipulation, and readministration of immune-modulator substances. Troops could be immunized against diseases endemic to areas of conflict and against known CTBW agents just prior to deployment. Biotechnology libraries of immunogens and genomic immunocompetence enhancers that are globally keyed to relevant diseases and CTBW threats would be developed.

The concept of enhanced immunocompetence extends beyond the approach of vaccination against specific antigenic entities and enters into the alteration of the genomic memory, or responsiveness, of the lymphocytes. It includes developing the ability to stimulate and enhance lymphocytes for specific recognition of, and responsiveness against, classes of antigens and their potential variants. The concept will provide the Army with the capability to respond rapidly to previously unknown or newly resistant diseases, as well as to new CTBW agents. The Army will be able to quickly detect, identify, and develop the appropriate protection for troops. This concept pushes the field of immunology in militarily relevant diseases well beyond current military medical programs.

NOVEL MATERIALS FOR NEW CAPABILITIES

Novel materials could make a major contribution to U.S. military capability in the next century. Biotechnology can reliably produce molecules or materials with complex, highly regular structures. In most cases, synthesis and production occur under mild reaction conditions. Importantly, the "production equipment" can be cells or small organisms rather than laboratory apparatus or conventional chemical processing equipment. Thus, the blueprint and synthetic equipment can be smaller than any current nonbiotechnological manufacturing apparatus. As indicated, within the constraints of the types of synthesis and production conditions appropriate for biosystems, the possibilities are limited only by imagination and funding. Through molecular engineering, a biotechnology in which the Technology Group suggests greater Army involvement, one can surpass the mimicry and adaptation of naturally occurring compounds that characterize today's approach to biotechnology. Advances in this discipline will enable the design of novel molecules and materials. Some of the Army-relevant capabilities achievable with new materials include:

- fibers with exceptional strength/weight ratios for body armor;
- compounds with greatly enhanced capabilities over conventionally synthesizable varieties, such as surfactants and lubricants;
- battle-theater-produced fuels, explosives, or ammunition components;
- living biocamouflage materials, which grow on equipment or structures (similar to moss or lichen) and adapt to local coloration or reduce radar reflectance, and which self-decontaminate and self-regenerate;
- bioantifreeze for human consumption in regions of extreme cold; and
- foods that satisfy nutritional and taste standards without the logistic tail required to deliver homestyle meals to the battlefield.

IN-FIELD MEDICAL DIAGNOSTIC AND THERAPEUTIC SYSTEMS

This particularly significant contribution from biotechnology could enhance capabilities to:

- reduce casualties from nonmechanical trauma (i.e., personnel not able to stand and fight because of disease, CTBW exposure, etc.);
- restore such casualties rapidly to self-evacuation status; and
- speed their return to duty.

The soldier is the most costly, sophisticated, and ubiquitous of the Army's weapon systems. Any capability that increases the number of effective personnel will, in almost direct proportion, increase warfighting effectiveness and reduce warfighting costs and logistics. Certainly, a 20 to 30 percent increase in effective personnel can be decisive in battle. Such an increase is realistic considering the historic numbers of disease casualties in deployed troops, not to mention the potential for disastrous casualty numbers from CTBW threats.

Biotechnology can provide systems that identify medical threats, select and generate the best medical countermeasures for interdiction, facilitate return to battle or self-evacuation (which ties up fewer troops), and design and generate prophylactic countermeasures in the battle theater. These capabilities would require aggressive prosecution of gene technologies and the technologies for biosensors, bioproduction, molecular engineering, and biocoupling that were described individually in Chapter 26.

EXTENDED HUMAN PERFORMANCE

This capability does not refer to better human health or nutrition but to extended performance through bionics, orthopedics, and the coupling of the human nervous system (central or peripheral) to machines. This area is not typically thought of as a biotechnology. It is included here because (1) it involves coupling biological systems and entities to machines; (2) it requires exploitation of engineering, physiology, biochemistry, and computer science; and (3) it has the potential for providing revolutionary increases in personnel performance.

In this area, Hollywood is far ahead of military reality, perhaps because the potential benefits are intuitively obvious but technically challenging. Consider the advantages for equipment operators such as aircraft pilots or armored-vehicle drivers if they could control their equipment through thought processes or "taps" into their neural systems. They would have no need to use eye-hand coordination, nor would they need to use a finger, hand, or foot that might be slow to react or difficult to operate simultaneously with other actions. But as futuristic as these concepts may appear to some, at least three automotive manufacturers are already engaging in active research that utilizes advanced headrest sensor suites to integrate cognitive signals from human operators for real-time modulation of suspension systems and other vehicle attributes. The Army must not find itself in a position in 30 years wherein consumer products (especially from other countries) lead U.S. military technological advancements. Extended human performance capabilities would greatly expand the types of missions for which manned and unmanned platforms could be used.

More sophisticated areas for expanded personnel performance through biotechnology include electrophysiological coupling (not auditory or visual, but central nervous system coupling within the central nervous system at the relay nuclei level without using normal sensory pathways). The goal of this approach would be fast, real-time information feed into personnel and the reverse process for information feed out to control equipment. Such information could include integrated intelligence data and enhanced sensory data regarding the immediate environment. Eventually, voiceless, two-way, real-time, thought-based communication with central data and analytical centers may be possible. This would be the equivalent of constant communication with a remote *super-genius* ectopic brain: something like the computer Hal of the novel and movie *2001: A Space Odyssey*.

ANTIMATERIEL PRODUCTS

The biotechnologies of gene manipulation, targeted delivery systems, and bioproduction will make possible the production and targeted delivery of products that could disable propulsion systems (attacking fuel and lubricants or clogging airways and critical passages); change the characteristics of soil or vegetation (to deny terrain to vehicles and troops); or degrade warfighting materiel (particularly those with organic components). The Technology Group is sensitive to the prohibitions against biological warfare, and the bioproducts considered here only target materiel or terrain.

Concerns in the past about these capabilities have typically centered on questions of control and containment: how to prevent effects against friendly materiel and how to guarantee that mutations won't produce an *Andromeda Strain*-like scenario. In 30 years, assuming that certain ethical questions are resolved, the fields of gene manipulation and control will provide answers to such concerns. They could provide such capabilities (to the United States as well as to its enemies) with very low risk. Pursuit of these technologies could enhance our capability to determine where and what we will fight.

28

Systems Panels Matrix

To find needs or requirements that could be drawn from new biotechnology initiatives, the Technology Group used a modified QFD procedure to match the key biotechnologies identified above with the findings of the STAR Systems Panels. Table 28-1 presents the results of this identification process. When this information was rearranged in a summary matrix, however, a number of high-payoff opportunities became visible at the intersections between biotechnologies and systems requirement (Figure 28-1).

The Systems Panels were arranged as columns, and the biotechnology areas as rows. R&D applications from column three of Table 28-1 were entered in the appropriate cells of this matrix. The importance of the biotechnology application to the system requirement is denoted by a code letter in the upper left corner of each cell: "H" for biotechnology of high importance to the system, "M" for moderate importance, and "C" for technology that can make some contribution to the system's capabilities. Figure 28-1 is the summary matrix. For each Systems Panel, the Technology Group then determined one or two biotechnology application(s) with the highest importance. These applications are listed in the bottom row of the matrix in Figure 28-1. The Technology Group then developed a road map for achieving two or three key products in each of these areas (see Chapter 29, "Opportunity Road Maps: How to Get There"). Neither the summary matrix nor the road maps are useful as stand-alone portions of the report; rather, they should be used with the narratives that describe them.

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Airborne Systems		
Aircraft	Bioproduction	Portable emergency fuel production systems deployable in remote areas to produce small quantities of light rotary and fixed-wing aircraft fuel from indigenous generic feedstocks
	Biomolecular engineering (novel materials)	Field-generated camouflage; biocomposite armor
	Bionics	Control systems; training
Space-based systems; reconnaissance; surveillance; and targeting	Bioproduction; bionics	Microgravity influence for manned space vehicles; extended human performance; deployable biosensors
Electronics Systems		
C^3I systems	Biocoupling; bionics	Neural nets and biosensors
Air and missile defense	Biomolecular engineering	*Biocamouflage*
Surveillance; targeting	Biocoupling	Biosensors
Computers and software; advanced electronics	Biomolecular engineering; biocoupling	Biochips; biomemory; biocomputers (smaller, faster, self-repairing, and self-replicating)
Health and Medical Systems		
Selection	Biomolecular	Enhanced personnel performance; enhanced engineering personnel training; compounds to reduce chronic disease
	Gene technologies	Reduced genetically linked disease; enhanced immunocompetence; extended performance

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Health and Medical Systems–continued		
Selection (continued)	Targeted delivery systems	Correction of biological lesions producing diseases and behavioral disorders
	Biocoupling; bionics	Screening devices with biosensor modules; characterization of applicants for behavioral components and capabilities
Training	Biomolecular	Enhanced personnel performance; modulation of engineering training; enhancement of memory, recall, learning process; biological transfer of information in real time and batch transfer of information and experience-based data
	Gene technologies	Extended performance
	Targeted delivery systems	Batch transfer of information and experience-based data; specific performance enhancement
	Bionics	Rapid batch transfer of information and experience-based data; biofeedback-based modulation of learning and performance; mimicry of biomaterials and biomechanics
Threat assessment	Biomolecular	Prophylaxis and therapy for CTBW and countermeasures engineering infectious disease; rapid diagnosis and triage; deployable detection and characterization
	Gene technologies	Deployable detection and characterization of CTBW and infectious disease; biodecontaminants for CTBW, disease, and wastes
	Targeted delivery systems	Triggerable release of prepositioned countermeasures with personnel applications that are environmentally safe and biodegradable
	Bioproduction	Deployable bioproduction of prophylaxis and therapy for CTBW and infectious diseases; deployable production of novel materials

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Health and Medical Systems–continued		
	Biocoupling; bionics	Biosensors for intelligence gathering and diagnosis; detection and interdiction of bionic-based threats; reality, continuity, and correlation sorting of data inputs
Prevention and maintenance	Biomolecular engineering	Extended performance of compounds
	Gene technologies	Extended performance via modulation of genetic control
	Targeted delivery systems	Triggerable release of in situ prophylactic and therapeutic countermeasures
Casualty assessment	Biomolecular engineering; gene technologies; bionics	Diagnosis; DNA probe for assessment of injuries at the genetic level; diagnosis and monitoring of casualties (expert systems)
Fast forward treatment	Biomolecular engineering; gene technologies	Diagnosis and treatment with pharmaceuticals with fewer side effects; enhanced corpsman-level bioproduction diagnostic capability
	Bioproduction	Deployed production of therapeutics prosthetics (O_2, H_2O, blood substitutes, and pharmaceuticals)
Forward evacuation	Biomolecular engineering; targeted delivery systems	Field-expedient therapies for trauma and CTBW or disease (pain, shock, blood clots, physical trauma)
Return to duty	Biomolecular engineering	In vivo and in vitro individual regeneration and regrowth of skin, bone, neural and vascular systems
	Gene technologies	Enhanced immunocompetence
	Bioproduction	Deployed production of therapeutics and prosthetics (O_2, H_2O, blood substitutes, and pharmaceuticals)

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Health and Medical Systems–continued		
Rear-echelon hospital	Gene technologies	In vivo and in vitro enhanced individual regrowth and regeneration of skin, bone, nerve, vascular, and compact organ systems by genetic content
Lethal Systems		
Directed energy countermeasures	Biomolecular engineering	Novel biomaterials for countermeasures
Propellants and explosives (energetics)	Bioproduction	Novel nitrate-based materials for conventional munitions; deployable "room-temperature" production of explosives and munitions
Mobility Systems		
Vehicles; armor (metallurgy)	Biomolecular engineering; bioproduction	Fuel production from generic feedstocks (vehicle-portable emergency fuel and deployable depot-level fuel and lubricant production); lightweight materials; novel materials and coverings for signature reduction, biocamouflage, and stealth; terrain, bridging, and construction equipment
	Biomolecular engineering; gene technologies	Biomaterials for bonding, bioadhesives
Personnel and Performance Systems		
Training and performance	Gene technologies; biomolecular engineering; targeted delivery systems; bionics; biocoupling	Enhanced training; extended performance
Assessment; selection; prediction (model-based testing)	technologies	Bionics; geneEnhanced selection for potential capability

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Personnel and Performance Systems–continued		
Performance maximization delivery systems	Biomolecular engineering; targeted	Time- and situation-triggered pharmaceuticals
	Bionics; biocoupling	Physical augmentation for information transfer; personal informatics for augmentation of individual and interpersonal information exchange; counter-psychological warfare for reality assessment and data base assessment
Special Technologies and Systems		
Individual-soldier or small-unit survivability	Gene technologies	Advanced materials
	Biomolecular engineering; bioproduction	Novel bio-organic materials; stealth, signature-reduction, and low-observable technology; smoke and obscurants with tailor-made electromagnetic characteristics; individual and unit CTBW protection and defense [c]
Individual-soldier/ small-unit support and performance	Bionics; biocoupling	Performance enhancement; robotic systems; computer science and artificial intelligence [d]
Support Systems		
Ammunition; supply maintenance; storage; and distribution	Bioproduction	Room-temperature and mild conditions of nitrate-based ordnance fuels; production site remediation of hazardous wastes
Fuel and lubricant supply, storage, and distribution [e]	Biomolecular engineering; bioproduction; gene technologies	Hydrocarbon-based fuel; lubricants; food; water
Food supply; storage; and distribution	Bioproduction; gene technologies	Food and waste-to-fuel and consumables interconversions and in-country available feedstocks

TABLE 28-1 Biotechnology Applications to STAR Notional Systems and Requirements

Notional Systems or Requirement [a]	Relevant Biotechnology [b]	R&D Applications
Support Systems–continued		
Water supply; storage; and distribution	Gene technologies	Multivector pathogen identification and neutralization in far-forward indigenous water supplies

[a] Identified by Systems Panel.
[b] See preceding discussions.
[c] See also Health and Medical Systems Panel matrix.
[d] See also Personnel and Performance Systems Panel matrix.
[e] See also Airborne Systems Panel matrix.

KEY BIOTECHNOLOGIES	STAR SYSTEMS PANELS: AIRBORNE	HEALTH and MEDICAL	LETHAL	MOBILITY	PERSONNEL/ PERFORMANCE	SUPPORT	SPECIAL TECHNOLOGIES	ELECTRONICS
GENE TECHNOLOGIES	H Transduction of fuel-producing gene, expression of product in kg quantities.	H Immunocompetence. Extended performance.		M As in airborne; for fuels.	C Extended training and performance. Selection.	H As in airborne; for fuels. Waste management.	C Advanced materials.	
BIOPRODUCTION TECHNOLOGIES	H Culture and scale-up of fuels.	H Field expedient prophylaxis and therapy. Deployed drug production.	H Room temperature explosives, and deployable production.	H As in airborne; for fuels. Bioadhesives.		H As in airborne; for fuels. Deployed food supply, water.	M Advanced materials.	
TARGETED DELIVERY SYSTEMS		M Correction of lesions. Selected performance enhancement.			M Extended training and performance.			
BIOMOLECULAR ENGINEERING	H Test and selection of oxygen-rich fuel molecule. Biocamouflage.	H Disease reduction. Training. CTBW triage, therapy. Casualty management.	H Novel biomaterials for countermeasures.	H As in airborne; for fuels. Biocamouflage. Lightweight armors.	H Extended training and performance.	H Far-forward logistics: food; fuel; water; and waste.	H Advanced materials. Stealthy and obscurant biocomposites.	H Multi-threat recognition molecules.
BIOCOUPLING	M Integrated protein-based environmental sensors and deployable arrays.	H CTBW screening. Biosensors for screens disease and CTBW.						H Neural networks and adaptive neuro-electronics. Deployable arrays. Integrated electronics. Biocomputers.
BIONICS	C Extended performance of man-machine interfaces.	C Characterize behavioral capability. Mimic biomaterials and mechanics.		M As in airborne; for man-machine.	H Physical augmentation and information transfer.		C Mechanisms of memory and information processing.	C Adaptive man-machine electronics.
Examples of Key Opportunities for High Leverage of Resources to Achieve 10-30 year Products for Army	Deployable bioproduction of fuel. Biosensor systems.	Biosensor systems. In-field diagnostics and therapy. Extended human performance. Enhanced immunocompetence.	Novel materials.	Deployable bioproduction of fuel.	Extended human performance.	Deployable bioproduction of fuels. Novel materials. In-field diagnostics and therapy.	Novel materials. Extended human performance.	Biosensor systems.

KEY: H = High M = Moderate C = Contributory

FIGURE 28-1 Summary matrix of key biotechnologies and capabilities of STAR Systems Panels.

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Opportunity Road Maps: How to Get There

The following road maps include the time lines, milestones, and decision requirements for developing one or two key products in each of the seven high-payoff areas identified in the summary matrix. These road maps are not endpoints, however; they do not, for example, include the cost and manpower requirements that an Army decision-maker would need to choose among research initiatives. But they do provide some idea of how soon the following products might be available to the Army:

- *Deployable bioproduction of fuels*. Portable, deployable fuel supply (Figure 29-1);
- *Biosensor systems*. Deployable multithreat arrays; integrated bioelectronics (Figure 29-2);
- *Enhanced immunocompetence*. Panpathogenic resistance to disease and CTBW agents (Figure 29-3);
- *Novel materials*. Multithreat protective fibers, fabrics, and composites (Figure 29-4);
- *In-field medical diagnostics and therapy*. Very rapid and specific in-field diagnostics (Figure 29-5);
- *Extended human performance*. Enhancement and bionic man–machine interfaces (Figure 29-6);
- *Antimateriel products*. Antimachine and antisupply capabilities (Figure 29-7).

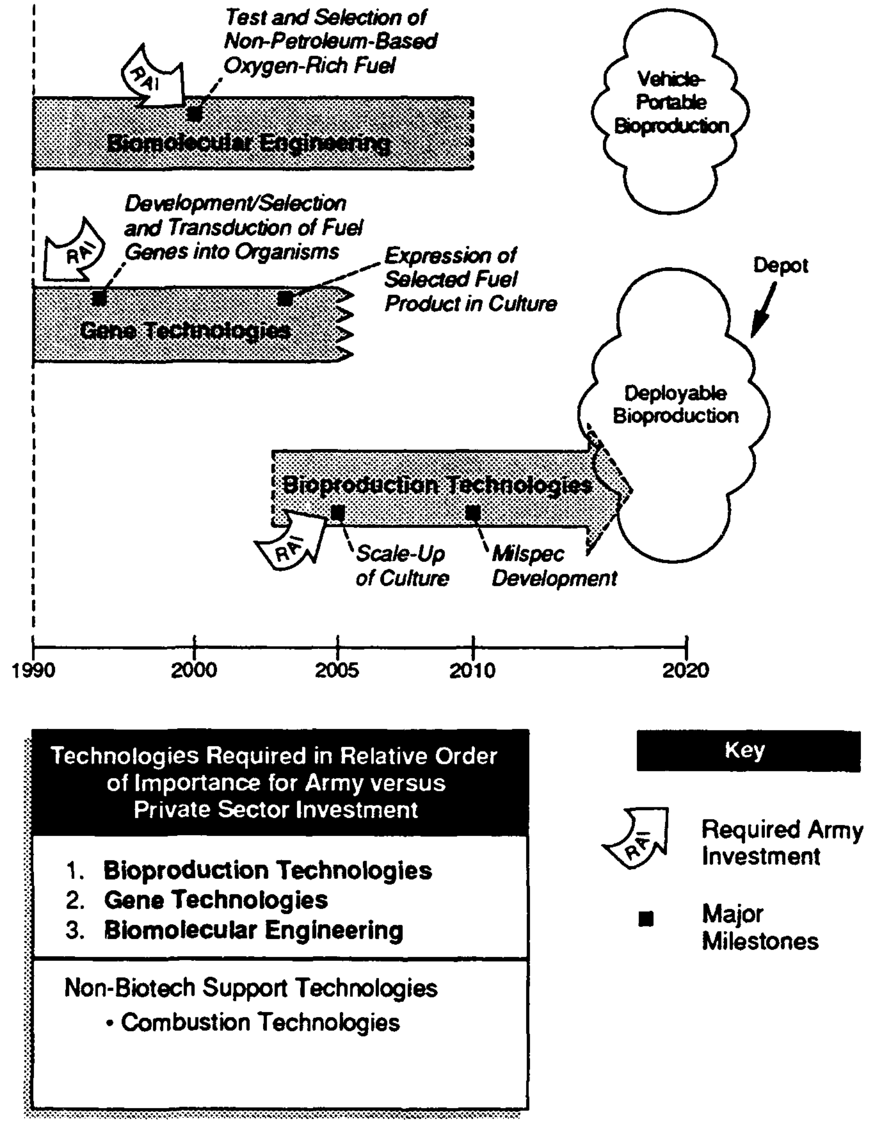


FIGURE 29-1 Road map for deployable bioproduction of fuels.

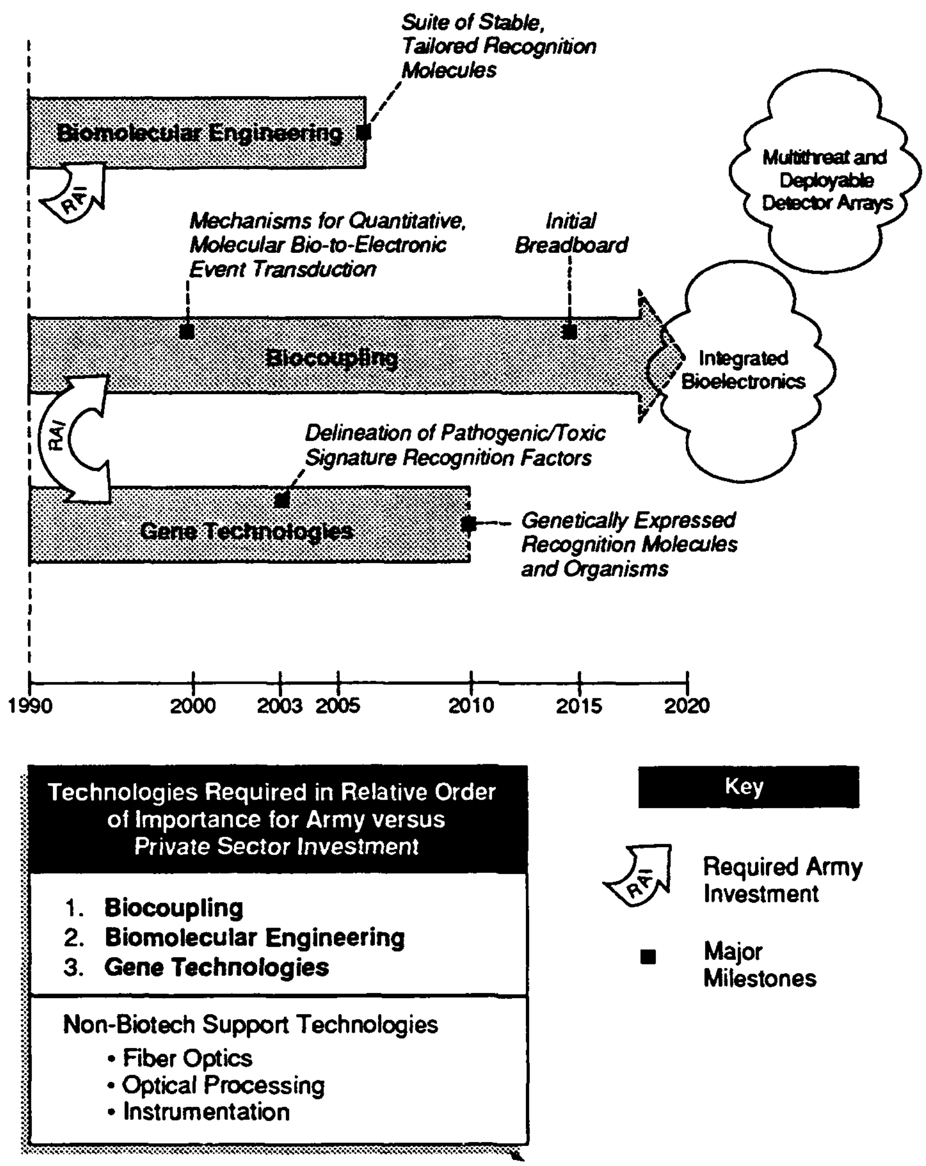


FIGURE 29-2 Road map for biosensor system.

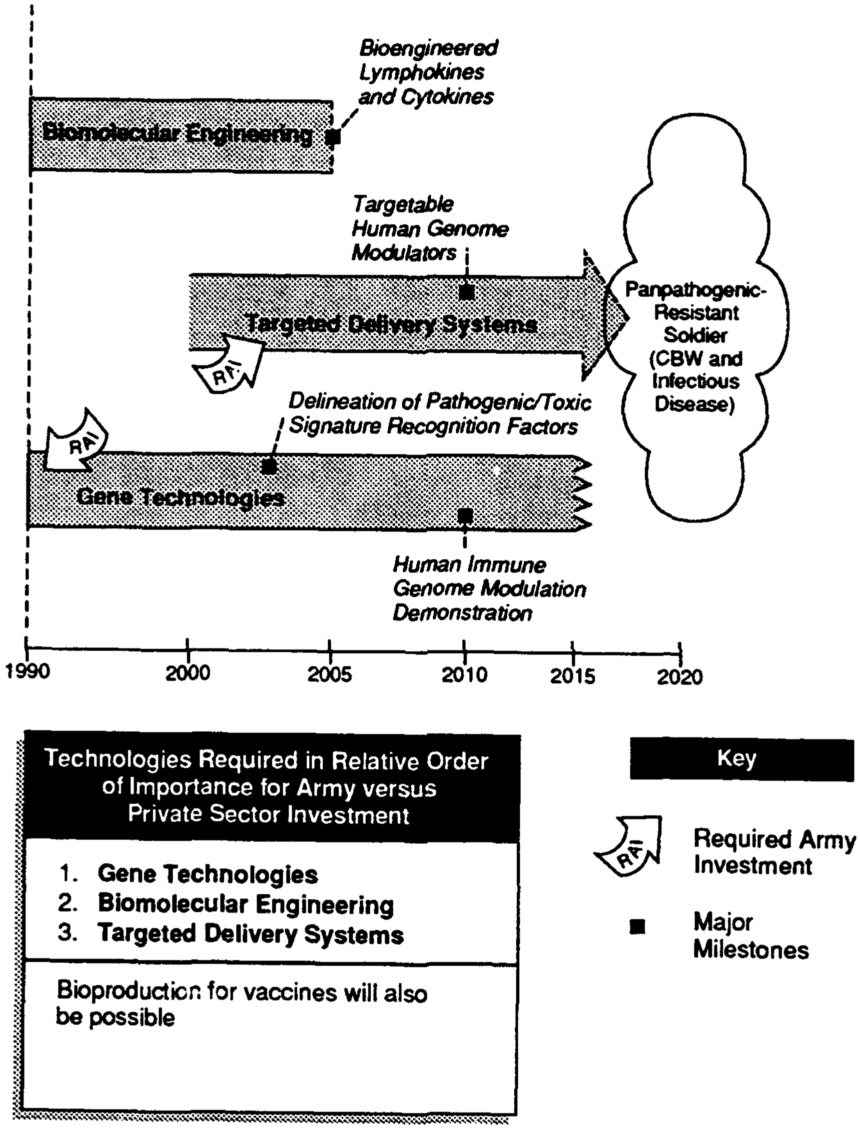


FIGURE 29-3 Road map for enhanced immunocompetence.

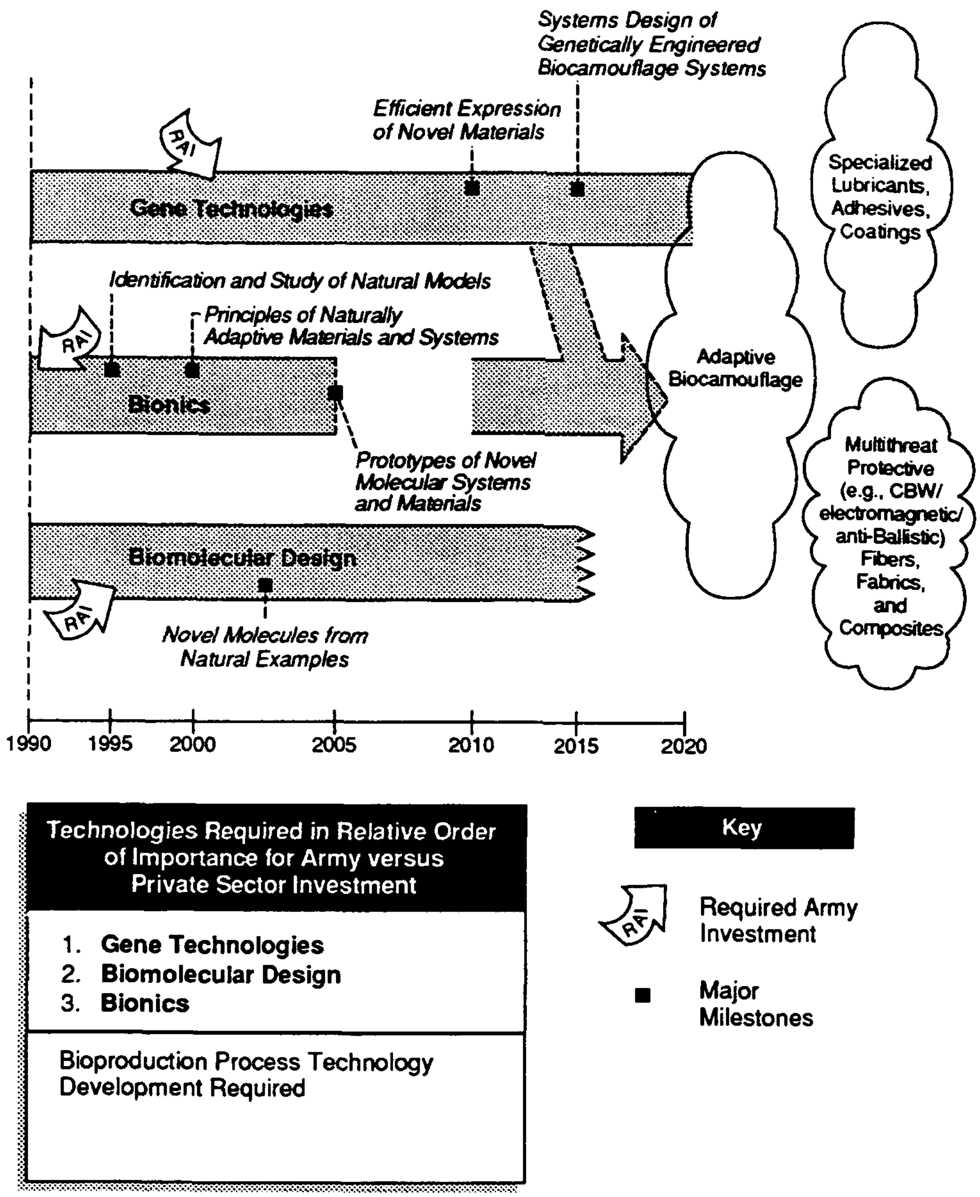


FIGURE 29-4 Road map for novel materials.

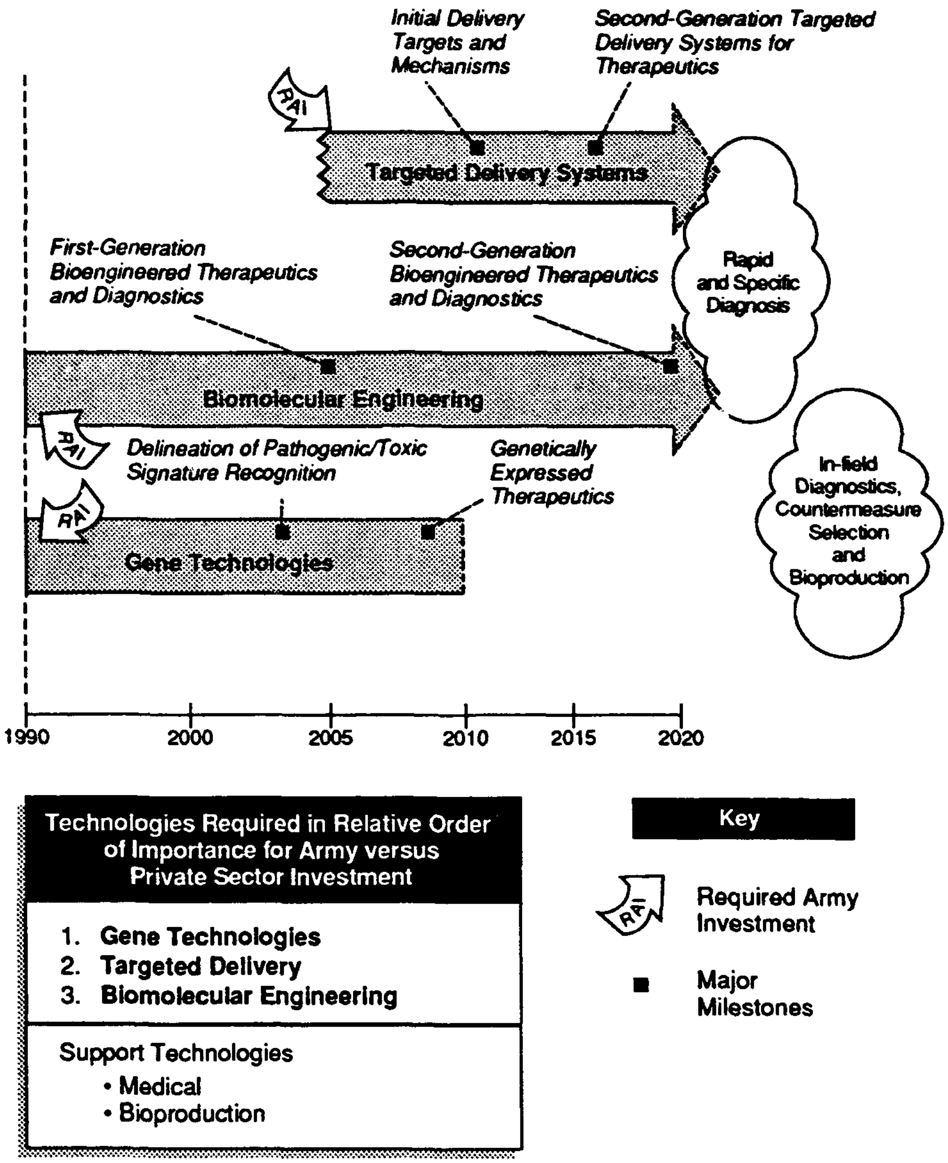
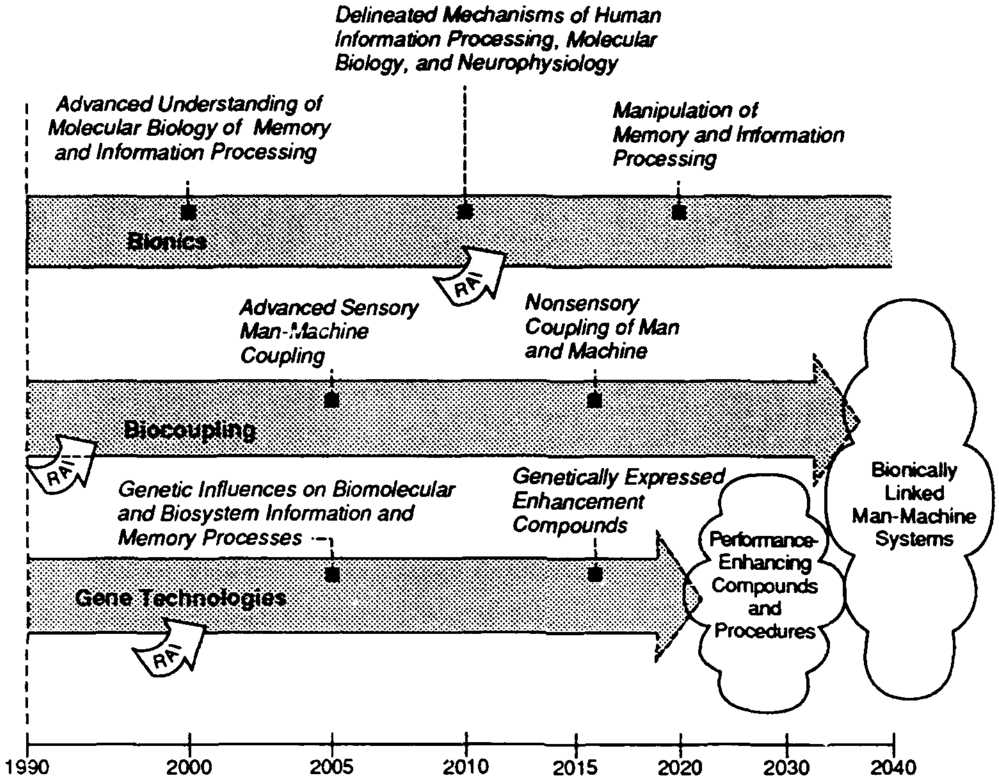


FIGURE 29-5 Road map for in-field medical diagnostics and therapy.



Technologies Required in Relative Order of Importance for Army versus Private Sector Investment
1. **Bionics** 2. **Biocoupling** 3. **Gene Technologies**
Support Technologies • Biomedical

Key

RAI — Required Army Investment

■ — Major Milestones

FIGURE 29-6 Road map for extended human performance.

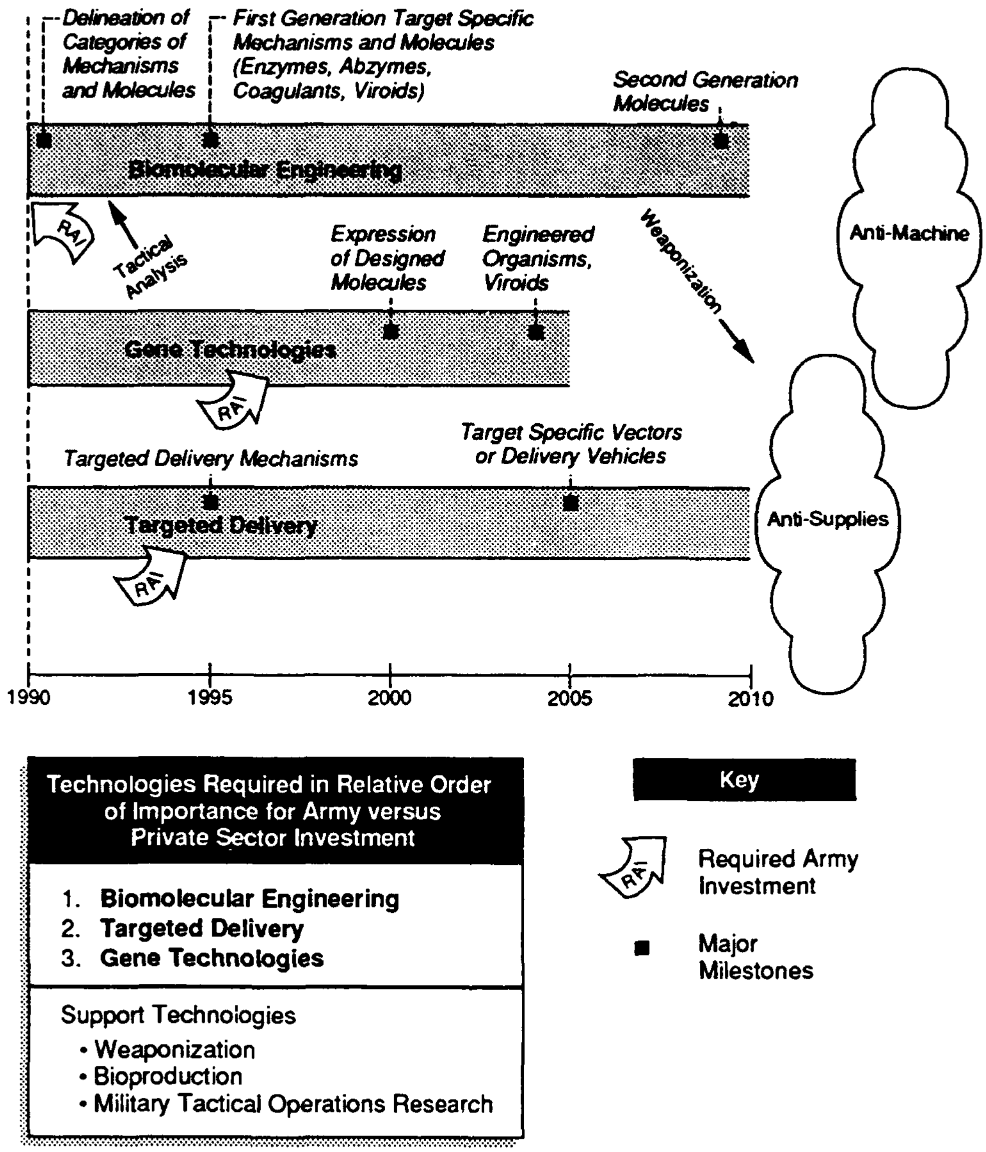


FIGURE 29-7 Road map for antimateriel products.

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Biotechnology and Countermeasures Against Chemical and Biological Warfare

Military conflicts in the next three decades will certainly involve the threat—and probably the use—of CTBW agents. Although some major military powers are preparing to sign treaties prohibiting both the repositioning and the stockpiling of chemical warfare agents, research on such weapons and ownership of them are actually proliferating. Biological weapons have been banned for many years, but it is generally believed, throughout the world, that such warfare capability does exist in several high-threat countries. Toxin-based weapons also have been developed by some countries, but political communities cannot agree on allegations of use. Ironically, as the focus of our international military role shifts from the sophisticated Warsaw Pact threat to the broader third-world spectrum of regional conflicts around the world, the probability of CTBW increases.

The consensus within DOD and the intelligence community is that the threat of these highly effective weapons will persist. Therefore, programs must pursue the full range of countermeasures, including detection and identification, protection, medical prophylaxis and therapy, and decontamination. Biotechnology can play a major role in developing and improving CTBW countermeasures. By contributing core information on the nature and actions of the threat agents, biotechnology can support the strategies for defeating them. The field can also contribute novel materials and capabilities for developing countermeasures.

Various CTBW agents exhibit a wide range of physical, chemical, and toxicological characteristics in their use scenarios. But these sobering facts are true of all of them:

- They are highly effective weapons of mass destruction that require much less sophistication to possess and use than nuclear weapons.
- Our present physical and medical countermeasures—the masks, suits, and drugs now available—allow only partial retention of warfighting capability.
- The precision of our knowledge about details of this threat (i.e., the exact chemicals, toxins, or organisms and their toxic mechanisms and physiological targets) will decrease as CTBW technology spreads throughout the world.
- Verification of the production or stockpiling of these weapons by either signatories or nonsignatories of treaties will be impossible or equivocal because of technical, political, and public uncertainties.

Considering the above factors, the use or threat of CTBW provides a significant tactical advantage to an aggressor. Deterrence must be equally effective, yet deterrence by retaliation in kind is not usually an option or an effective posture against chemical attack, and it is *never* an option for the United States against toxin or biological attack. A chemical attack would provoke a greater conventional response than would a conventional attack. If the attacked party holds back and responds in a graded fashion, then the CTBW threat has been effective. A preferable deterrent is a system of physical, instrumental, and medical countermeasures that eliminate the efficacy of CTBW agents without degradation of performance.

The usual categories of CTBW countermeasures include:

- detection and identification;
- physical protection;
- medical prophylaxis and therapy; and
- decontamination.

Although *retaliation in kind* with biologicals and toxins is considered a countermeasure by some countries, the United States does not consider it so. These agents are prohibited by law in the United States, and biotechnology will not be considered here for retaliatory countermeasures.

DETECTION AND IDENTIFICATION

The rapid and accurate detection and identification of use of CTBW agents are necessary to provide warning and to guide medical intervention and treatment. Detection and warning allow troops to don protective gear and reduce exposure. Accuracy and speed of detection are essential—accuracy because protective gear donned unnecessarily reduces fighting effectiveness, and speed because even small exposures to most agents can result in incapacitation. Identification of the challenging agents is necessary for guiding medical intervention. Appropriate medical intervention reduces casualties and promotes the *stand-and-fight* and *fast-return-to-duty* goals of medical prophylaxis and therapy.

Today's detection and identification techniques are based on analytical and physical chemistry; antibody-antigen recognition may be possible in the near future. Current techniques are too slow in detecting some agents, do not detect all agents now known, and are subject to false alarms that greatly reduce their effectiveness. Moreover, to detect an agent molecule or organism, present techniques, and even the next generation (mass-spectrum-based detectors), require that distinguishing characteristics of the agent be known years in advance of the fielded capability. These techniques will never keep up with the evolving CTBW threat. Thus, the single most perplexing problem in the area of detection and identification is the fact that one does not have and will not have a comprehensive list of threat agents. Any such list can change faster than it can be updated by our intelligence capabilities. This is particularly true of toxin and biological agents.

Biotechnology can contribute to the solution of this problem. Embedded in the genome of organisms and exploitable by biotechnology is highly specific molecular sequence information for the derivation and assembly of biological molecules and structures. This information can be used to distinguish categorically between agents and nonagents, even if they have similar characteristics and background interferences.

Gene technologies (along with the medical and biological understanding they have produced), biomolecular engineering, and biocoupling can combine to take detection and identification into the next generation of CTBW defensive strategies and beyond. The step past chemical and antibody recognition techniques is to devise a suite of *physiological receptors*: molecular systems that mimic human receptors for toxic agents and can distinguish between a toxic and a nontoxic challenge. Examples include the cell-surface-receptor binding step that precedes pathogen entry into a cell or the binding of a chemical to a neuronal receptor site. Conceptual work on these systems has begun only recently. The step past these techniques is the prediction of molecular structure and function to sort toxic from nontoxic, or the analysis of the genetic code of organisms to distinguish pathogenic from nonpathogenic entities.

These new approaches, which use specific receptors, the genetic code, and biomolecular structure–function relations, would provide not only warning of the presence of a threat, but also data on the physiological basis of the hazard and, thus, the appropriate medical intervention. Biotechnology will be absolutely essential to the success of these techniques and to any detection and identification program that will keep up adequately with the evolving CTBW threat.

PHYSICAL PROTECTION

Physical protection against CTBW agents consists of methods used to provide physical barriers between the soldier and the threat. Examples include masks with air filters, suits impervious to agent penetration, and shelters with air filtration and protected entries and exits. Physical protection will always be a critical aspect of CTBW defense because medical intervention after heavy exposure will not completely neutralize the effects of some types of agent (e.g., the simple corrosives such as phosgene, alkylators such as mustard agents, or the highly potent, efficacious nerve agents).

The primary concern with physical protection is the resulting task degradation, presently estimated to exceed 30 to 50 percent for some tasks. Physical barrier methods also severely shorten the duration of soldier performance. Moreover, some critical tasks cannot be routinely performed in CTBW protective gear because of such performance-degrading factors as a mask that restricts vision, breathing, talking, eating and drinking, and elimination; a suit that restricts the evaporation of sweat and the transfer of heat buildup; heavy rubber boots and gloves that greatly reduce dexterity; and a hood and poncho of rubber-like material that essentially eliminates ventilation and heat transfer. In hot climates, the full gear needed to protect against liquid vesicant or nerve agents has been compared to wearing a diving suit in a sauna. A soldier wearing gear in such conditions would be able to perform effectively for half an hour.

Biotechnology can play a role in improving physical protection, primarily through the development of materials that protect with less degradation of performance. In general terms, the new materials must be lighter, stronger, more impervious, and cheaper, while providing for heat transfer. Novel materials are needed. Concepts include combining the lightness and strength of silk or Kevlar-like fibers with the sheet characteristics (imperviousness) of rubberlike compounds. Pores for heat and vapor transfer must exclude the CTBW agents, perhaps with special chemical or enzymatic catalysts embedded as "pore guards." Blast-attenuating biocomposites are already in prototype evaluation. In 20 years, composite barriers to CTBW agents, incorporating special impedance mismatching characteristics to attenuate some blast and sonic interaction, will be possible; they also can be designed to help defeat white-phosphorus munitions.

MEDICAL COUNTERMEASURES

Medical prophylaxis and therapy against CTBW agents have the goals of (1) preventing degradation of performance and allowing soldiers to stand and fight, (2) decreasing morbidity and speeding the return to duty of those who experience some incapacitation, and (3) preventing the mortality of those who receive potentially lethal exposures. The realm of biomedical intervention is almost synonymous with biotechnology, and great strides can be made toward these goals by accentuating biotechnology now.

Unlike the detection and identification program, the current medical countermeasures program has the potential to target mechanistically similar compounds (nerve agents) and not just particular agents. However, many of the present medical countermeasures are aimed at individual disease or biological agents. Future programs must be as generic as possible; they must pursue such concepts as blood-borne *interceptor molecules* for blood-borne agents, cell-receptor blocking agents, blood filtering technologies, and targeted delivery of drugs to specific body sites. Also part of today's program are barrier compounds applied directly to the skin. This approach, coupled with sacrificial binding sites and agent-degrading moieties (e.g., enzymes), could greatly reduce the physical protection needed on the battlefield.

Biotechnology offers great promise for new approaches to counter blood-borne toxic molecules. For prophylaxis, concepts include catalytic interceptor molecules, which mimic the agent's target site, degrade the agent molecule after it binds, then reset. The interceptor-agent reactions occur at high reaction rates. Therapeutic concepts include extracorporeal filtration and antibody-based filtration beds. Broad-spectrum protection against pathogens will be feasible through the pharmacologic blockade of initial cell-binding receptors. As biotechnologists understand more about the immunologic recognition of pathogens and responses, they are likely to develop new methods for exposure and stimulation of the immune system that will enhance immunocompetence. New methods for the administration and delivery of prophylactic and therapeutic agents will be feasible with drug microencapsulation and targeted delivery systems. Rapid in-field diagnosis and triage for CTBW casualties by nonmedic cohorts will be feasible by combining biotechnology and artificial intelligence approaches.

DECONTAMINATION

Decontamination is required for several categories of CTBW exposure: personnel, the equipment of battle, support facilities, and terrain. Most of the work on decontamination has focused on the chemical part of the CTBW threat; much less work has been done to address decontamination of toxin and biological agents. Methods for decontaminating equipment have not changed greatly for a decade. Decontamination of personnel relies on resins and on washing, which produce contaminated waste. The decontamination of electronic equipment relies primarily on hot air for chemical exposures. As decontamination techniques, the current methods such as hot-air blowers, resins, scorched earth for terrain, and washing with DS2 (a corrosive decontaminating solution) can all be improved.

In particular, biotechnology offers enzymatic techniques for decontaminating personnel, smaller surface areas, and terrain (a form of bioremediation). When circumstances prevent the use of corrosive or toxic compounds (e.g., for skin or wound decontamination), the decontamination of toxin and biological agents could be done through the use of genetically engineered cells such as macrophages. This approach is a biotechnological update on the use of maggots for the cleaning of wounds. Some basic research programs in the enzymatic decontamination of chemical agents are under way, but there are no programs at present in engineered microbes.

SUMMARY

CTBW will remain, and perhaps grow, as a threat; it provides a significant tactical advantage to an aggressor. Deterrence will not be achievable by treaties or by retaliatory threats and postures short of nuclear response. Deterrence can best be achieved by a system of countermeasures that eliminate the efficacy of CTBW. Biotechnology will prove pivotal in developing such countermeasures. By exploiting biotechnology, the Army can greatly enhance its defenses against CTBW and deter its use.

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Biotechnology Tutorial

This tutorial is adapted from *Biotechnology: Opportunities to Enhance Army Capabilities* (Army Materiel Command, 1989). The material is being repeated here in updated form because the biotechnology field is new to many in the Army technology development and systems planning community who may not have ready access to the source publication.

OVERVIEW

Biotechnology is the manipulation of living systems, or parts of these systems, to produce or modify products. Using natural biological organisms and processes to produce substances is not a new concept. For centuries humans have relied on microorganisms to make bread, cheese, alcoholic beverages, and the like. Antibiotics are extracted from various strains of molds and bacteria. Animals and plants have been gradually improved through genetic husbandry (i.e., the breeding of animals and plants to produce offspring with the desired combinations of characteristics) and protected from diseases and insects through antibiotics and pesticides. Biotechnology became a science rather than an art when the actual biochemical changes involved in these processes were understood and controlled. The discovery of how microorganisms function and the unraveling of the mysteries of DNA (deoxyribonucleic acid) have initiated a scientific revolution that promises to be at least as great as the one ushered in by atomic physics.

Living organisms display a remarkably sophisticated ability to apply ordinary physical and chemical laws for their own uses. The science of biotechnology encompasses the search to understand these fundamental abilities of living organisms and harness them for use in the performance of particular tasks. The results of biotechnology research can be segregated into two categories: knowledge (understanding of the principles governing the biological processes) and applications (controlling the products that can be made). Already, pharmaceutical manufacturers have used genetically engineered microorganisms to clone great quantities of proteins, such as insulin, and other modifiers of biological response, such as antibiotics and vaccines. Specialty-chemical industries have used genetically engineered microorganisms in the production of alcohol, vitamins, high-grade oils, adhesives, and dyes. The synthesis of further, novel chemical compounds and organisms is practically limitless and poses quite an opportunity for biotechnologists.

BASIC BIOLOGY

Biotechnology primarily concerns the cellular and molecular activities of living things. To understand what biotechnology has already achieved and how it can be further applied, some basic knowledge about living organisms is important, especially regarding the structure and function of cells, protein molecules, and the genetic materials, DNA and RNA (ribonucleic acid).

CELLS

The basic unit of biological organization is the cell. Some living organisms, such as microbes, are made of a single cell; others, such as the human body, contain more than a hundred billion cells. Four types of microbes with properties especially important to the biotechnologist are fungi, algae, bacteria, and viruses. Yeast and bread molds are types of fungi that humans have used for centuries. Algae have the ability to derive chemical-bonding energy from sunlight. And bacteria have an astounding chemical versatility. Generally, cells may consist of thousands of complex chemicals constructed from simple building materials (largely carbon, oxygen, hydrogen, and nitrogen) found in the environment. The process within the cell that converts raw materials into useful substances is called metabolism.

PROTEIN MOLECULES

Within the cell, the metabolic process is coordinated and initiated by enzymes, which are proteins consisting of chains of individual amino acids. The number, type, and order of the amino acids give the protein molecule its individuality. There are 20 primary, naturally occurring amino acids. Given that they may combine in chains of any order and number, and that they form three-dimensional shapes, alone or in combination with other chains, the variety of possible protein molecules is immense. The human body, for example, has more than 30,000 distinct types of proteins, each with a different function: some carry oxygen, some protect from infections, others give muscle tendons their strength and resilience. A great deal of biotechnology research is concentrated on proteins that act as enzymes.

Enzymes are biological catalysts (enhancers) that speed up chemical reactions. They are typically named after the reaction they assist. For instance, the enzyme alcohol dehydrogenase catalyzes the removal of hydrogen from a molecule of alcohol. The key to an enzyme's power lies in its three-dimensional shape. Every chemical compound has a characteristic shape, and an enzyme will interact only with a shape that it matches or recognizes, in much the same way as a key fits a lock. Once an enzyme joins with its particular compound and completes its task, it is released, intact, ready to act again, as often as a million times per minute. These properties of enzymes—high selectivity and high catalytic turnover—offer the biotechnologist incredible speed and precision in controlling which molecules are selected to react and the homogeneity of the final product. Without the guidance of enzymes, chemical reactions within the cell would be chaotic.

GENETIC MATERIALS

The nature and function of living things depends greatly on the activities within individual cells. Within each cell, raw materials are metabolized, with the aid of enzymes, into substances useful to the organism. The blueprint, or set of specifications, designating exactly which substances the organism requires is stored by the genes. Each cell of an organism, even an organism as complex as the human body, contains the entire blueprint or genetic code of the whole organism.

The genetic code is a compilation of genes. Genes are made of DNA. A gene directs the production of proteins in accordance with the pattern of its DNA. DNA contains four basic building blocks called nucleotides. The nucleotides form long chains of varying patterns and lengths. It is these differences that lead to the production of different proteins. The DNA molecule is composed of two nucleotide chains bonded together and twisted into a double helix. While the length and pattern of DNA chains vary, the pairing of nucleotides between the chains follows fixed rules. This unvarying partnership of nucleotide bases enables the cell to make exact copies of its DNA blueprints and to then assemble proteins in a consistent, reproducible way.

Genetic engineering, the science of altering the genetic material within a cell to cause it to perform new functions, is possible because of the universality of this genetic code. Every living organism uses very similar systems to translate genetic information into proteins. This similarity allows a scientist to take the human genetic material that directs the production of insulin and insert it into bacteria, where it will reproduce human insulin. This genetic transfer transforms the bacteria into a miniature insulin factory.

KEY BIOTECHNOLOGY TOOLS

Key techniques developed by biotechnologists include the direct manipulation of genetic components, molecular modeling to understand structure–function relationships, protein engineering to produce specific proteins, and bioprocessing for biotechnology products.

GENETIC ENGINEERING AND BIOPROCESSING

Genetic engineering is the manipulation and control of gene expression, or the transfer of genetic material between organisms in order to increase production (expression) and/or improve product recovery. Genetic engineering, in its broad sense, may involve any of the following:

- recombinant DNA/cloning;
- the use of restriction enzymes (to cut DNA at specific locations);
- the transformation or transfection of cells (to insert foreign genes into new organisms);
- gene probes (to detect the presence of specific DNA or RNA sequences);
- monoclonal or polyclonal antibodies (to detect protein products);
- polymerase chain reactions (to amplify DNA);
- abzymes (catalytic antibodies) to cut proteins at specific locations;
- the use of specific cloning vectors;
- DNA, RNA, or protein isolation and purification;
- cell fusion, including hybridomas, for the amplification of antibody products; and
- the formation of transgenic animals and plants through the introduction of cloned DNA into fertilized eggs or plant tissue.

FERMENTATION AND BIOPROCESSING

Bioprocessing is the establishment and maintenance of organisms or systems for the production of desired products. These products can be either natural products or novel products derived through recombinant DNA procedures. Fermentation and bioprocessing include the following:

- using bioreactors for microbial and cell culture;
- immobilizing cells, enzymes, or antibodies;
- controlling cell growth in large volumes;
- cell harvesting and recovery; and
- purifying products.

MOLECULAR MODELING

Molecular modeling is the simulation of macromolecular structures in order to relate conformational characteristics (three-dimensional shape) and energy states to function. The use of computers to design and modify new macromolecules offers a tremendous advantage by shortening the time required to bioengineer the *best* or optimized solution to a particular problem. Computer calculations of bond energies, energy constants, folding, and stabilities assist in these tasks:

- identifying the most stable conformations of protein structures and active sites;
- guiding appropriate structural modifications or analog constructions; and
- *de novo* design of desired structures for specific functions.

Although computer technology significantly shortens the laboratory work required to obtain a particular product, a major challenge still facing biotechnologists, even if the entire primary sequence is identified, is predicting the exact shape a protein chain will have when it folds.

The field of biotechnology will expand rapidly in the next two decades, and this overview will rapidly become outdated. The reader is admonished not to consider this overview exhaustive.

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Biotechnology Glossary

This glossary, like the tutorial in the preceding chapter, has been adapted and revised from a report previously prepared for the Army Materiel Command, *Biotechnology: Opportunities to Enhance Army Capabilities* (Army Materiel Command, 1989).

Ablate. To remove by cutting, erosion, melting, evaporation, or vaporization.

Abzymes. Catalytic antibodies.

Affinity chromatography. A technique used in bioprocess engineering for the separation and purification of almost any biomolecule on the basis of its biological function or chemical structure.

Allosteric enzyme. An enzyme that can exist in two distinct spatial conformations, often more active in one form than another.

Amino acids. An organic compound carrying an amino group ($-NH_2$) and a carboxyl group ($-COOH$), the building blocks of proteins.

Antibiotic. A chemical substance used to interfere with bacterial metabolism. Antibiotics can be produced biotechnologically or synthetically.

Antibody. Any immunoglobular protein produced in response to a specific antigen that counteracts the antigen's effect, especially by agglutinating bacteria or cells, precipitating soluble antigens, or neutralizing toxins.

Antigen. A compound foreign to the body, usually a protein (e.g., a toxin or enzyme) or carbohydrate substance, capable of stimulating an immune response.

Bacteriophage. A virus that seeks and kills bacteria; also called "phage."

Bacteriorhodopsin. A protein found in the purple membrane of salt-loving bacteria that acts as a light-driven, trans-membrane proton pump.

Bacterium. Any of a large group of microscopic single-cell organisms with a very simple cell structure; distinguished from viruses by a capability to reproduce without host genetic material.

Base. On the DNA molecule, one of the four chemical moieties that, according to their order and pairing, code for the different proteins. The four bases are: adenine (A), cytosine (C), guanine (G), and thymine (T). In RNA, uracil (U) substitutes for thymine.

Bioactive. Biologically active.

Bioadhesive. Macromolecules produced by biological organisms that bind substances together.

Bioassay. Determination of the effectiveness of a compound by measuring its effect on animals, tissues, organisms, or cells.

Biocatalyst. A biological substance that enhances a chemical reaction, enabling the reaction to proceed under conditions different than otherwise possible.

Bioceramic. Mineralized complexes produced by biological organisms under ambient conditions.

Biochemistry. The chemistry or chemical processes of living things.

Biocoupling. The coupling of biological molecules to electronic or mechanical systems.

Biodegradable. Organic compounds that can be broken down (especially into innocuous substances) or mineralized by living things such as microorganisms.

Bioelectric. Electric currents produced by living things, capable of receiving or responding to electric current.

Bioengineering. The use of living organisms or their capabilities to produce and/or modify products.

Biologic response modulator. A substance that alters the growth or functioning of a cell. Includes hormones and compounds that affect the nervous and immune systems.

Biolumninesence. The production of light by living materials.

Biomaterials. Molecules synthesized in any substance or material produced by or derived from biological systems.

Bionic. Biological capability, performance, or characteristics enhanced by biological, mechanical, electrical, or chemical means.

Biopolymer. A polymeric substance (such as a protein or polysaccharide) formed by a biological system.

Bioproduction. The production of products or substances by processes using, in whole or in part, biological systems.

Bioremediation. The use of natural or genetically engineered organisms or enzymes for the degradation of contaminants in situ or in controlled reactors.

Biosensors. A molecule of system using biological substances that recognize targets with high specificity.

Biosynthesis. The formation of compounds by living organisms of components.

Biotechnology. The development or modification of substances or products by a biological process.

Catalyst. An agent (such as an enzyme or a metallic complex) that facilitates a reaction but is not itself changed during the reaction.

Cell. The smallest structural unit of living organisms that is able to grow and reproduce independently.

Ceramic. Of or relating to the manufacture of any product made essentially from a nonmetallic mineral (such as clay) by heating (e.g., porcelain, brick).

Chromosomes. Threau-like components in a cell that consists of DNA and proteins. Genes are carried on the chromosomes.

Clone. A group of genes, cells, or organisms derived from a single ancestor. Because there is no mixing of genetic material (as in sexual reproduction), the members of the clone are genetically identical to the parent.

Cloning. The process of deriving cells/organisms asexually from a single parent and hence genetically identical to the parent and each other.

Crystallography. The science of crystal structure and behavior.

Cytokines. Proteins that modulate the immune system.

Diagnostic. A product used for the diagnosis of disease or medical conditions. Both monoclonal antibodies and DNA probes are useful diagnostic products.

DNA. Deoxyribonucleic acid, the self-replicating molecule that forms the genetic material (chromosomes) found in the cells of all living organisms.

DNA probe. A molecule (usually a nucleic acid) that has been labeled with a radioactive isotope, dye, or enzyme and is used to locate a particular nucleotide sequence or gene on a DNA molecule.

Double helix. A term often used to describe the configuration of DNA molecule. The helix consists of two spiraling strands of nucleotides (a sugar, phosphate, and base) joined crosswise by specific pairing of the bases.

Elastomers. Any of various polymers having the properties of natural rubber.

Enzyme. A protein catalyst that facilitates specific chemical or metabolic reactions necessary for life.

Eucaryote. A cell with a discrete nucleus.

Feedstock. The raw material used for chemical or mechanical processes.

Fermentation. A process of growing microorganisms for the production of various chemical or pharmaceutical compounds. Microbes are normally incubated under specific conditions in the presence of nutrients in large tanks called fermentors.

Fusion. The joining of the membrane of two or more cells in hybridomas; the creation of a daughter cell that contains the nuclear material from parent cells.

Gene. A segment of chromosome containing the genetic code for a discrete protein.

Genetic code. The mechanism by which genetic information is stored in living organisms. The code uses sets of three nucleotide base pairs (codons).

Genetic engineering. Technology used to alter the genetic material of living cells in order to make them capable of producing new substances or performing new processes.

Genetic screening. The use of a biological test to screen for specific genes related to characteristics, inherited diseases, or medical conditions.

Hormone. A chemical that acts as a messenger or stimulatory signal, relaying instructions to stop or start certain physiological activities. Hormones are synthesized in one type of cell and then released to direct the function of other types of cells.

Hybridoma. The cell produced by fusing two cells of different origin. In monoclonal antibody technology, hybridomas are formed by fusing an immortal cell (one that divides continuously) and an antibody-producing cell.

Idiotype. The portion of an antigen that can be recognized by more than one antibody.

Immune system. The aggregation of cells, biological substances (such as antibodies), and cellular activities that work together to provide resistance to disease.

Immunity. Nonsusceptibility to a disease or to the toxic effects of antigenic material.

Immunoassay. A technique for identifying substances, based on the use of antibodies.

Immunodiagnostics. The use of specific antibodies to identify or measure a substance. This tool is useful in diagnosing infectious diseases and the presence of foreign substances in a variety of human and animal fluids (blood, urine, etc.).

Immunotoxins. Specific monoclonal antibodies that have a protein toxin molecule attached. The monoclonal antibody is targeted against a tumor cell, and the toxin is designed to kill that cell when the antibody binds to it.

Interferon. A class of lymphokine proteins important in the immune response. There are three major types of interferon: alpha (leukocyte), beta (fibroblast), and gamma (immune). Inteferons inhibit viral infections and may have anticancer properties.

Interleukin. A type of lymphokine whose role in the immune system is being extensively studied. Several types of interleukin have been identified. Interleukin-1 (IL-1), derived from macrophages, is produced during inflammation and amplifies the production of other lymphokines, notably interleukin-2 (IL-2). IL-2 regulates the maturation and replication of T lymphocytes.

Isomer. A chemical compound that contains the same elements and numbers of atoms as another compound or ion, yet is arranged in a different structure and exhibits different properties.

Isomerase. An enzyme that converts one isomer to another.

Isotropic. Identical in all directions.

Kevlar. The trade name of high-modulus synthetic aramid polymer based on the condensation product of *p*-phenylene diamine and terephthalic acid.

Labile compound or complex. Unstable under certain conditions.

Leukocyte. A colorless cell in the blood, lymph, and tissues that is an important component of the body's immune system; also called white blood cell.

Ligand. A group, ion, or molecule coordinated to the central atom in a coordination complex.

Lipid. Any of a variety of compounds insoluble in water but soluble in ethers and alcohols; includes fats, oils, waxes, and steroids.

Lymphokines. Proteins that modulate the immune system.

Lysozyme. An enzyme present in, for example, tears, saliva, egg whites, and some plant tissues, that destroys the cells of certain bacteria.

Macromolecule. A large molecule, by biological standards, such as a nucleic acid or proteins. Usually has a complex structure.

Metabolism. Any of the biochemical activities carried out by an organism to maintain life.

Microorganism. Any organism that can be seen only with the aid of a microscope; also called "microbe."

Molecule. The smallest particle of a substance that retains all the properties of the substance and is composed of one or more atoms.

Monoclonal antibody. A highly specific, purified antibody that is derived from only one clone of cells and recognizes only one antigen.

Morphology. The structure and form of an organism, excluding its functions.

Natural active immunity. Immunity that is established after the occurrence of a disease.

Natural passive immunity. Immunity conferred by the mother on the fetus or newborn.

Nitrogen fixation. A biological process (usually associated with plants) whereby certain bacteria convert nitrogen in the air to ammonia; one step in creating biomass from air.

Nucleic acids. Large molecules, generally found in the cell's nucleus and/or cytoplasm, that are made up of nucleotide bases. The two kinds of nucleic acid are DNA and RNA.

Nucleus. The discrete structure within eukaryotic cells that contains chromosomal DNA.

Ordnance. Collectively, military weapons; specifically, ammunition or items containing high explosives.

Passive immunity. Immunity acquired from receiving preformed antibodies.

Pathogen. Any disease-producing microorganism.

Peptide. A very short (2- or 3-link) chain of amino acids linked by amide [peptide] bonds—bonds resulting from a condensation reaction between the amino group of one amino acid and the acidic group of another.

pH. A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity.

Photosynthesis The conversion by plants of light energy into chemical energy, which is then used to support the plant's biological processes.

Plasmid. A small circular form of DNA that carries certain genes and support molecules and is capable of existing independently in a host cell.

Plasmin. A proteolytic enzyme that dissolves the fibrin of blood clots.

Plasminogen. The precursor of plasmin that is found in blood plasma and serum.

Polyclonal. Derived from different types of cells.

Polymer. A large molecule consisting of a chain of repeating smaller molecules.

Polymerase. A general term for enzymes that carry out the synthesis of polymers, including nucleic acids.

Polypeptide. Chain of amino acids joined by peptide bonds (shorter than a protein).

Polysaccharides. Any carbohydrate that is a polymer of simple sugars.

Prophylaxis. The prevention of, or protective treatment for, disease or hazard.

Protein. A compound class containing carbon, hydrogen, oxygen, and nitrogen; a chain of amino acids linked by peptide bonds, usually with a discrete, structurally dependent function.

Prokaryote. A cell without a discrete nucleus; generally considered to be a more primitive life form than a eucaryote.

Promotor sequence. A sequence of genetic material that turns on decoding and expression of genes.

Receptor. A molecule or aggregate, in or on a cell, that recognizes molecules and produces a response, usually metabolic, physiological, or mechanical.

Recombinant. The rearrangement of genes.

Restriction enzyme. An enzyme that breaks DNA in highly specific locations, creating gaps into which new genes can be inserted.

RNA. Ribonucleic acid, a universal polymeric constituent of all living cells, consisting of a single-stranded chain of alternating phospate and ribose units with the bases adenine, guanine, cytosine, and uracil bonded to the ribose, the structure and base sequence of which are determinants of protein synthesis.

Sensor. A device that responds to a stimulus and produces a detectable response.

Splicing. The removal of introns and joining of exons from DNA to form a continuous coding sequence in RNA.

Substrate. Material acted on by an enzyme in a biochemical reaction.

Toxin. A poisonous substance, usually produced by biological organisms.

Transducer. A device that translates signals and/or energy between systems; also, in biotechnology, something that brings about the transfer of genetic material from one microorganism to another.

Transduction. The transfer of genetic material from one host cell to another by a virus or phage vector.

Transfection. The infection of a cell with nucleic acid from a virus, resulting in replication of the complete virus.

Vaccine. A biophylactic that contains an antigen derived from neutralized whole organisms or parts of organisms, and which is used to develop immunity against disease. Vaccine preparations can be natural, synthetic, or derived by recombinant DNA technology.

Vector. An agent (e.g., plasmid or virus) used to carry new DNA into a cell.

Virus. A submicroscopic organism that contains genetic information but cannot reproduce itself. To replicate, it must invade another cell and use parts of that cell's reproductive machinery.

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Biotechnology Human Resource Forecast: the Science and the Talent—Concerns for 2020[1]

The most significant and difficult issue the Army will face in attempting to come to grips with the implications of advances in biotechnology over the next 30 years is the issue of human capital. Who will manage this science? Where are the centers of talent? The February 1990 issue of *Scientific American* poses the question precisely by asking, "Who will do science?" (Malcom, 1990.) Further evidence of the gravity of the situation is discussed in the Association of American Universities' study published in January 1990. The report, *The Ph.D. Shortage: The Federal Role*, was prepared by a nine-member group primarily made up of graduate school deans. Among its predictions: "This nation faces a serious shortage of Ph.Ds. A sharply increased demand will outstrip Ph.D. production before the turn of the century. Industry, government, and universities will be pitted against each other in a battle for critical human capital" (Association of American Universities, 1990).

Despite these concerns about the supply of qualified scientists and academicians, the pace of technological change (including biophysics, biochemistry, and biomedical research) is so rapid that it is beyond the capacity of any single firm or nation to manage. Clearly, developments in this technology far exceed the pace of innovation over the past two decades. In a seminal work, *Workforce 2000: Work and Workers for the 21st Century*, the Hudson Institute suggests that biotechnology "will be a race to stay ahead or a race to catch up" (Hudson Institute, 1988).

Planning strategically over a 30-year horizon is, at best, difficult. There are, however, several indicators that can help measure the degree of difficulty in managing the change needed to remain competitive in the future. Demographics, education, economics, and organizational issues all come into play when one attempts to define trends on the basis of currently available data.

It has become almost passe to point out that science and technology are in trouble in the United States. We regularly read in the press about a decline in research spending by U.S. corporations and the concern it is causing in the

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[1] This forecast and assessment of future human resource requirements was prepared by David W. Morris under contract to the National Research Council and at the request of the Biotechnology and Biochemistry Technology Group. The Technology Group is in substantive agreement with the arguments and conclusions presented here by Mr. Morris.

economic, scientific, and academic communities. For the first time in 14 years, spending on corporate R&D has not kept pace with inflation. The corporate world has shifted its allocation of economic resources for research toward applied science and specific product development and away from basic research. Furthermore, a smaller portion of biotechnical research is being accomplished in large laboratories where resources can be pooled, thus limiting the opportunity for significant advances. To maintain and improve the competitive stance of the science community and economy, we must deal with an array of converging demographic and educational trends.

Presently, the 18- to 24-year-old group (which includes most of the new entrants into colleges and universities) is decreasing, both in absolute numbers and in proportion to the population. Members of minority groups make up a growing part of the shrinking pool. By the year 2010, one in every three 18-year-olds will be African-American or Hispanic, in comparison with one in five in 1985. By the turn of the century, minority members, women, and immigrants will account for about 85 percent of new members of the workforce, whereas only one generation ago women made up some 30 percent of the workforce. By the year 2000, about half of the workforce will be female. This information is pertinent, particularly in light of the fact that only 900 female citizens received doctorates in chemistry between 1970 and 1982. In addition, of the 341 people who received Ph.Ds. in math in 1988 (compared with 619 in 1978), only one was African-American, two were Native Americans, and three were Hispanic. Fewer than 80 African-Americans have received doctorates in physics in the past 11 years, and fewer than 100 doctorates have been awarded to Hispanics, in the same fields. The future of scientific talent, particularly in biotechnology, will be starkly reduced unless major long-term initiatives are introduced in the near future.

In a series of articles from December 1988 through September 1989, *Business Week* addressed the issue of investment in human capital. It cited statistics showing that during the 1970s the U.S. labor force grew at an annualized 2.7 percent rate, but that for the next two decades the rate would be just over one percent. The demand for natural scientists, whose average skill requirements are among the highest in the economy, is projected to add up to 70 percent more workers between now and the year 2000. In *Workforce 2000*, the authors state, "Between now and the year 2000, for the first time in history, a majority of all new jobs will require postsecondary education. Many professions will require nearly a decade of study following high school." From these figures, one would assume that there will be a crisis on the supply side of educated and experienced biotechnology scientists.

In contrast to this rather bleak picture, the private sector is making incredible strides in biotechnology. Almost daily in the *Wall Street Journal*, one reads about new discoveries. Some recent examples in January 1990 were human genes that could turn plants into factories for medicines, nerve proteins that offer hope for victims of paralysis, and the ability to genetically modify or amplify food production. Almost all of these discoveries are the result of entrepreneurial scientists in startup biotechnology companies backed by venture capital.

The dramatic growth in venture-backed biotechnology businesses over the past decade attests to the fact that there is a pool of vital talent being attracted to higher-risk scientific ventures. Because only about a half dozen of the biotechnology startups of the past 10 years have been profitable, one can anticipate a recycling of scientific talent over the next 8 to 10 years. It is not expected, however, that this pool of talent will be attracted to academe or to government opportunities. In an article in the January 24, 1990 edition of the *New York Times*, the Association of American Universities reported:

> Approximately 65 percent of those who received doctorates in the physical sciences in 1987 had employment commitments in nonacademic sectors, with 50 percent in industry and 15 percent in other sectors. Across all fields, 50 percent of the 1987 doctorate recipients had employment outside academe.
>
> (New York Times, 1990)

With the companies backed by venture capital, as well as major biotechnology research labs continuing to establish strategic liaisons globally, the Army must increase its support of Independent Research and Development. The Army must identify emerging biotechnology it judges to have important defense applications and seek formal strategic relationships with the sources of those technologies on a global basis. It is almost impossible to foresee the Army being able to leverage from within, or, indeed, to compete economically, with either academia or private industry in the recruitment of biotechnologists. Therefore, it is critical to target support for extramural research programs with university and even with venture-backed startups identified as having excellent specialized biotechnology results for Army needs. This trend is already in place in the private sector. According to Shearson Lehman Hutton, the New York investment firm, by February 1989 more than 28 large pharmaceutical companies owned shares in 26 of the 46 biotech startups it surveyed. Scientists, industry, and nations will continue to invest strategically in biotechnology for its potential long-term payoff. Indeed, in February 1990, Genentech entered into a sale of 60 percent of its stock to Hoffman-LaRoche, a French pharmaceutical giant.

In light of the turnover in the startup biotechnology companies, the long-term demographics, and the disarray of the scientific curriculum in U.S. elementary and secondary schools, the United States must invest in making science a more attractive academic and career path for today's students. There is a need to stress radical national initiatives for extending the school year, for developing and creating general awareness of the potential for contribution to science in the field of biotechnology. The Army ought to consider long-term, specifically targeted, economically substantial initiatives to promote these issues. The competition for qualified personnel will increase exponentially over the 30-year time horizon. Therefore we must strive as a nation to increase the supply of competent scientists in the field.

References

Army Materiel Command. 1988. Biotechnology: Opportunities to Enhance Army Capabilities. STR Technical Report 89-3. Army Materiel Command, Directorate for Technology Planning and Management. (December):53-64. Adapted and reprinted with permission.

Army Science Board. 1989. International Cooperation and Data Exchange to Enhance Army's Technical Base. Army Science Board Summer Study. Army Science Board Office, U.S. Department of the Army. Arlington, Virginia.

Association of American Universities. 1990. The Ph.D. Shortage: The Federal Role. Washington, D.C.: Association of American Universities.

DOD. 1991. Critical Technologies Plan. U.S. Department of Defense. Washington, D.C. May.

Hudson Institute. 1988. Workforce 2000: Work and Workers for the 21st Century. Prepared for Employment Standards Administration, U.S. Department of Labor, by the Hudson Institute. p. 191. Indianapolis, Indiana. September.

Kamely, D.A., M. Chakrabarty, and S.E. Kornguth, eds. 1990. Biotechnology: Bridging Research and Applications. Proceedings of the U.S.-Israel Research Conference on Advances in Applied Biotechnology June 24–30, 1990. Haifa, Israel. Kluwer Academic Publishers.

Malcom, S.M. 1990. Essay: Who will do science in the next century. Scientific American. 262(2):112.

New York Times. January 24, 1990. Shortage of Ph.D.s Imminent, Report Says. January 24. B5.

Nigro, Pietro. 1989. Application of Membrane Affinity Separation for Biomolecule Purification and Diagnostics. Pp. 252–260. 7th Annual Membrane Technology/Planning Conference. November 17–19, Cambridge, Mass.

NRC. 1989. Opportunities in Biology. Committee on Research Opportunities in Biology, Board on Biology. Commission on Life Sciences. National Research Council. National Academy Press.

Olson, Steven. 1986. Biotechnology: An Industry Comes of Age. Academy Industry Program. National Academy of Sciences. National Academy Press. Washington, D.C.

U.S. Department of the Army. 1990. Army Technology Base Master Plan. 1990. Volumes I & II. U.S. Department of the Army. Washington, D.C. November.

PART VI

ADVANCED MATERIALS

ADVANCED MATERIALS TECHNOLOGY GROUP

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Summary of Findings for Advanced Materials

The technology assessments and forecasts made in this section describe various technologies in the area of materials science and engineering that are expected to have relevance to future Army needs. Due to budget constraints, it is not expected that the Army will actively fund all indicated areas; as a minimum, this Technology Group suggests that each of the technologies be monitored by cognizant Army personnel. Five of the technologies are deemed to have major potential impacts for the Army and should be identified as "strategic technologies" with appropriate funding commitments. Each of these technologies has been selected specifically because it could (with proper emphasis) lead to major improvements in the lethality, survivability, or reliability and maintainability of Army systems over the next 30 years. A brief summary of these technologies and their expected impact on the Army follows.

STRATEGIC TECHNOLOGIES

Affordable Resin-Matrix Composites

Major breakthroughs in processing (e.g., the elimination of the need for autoclaving through the use of thermoplastics) will lead to significant reductions in the cost of resin-based composites, making them much more attractive for general Army use. Ordered polymers or rigid-rod polymers will be used to form in-situ reinforcements, thus eliminating hand lay-up operations that are labor-intensive.

Cost reductions obtained through technological breakthroughs will lead to an increased use of these resin-based composites in Army vehicles. These benefits, coupled with those obtained through the use of advanced ceramics and light metals, will result in a new breed of lighter ground vehicles that are more affordable, are transportable by air, exhibit improved ballistic hardness, and are more compatible with low-observable approaches than are current structures.

Reaction-Formed Structural Ceramics

Currently most ceramic articles are made and consolidated by powder sintering processes. Certain difficulties with this approach (such as large shrinkage factors and deleterious reactions between matrix and reinforcing fibers) have led ceramists to investigate reaction-forming processes, in which consolidation is aided by the simultaneous reaction of constituents to form objects with near-net shape and dimensions. Two examples are (1) the formation of alumina matrix composites by the reaction of molten aluminum and oxygen and (2) the very rapid, self-propagating high-temperature synthesis (SHS) reactions that have been used to form titanium boride (TiB_2) armor.

The ability to form near-net-shape ceramics and ceramic composite articles by reaction forming will lead to considerable cost savings for ceramic parts. This in turn will open up new opportunities for ceramics in armor, antiarmor, and (diesel) engine components.

Light Metals and Intermetallics

Until very recently, it would have been appropriate to view aluminum alloy development as evolutionary, with advances coming slowly over time. However, the recent announcement of Weldalite™, an Al-Li alloy with strengths exceeding 100,000 pounds per square inch (100 kpsi)[1] or about 700 megapascals (700 MPa), suggests that even in a technology as mature as aluminum alloys, there is still room for major developments (Pickens et al., 1989). The current achievement of an aluminum alloy with greater specific strength and stiffness than steel will certainly be a factor to consider in choosing materials for future equipment of the Army. Likewise, this Technology Group expects that developments in intermetallics, especially those based on titanium aluminide (Al-Ti), will eventually lead to replacements for superalloys with half the density of nickel-based or cobalt-based materials.

Current and future developments in light alloys (aluminum and magnesium) and intermetallics (e.g., Al-Ti alloys) could lead to significant weight savings in ground vehicles and aircraft through reductions in the weight of structural components and gas turbine engines.

Metal-Matrix Composites

Most prior research and development (R&D) work on metal-matrix composites (MMCs) has concentrated on composites having aluminum matrices; the major objective has been to increase the elastic modulus. Such efforts have demonstrated that 30 to 50 percent increases in modulus can be achieved, which makes these aluminum composites comparable in stiffness to

[1] kpsi = 1000 pounds (1 kilopound) per square inch.

titanium. Perhaps more importantly, experience gained in these and other selected studies suggests effects that could be beneficial when applied to matrix metals other than aluminum. For example, incorporating various hard particulates in aluminum improves wear resistance. If this approach were applied to copper, it might yield improved materials for rail guns. The observation that particulate reinforcements can lead to dramatic reductions in grain size similarly could benefit the development of new shaped-charged and penetrator materials, in which small grain size is known to be highly desirable.

Based on these and other observations, this Technology Group suggests that in the next 10 to 20 years, a significant expansion of the MMC approach will take place. This development will have a major impact on the properties of steels, titanium, magnesium, intermetallics, copper, and heavy metals. For many of these metals, the emphasis will not be upon improving modulus but rather on improving other properties such as hardness, wear resistance, formability (through superplasticity brought about by grain-size reduction), and creep resistance.

By expanding the MMC approach to include a variety of other metals, the Technology Group anticipates that significant improvements can be achieved in gun-barrel erosion resistance, shaped-charge and penetrator performance, tank-tread wear resistance, rail gun performance, as well as many applications of interest to the Army. The potential of MMCs to significantly lighten high-firepower weapons so that they can be used by an individual soldier (i.e., a 20-pound shoulder-fired .50-caliber weapon) could revolutionize the combat capability of a rifle squad in low-intensity conflicts.

Energetic Materials

Currently the Army relies heavily upon two types of energetic materials for its explosives and propellants: HMX (cyclotetramethylene tetranitramine) and RDX (cyclotrimethylene trinitramine), respectively. Emerging technologies, however, may significantly change the energetics of the future. For explosives, new cage compounds that increase the atomic density of conventional explosives, and thereby increase their energy density, are expected to increase munitions performance. For propellants, an entirely new approach that relies upon the reaction energy of inorganics (such as thermite reactions) may provide a significant increase in the explosive power of future Army munitions.

These concepts, if successfully demonstrated, could lead to extremely compact and more efficient explosives and munitions for the Army of the future, thereby improving its lethality and survivability.

MEGATRENDS

In addition to the forecasts and assessments that deal with specific materials-related technologies, the Group believes it is worthwhile to include an assessment of "megatrends" that will affect a broad spectrum of materials and their uses. Three such megatrends appear especially relevant to future Army needs:

1. supercomputers to design materials and model performance;
2. technology demonstrators; and
3. multifunction materials.

The Role of Supercomputers in Designing Materials and Modeling Their Behavior

A recent report by the National Materials Advisory Board provides an authoritative and optimistic view of projected benefits that supercomputers will have on future materials technology (NRC, 1991). The report suggests that the advent of new and powerful supercomputers and advanced algorithms will make possible the computer simulation of materials behavior under a variety of environmental and manufacturing conditions. Simulation, in turn, is expected to provide cost-effective methodologies for producing tailor-made materials having optimal design for the intended application. Simulation modeling will also redirect the current tendency to overdesign with traditional materials in "proven" but cumbersome methods of usage.

Opportunities for applying the computational capability of supercomputers exist over a broad range of materials and materials problems, including: (1) band-gap engineering to design new infrared detector materials, (2) causes of stress-corrosion cracking, (3) weld simulation to improve weldability, (4) understanding high-strain-rate phenomenon (both single-cycle and repetitive), (5) developing new metal-forming procedures, and (6) modeling fracture mechanics. Another application that could have a large payoff for the Army is alloy design, where it may be possible to develop lightweight intermetallic alloys that could replace steel directly. For example, the titanium aluminides with densities about half that of steel exhibit a number of desirable properties but suffer from a lack of room-temperature ductility. In all cases, of course, data bases for the suggested applications will need to be developed.

One approach for improving the situation for intermetallics, where ductility is limited by their noncubic crystal structures, is to find alloying agents that will convert these undesirable structures (e.g., $D0_{22}$) to a more desirable cubic form (e.g., $L1_2$). Empirically, it has been found that small (8 percent) additions of copper can effect such a transformation in Al_3Ti.

A posteriori electronic structure calculations by Eberhart et al. (1990) provide a first-principles rationalization of that effect, as shown in Figure 34-1. The addition of 8 percent copper to Al_3Ti converts its crystallographic structure from a noncubic $D0_{22}$ form to a cubic $L1_2$ form, which has more desirable mechanical properties. Electron density maps (Figure 34-1b) derived from cluster calculations provide an explanation for this change and a starting point for future attempts to make custom-designed intermetallics for lightweight structures.

From such a starting point, it may prove possible in the future to perform such calculations *a priori* for other systems. This advance could shorten the time needed to achieve custom-design materials (by appropriate alloying) to meet the Army's continuing requirements for lighter-weight structures.

Increased Use of Technology Demonstrators

One of the largest obstacles in transferring a new material or processing technique from the laboratory to applications in components and systems is the uncertainty and risk of using an unproven entity for the first time. Computer simulation of a material's behavior in different environmental and stress conditions (multifactor stress aging) may serve to relieve some of these concerns, as noted above, but it is anticipated that a much greater use of technology demonstrators will be required in the future to ease the transfer.

The use of technology demonstrators, which is not new to the Army, can be illustrated by the following: The Materials Technology Laboratory recently conducted a program called the "Combat Vehicle Composite Hull" (Figure 34-2). In this case, the intent was to evaluate the concept of replacing welded plates on a combat vehicle hull with composites. The results, briefly, were a 25 percent weight saving at equal ballistic protection and a "proof-of-principle" demonstration of producibility by the selected processing procedures. The Technology Group expects that the proof-of-principle approach will assume a much larger role in future Army procurements to ensure timely transfer of new materials and, of equal importance, new processing and construction techniques. Promising areas for future technology demonstrators include composite and other advanced materials for gun systems and engine demonstrators using materials such as intermetallics, MMCs, and ceramics.

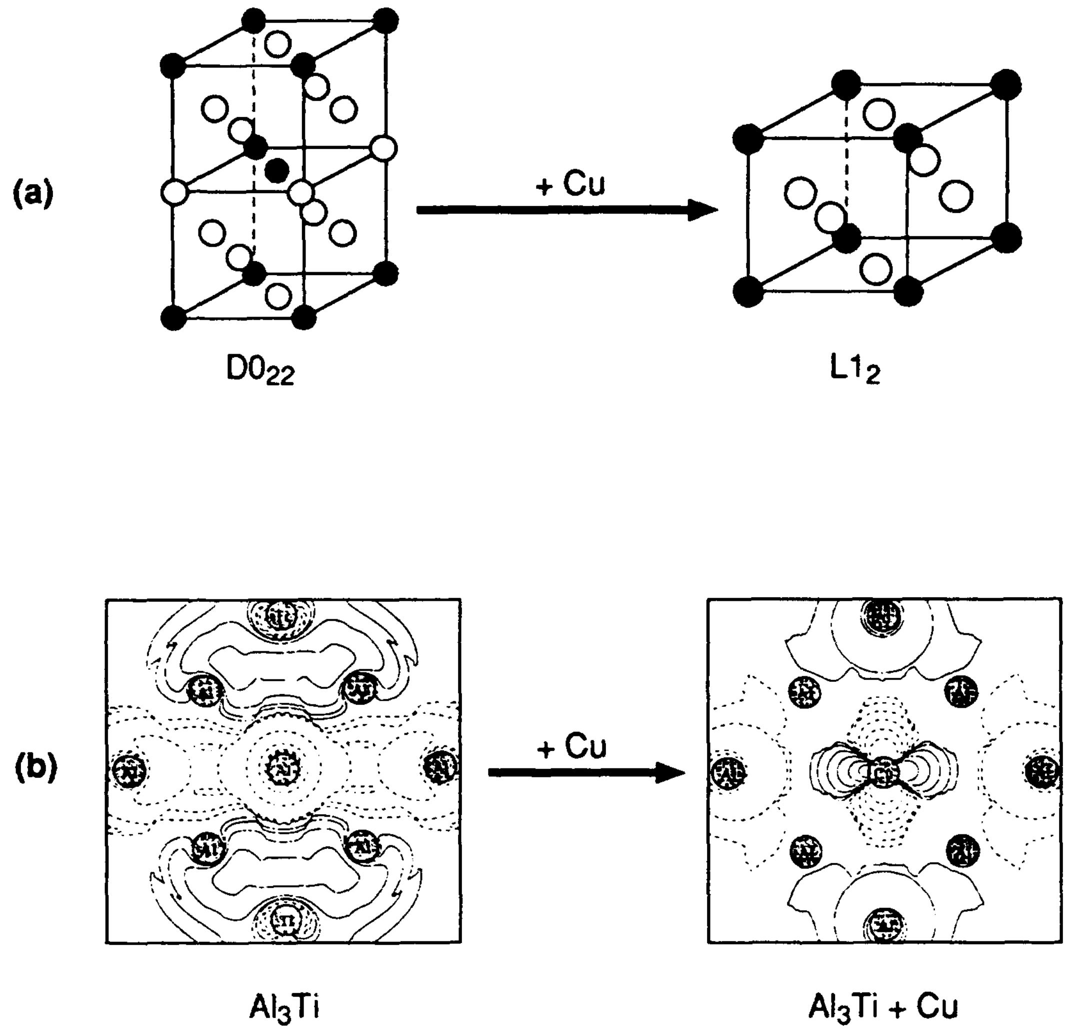

FIGURE 34-1 Structural change of Al_3Ti by addition of copper (a) is explained by electron density maps (b). Electron maps from Eberhart et al., 1990. Copyright © Taylor & Francis Ltd.

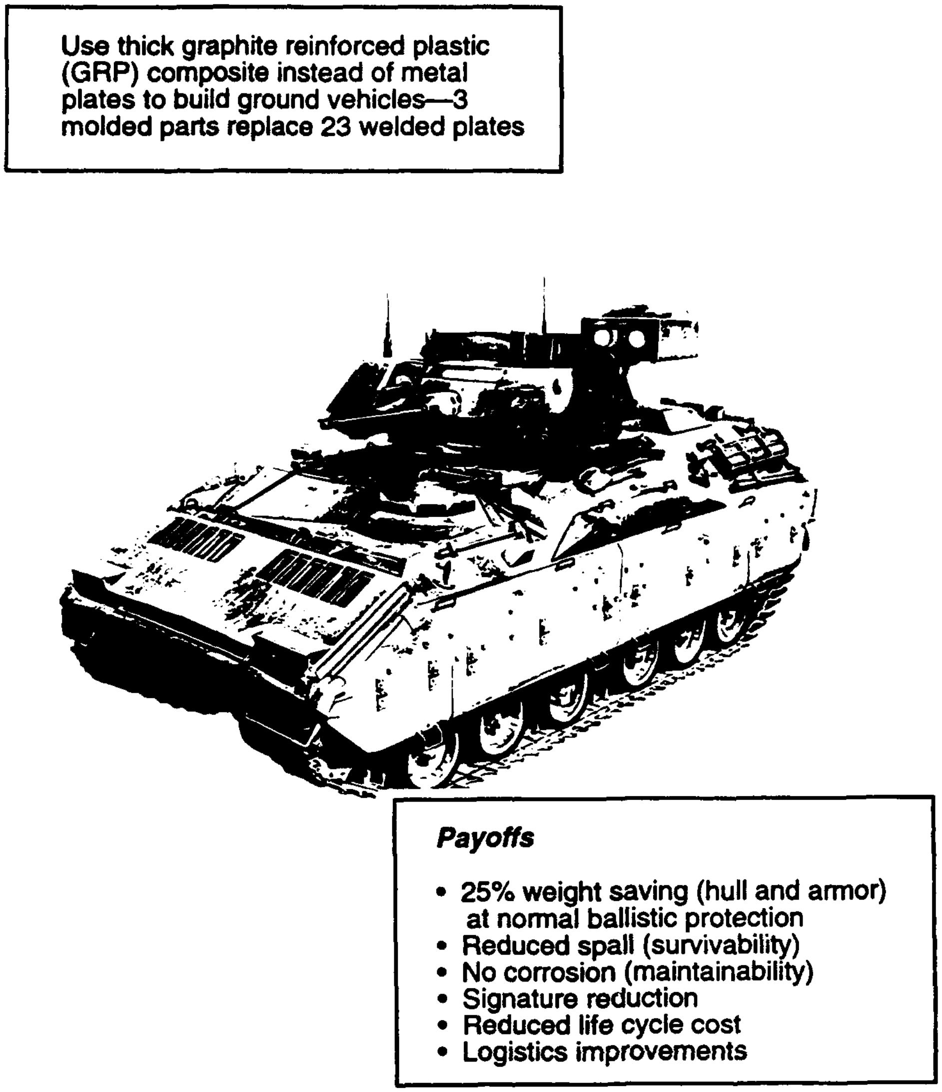

FIGURE 34-2 Technology demonstrator of composite hulls for combat vehicles. Concept courtesy of U.S. Army Materials Technology Laboratory.

Increased Use of Multifunctional Materials and Structures

In the future, the Technology Group anticipates a dramatic increase in the use of multifunctional materials—materials and even structures that are designed to serve more than one purpose. One example would be a ceramic composite that is designed to function as effective armor (e.g., for a tank) but is also designed to exhibit stealth characteristics at microwave frequencies and a variable emissivity in the infrared region for camouflage purposes. The driving force for designing such a material is, of course, to overcome the tendency to add layer upon layer of different materials on a tank's surface, for example. Each layer increases the vehicle's weight and detracts from its maintainability.

In the category of multifunctional structures, "smart structures" offer the prospect of substantially enhancing the performance of Army equipment. One concept employs embedded fiber-optic sensors to monitor cure temperatures and rates during manufacture of composites. These sensors will then monitor the stress and strain state of the vehicle during operation. Such structures provide the opportunity to monitor the "health" of the material, assess any damage, and perhaps even control vibration (Figure 34-3).

Many multifunctional materials and structures will of necessity be hybrid materials systems, where many different materials are brought together to accomplish certain design goals. Combining such materials, which may have different thermal expansion coefficients, moduli, and so on, will present a challenge to the designer, as well as to the materials scientist, to ensure overall compatibility. An example of such a structure is a proposed rail-gun barrel, which is shown in cross section in Figure 34-4. Here, electrical conductors, ceramics, and metal layers (to achieve adequate hoop strength) are combined. Many other such hybrid systems, particularly in the armor-antiarmor area, are expected to play a major role in the Army of the future, but they will be successful only through an integrated effort among designers, materials scientists, and production engineers.

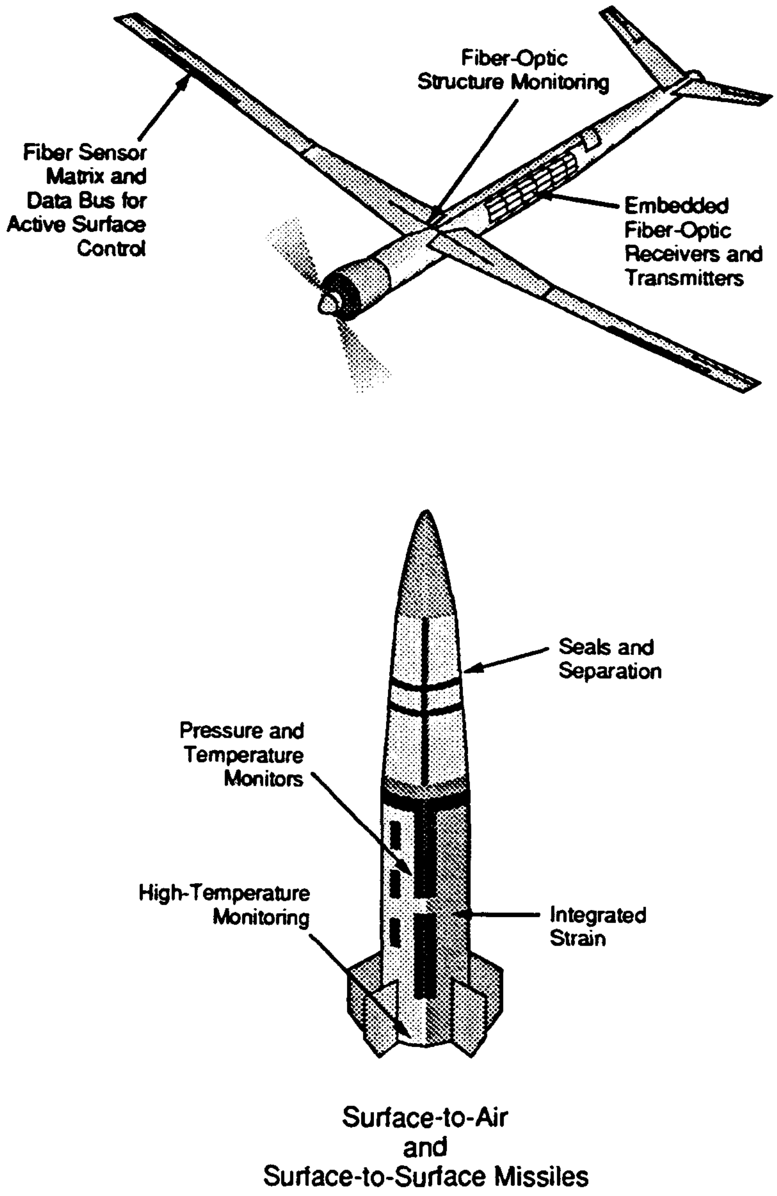

FIGURE 34-3 "Smart" structures will be used in advanced aircraft and in surface-to-air and surface-to-surface missiles to monitor and control a range of environmental performance parameters.

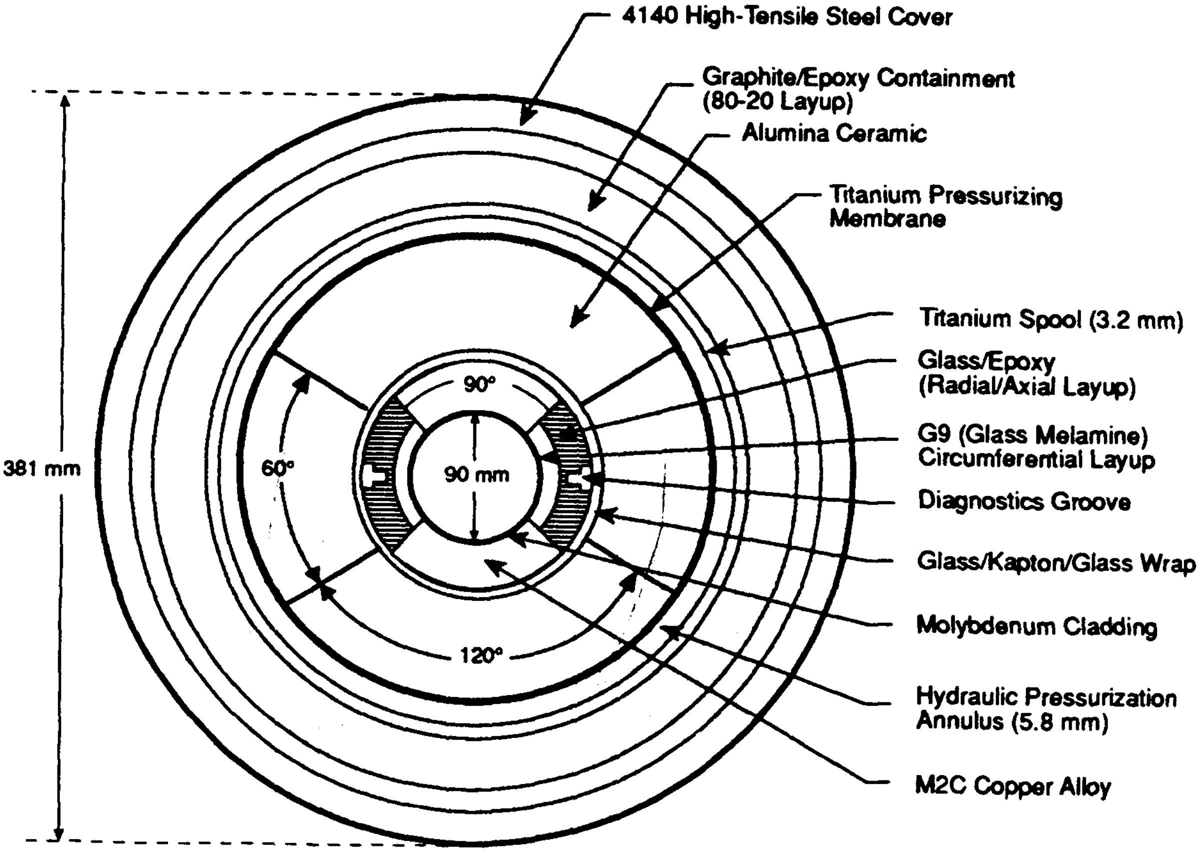

FIGURE 34-4 Cross section of a proposed rail-gun barrel, illustrating the increased role of composite structures in armor-antiarmor applications. Courtesy of U.S. Army Armament, Munitions, and Chemical Command.

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Resin-Matrix Composites

TOUGH ORGANIC-MATRIX COMPOSITES

Throughout the development of organic-matrix composites for structural applications, there have been conflicting requirements for high strength and stiffness coupled with high toughness. Toughness, which is defined in metallurgy as the area under the stress-strain curve for a material, is a measure of a material's ability to absorb energy with minimal damage, as well as to resist crack propagation. Early attempts at toughening organic-matrix composites by adding a rubbery phase to the base polymer have resulted in measurable increases in toughness levels but with an unwanted decrease in matrix stiffness. As Figure 35-1 indicates, composites made from tough matrix materials (thermoset or thermoplastic matrices) either have less than optimum static mechanical properties or do not exhibit the same toughness levels attainable with the matrix alone.

Future advances in molecular engineering of polymer structure and materials engineering of matrix composition may result in both strength and toughness in the same matrix material. At the constituent level, thermoplastic matrices are tougher than thermoset matrices in ability to absorb energy and resistance to crack propagation. Alloying or blending of an inherently tough polymer (e.g., a thermoplastic) into the base polymer has been successful. Engineering plastic blends, such as toughened nylon containing a polyolefin, are examples.

The type of reinforcement can also have a large effect on toughness. Impact performance of glass-reinforced polymers decreases, compared with the unfilled material. But for impact-modified polymers, the toughness is improved by the addition of chopped glass fibers. Carbon fibers with increasing strain capacity are being produced with higher toughness because of their inherent energy-absorbing fibrillar microstructure. A qualitative understanding of the role of fiber-matrix adhesion on toughness is just now emerging. Advances in tailoring this interphase offer a potential avenue for optimizing composite toughness in the future.

At the macroscopic level, engineering of organic-matrix composites through the use of toughened matrix material interleaved between plies is proving to be successful. The use of material variations and interleaving offers the possibility that composite structures with locally varying toughness can be fabricated. Integration of existing textile technology, which allows multiaxial placement of reinforcements, will be a major step in optimizing three-dimensional composite toughness. Toughness levels of organic-matrix composites, as measured by Izod impact strength, have been raised from a few

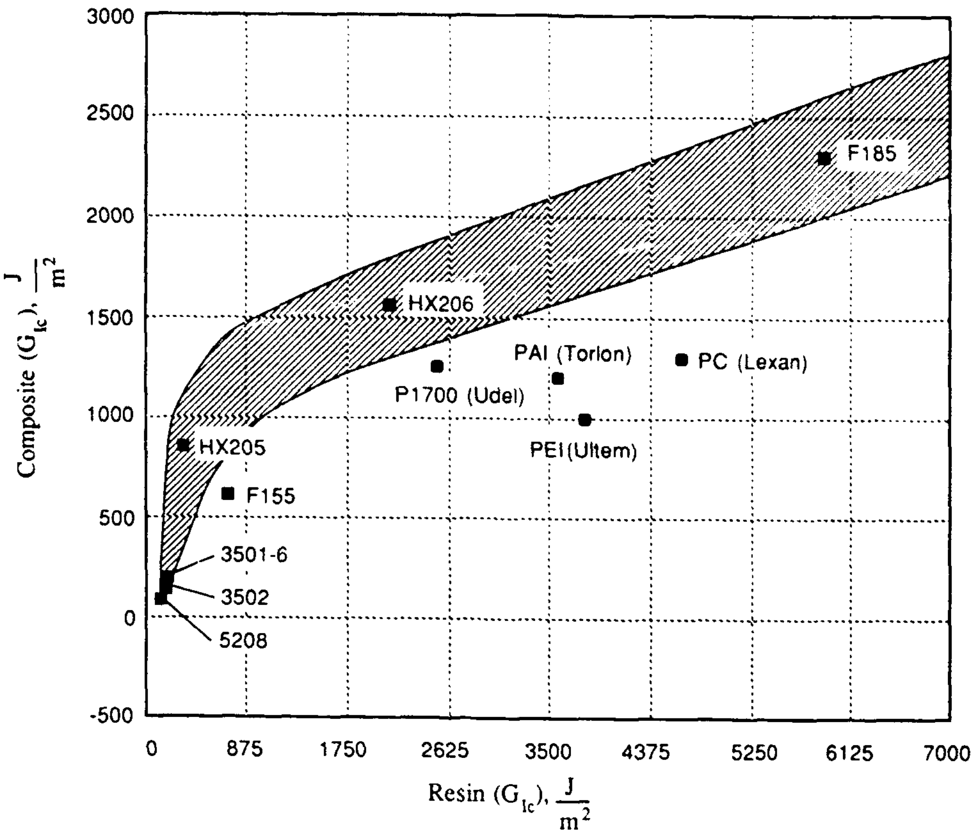


FIGURE 35-1 Composites made from tough matrix materials (thermoset or thermoplastic matrices) either have less than optimum static mechanical properties or do not exhibit the same toughness levels attainable with the matrix alone. Courtesy of NASA Langley Research Center.

foot-pounds per inch to over 30 ft-lb/in. (Figure 35-2). Although metals have an Izod impact strength around 100 ft-lb/in., the gap between the two classes is decreasing. Future research offers the possibility of organic-matrix composites with the same toughness levels as metals.

HIGH-TEMPERATURE ORGANIC-MATRIX COMPOSITES

Structural materials must perform over a wide temperature range. The properties of organic matrix material are very temperature-dependent. Where formerly only thermoset matrices could provide the required stability at high temperature, new semicrystalline and thermotropic liquid crystalline polymers can compete with, and in some cases exceed, conventional thermoset performance (Figure 35-3).

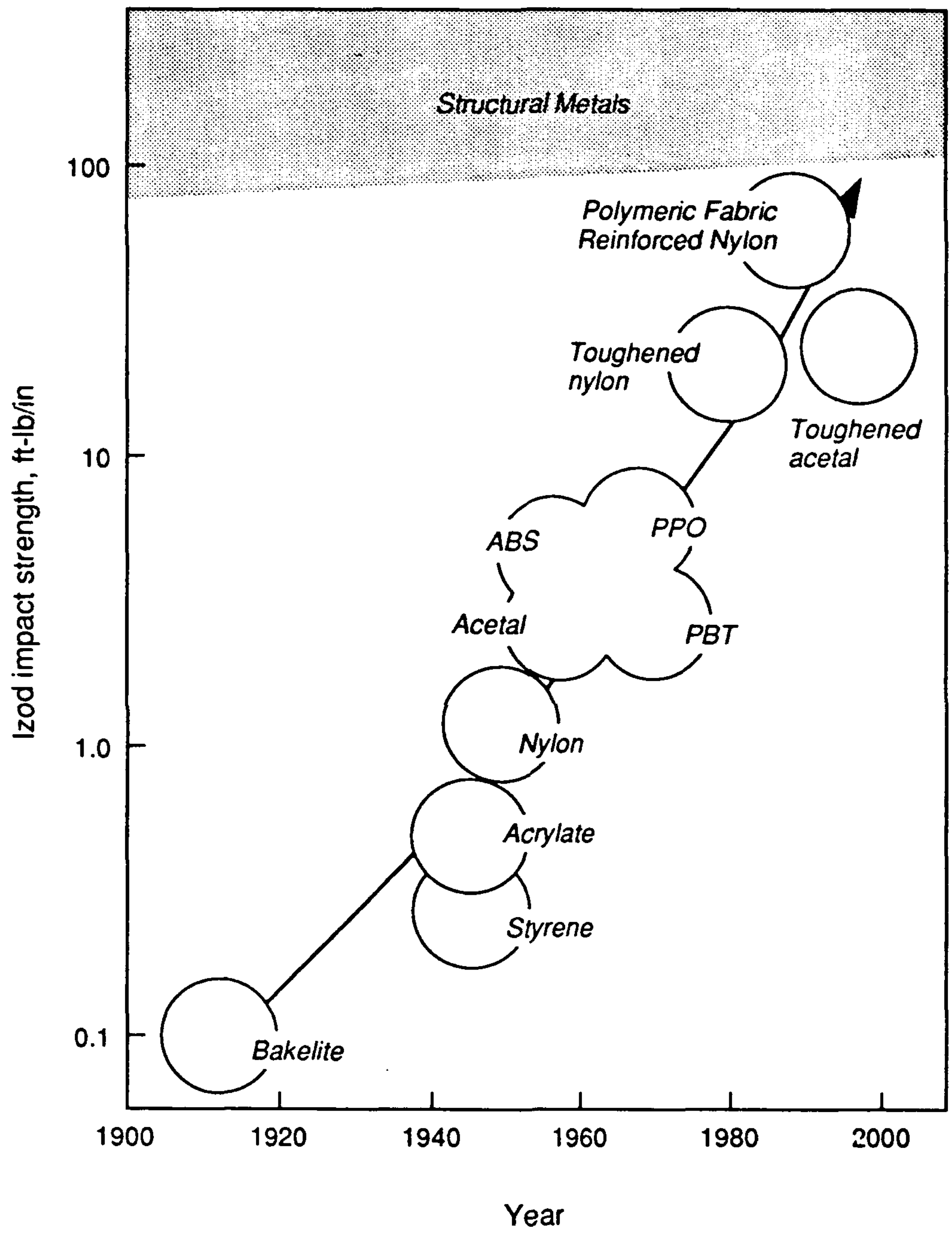


FIGURE 35-2 Toughness levels of organic-matrix composites as measured by Izod impact strength. ABS is acrylonitrile butadiene styrene; PPO is polyphenylene oxide; PBT is polybutylene terephthalate. Source: Advanced Materials and Processes, 1989. Copyright © ASM International.

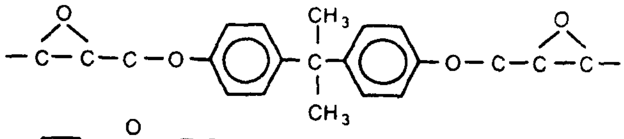
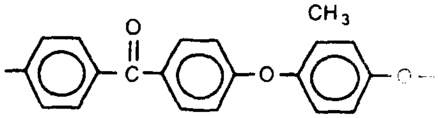
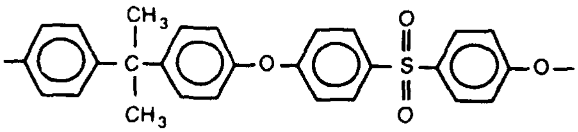
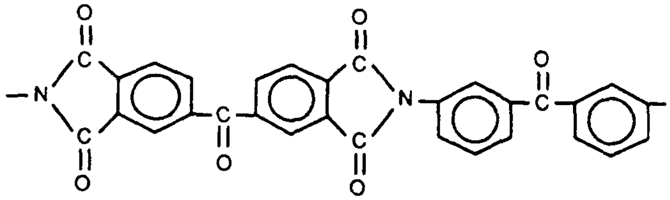
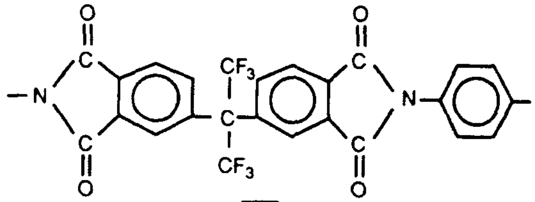
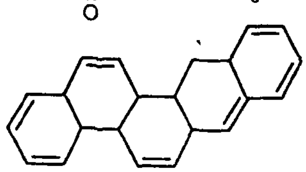
	T_g (°C)	
Epoxy	175	
Polyether ether ketone	143	
Polyarylene ether sulfone	190	
Polyketo imide	246	
Polyarylene imide	360	
Carbocyclics	> 400	

FIGURE 35-3 High-temperature semicrystalline and thermotropic liquid crystalline polymers. the glass transition temperature, T_g, indicates the upper limit of thermal stability.

The stability of polymeric systems depends ultimately on the chemical bonding between atomic elements in the polymer. For organic-matrix composites, molecular engineering of the polymer backbone (to reduce oxygen content, and then to increase aromatic content) has resulted in increases in temperature limits for continuous use and intermittent use (Figure 35-4). The addition of inorganic reinforcements also provides short-term increases in performance at high temperatures.

New possibilities for using organic-matrix composites and for taking advantage of their inherent specific strength are approaching a continuous-use temperature of 350°C; this overlaps with the temperature limitations of some current metal alloys (Figure 35-4). Advances in synthetic routes to produce ladder polymers containing carbocyclic or heterocyclic rings joined through the sharing of common sides offer the possibility of polymers with properties that lie between those of current thermoplastics and graphite.

Synthesis of new high-temperature polymers may be limited by the complexity and expense of the conventional chemical synthesis procedures required. However, biochemical approaches have been demonstrated for the production of commodity chemicals from starch and cellulosic materials. In the future, biosynthetic routes for new monomers having higher aromatic contents are a desirable possibility (Figure 35-5).

Polymers with higher temperature limits will find applications in the power plant region of vehicles, as well as in weaponry in which intermittent exposure to high temperatures occurs. Design of missiles and ordnance will benefit from incorporation of high-temperature polymers where one-time use is intended. Besides structural applications in or near hot areas, polymers will see growing usefulness as sealants and adhesives. Engine applications involving containment of fluids at elevated temperature and pressure are obvious beneficiaries of this material. Improved efficiency and reliability can be expected. Substitution of polymeric materials for metallic components in the hot areas of vehicles offers enhanced low observability.

ORDERED POLYMERS

To a large extent, the molecular structure and the morphology of polymers limits the mechanical properties that can be obtained with them. The carbon–carbon bonds prevalent in most organic polymers are very strong, but the density of these bonds per unit of cross-sectional area is low, because of the conformation of individual polymer chains. If the degree of alignment between polymer chains can be increased so that the density of bonds is increased, substantial gains in mechanical properties are expected. Efforts to create a higher degree of axial order between polymer chains have resulted in a generation of ordered polymer reinforcing fibers (Figure 35-6). Poly(paraphenylene terthalamide) is the first ordered polymer fiber with

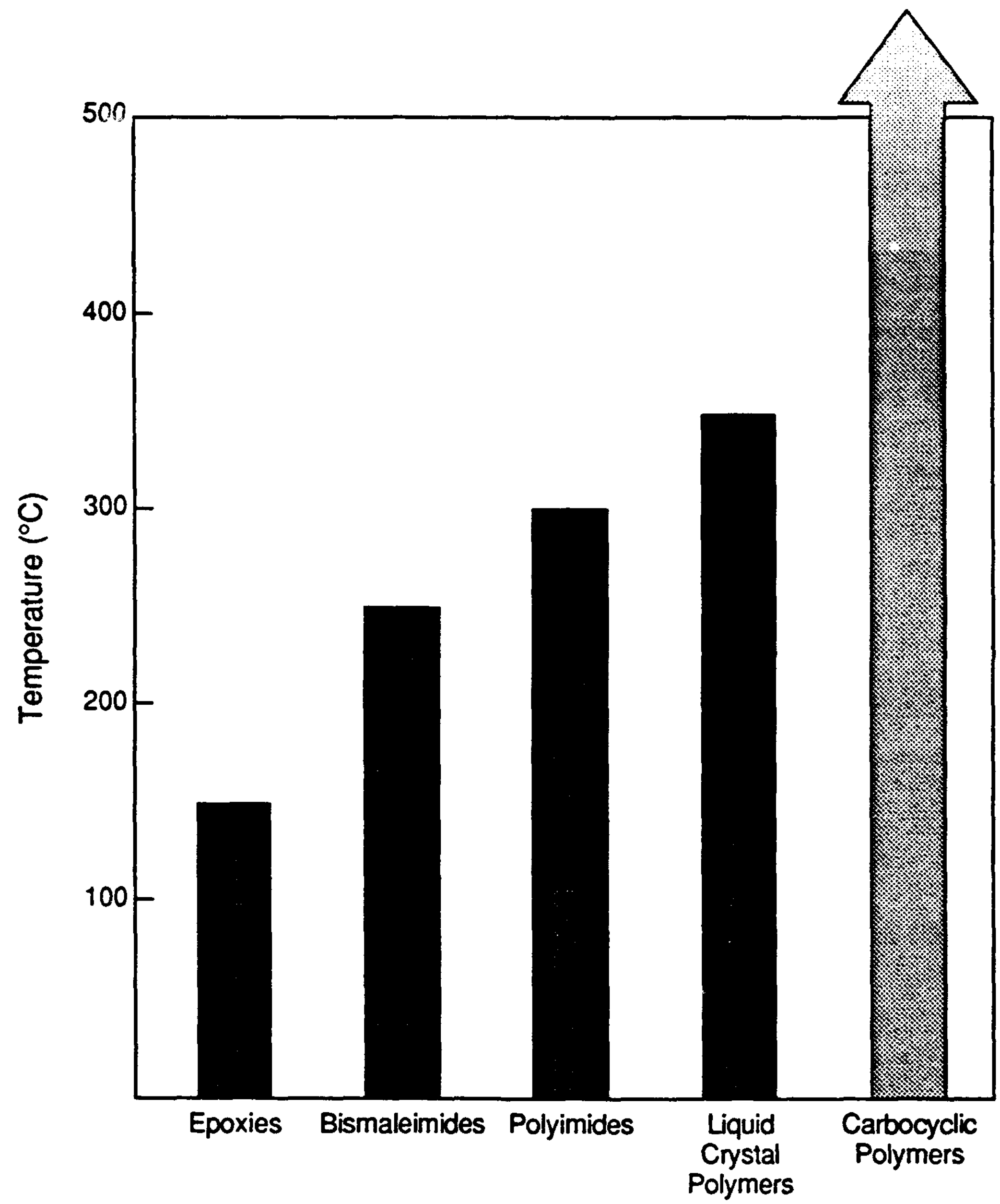


FIGURE 35-4 Continuous-use thermal stability of polymeric matrices.

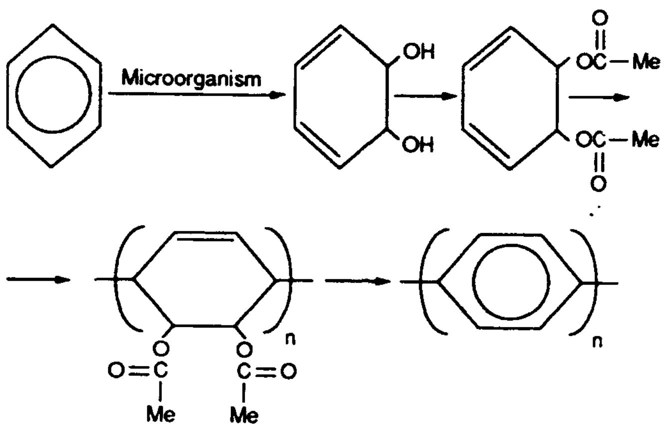


FIGURE 35-5 Biosynthesis of polyphenylene. (Concept courtesy of NAVAIR biotechnology research program.)

major commercial applications. A newer polymer fiber—poly(paraphenylene benzobisoxazole)—offers higher strength and higher temperature performance.

Significant new advances are possible by tailoring the chemical backbone of polymers to increase the rigidity of the chain itself. Linear carbon–oxygen bonds, aromatic linkages between carbon atoms, and other rigid atomic linkages contribute to stiffening the polymer backbone. While fibers and films can be made from these materials, their greatest potential may be the incorporation of these rigid-rod polymers within another host matrix, resulting in molecular-level reinforcement of the matrix polymer. Normally, polymers attain moduli of 5 billion pascals (5 GPa); threefold increases have been attained by incorporating rigid-rod polymers. The advantages for the continued development of this new class of materials are that molecular-level reinforcements are easier to process, have no fiber-matrix compatibility problems, and can be more easily fabricated into components with complex geometries. Substantial additional increases in mechanical properties are possible through combination with different matrices, even inorganic ones.

The ability to create polymers with mechanical properties that are orders of magnitude higher than conventional polymers, without incorporation of conventional reinforcements, offers many new application opportunities to the Army. Polymers are inherently transparent to electromagnetic radiation. A structure fabricated with reinforcing fibers of ordered polymers or molecular composites, or both, would offer new flexibility in the design of low-observable systems. The increase in specific modulus and strength would reduce weight and improve efficiency (see Figure 35-7). The small size of the molecular

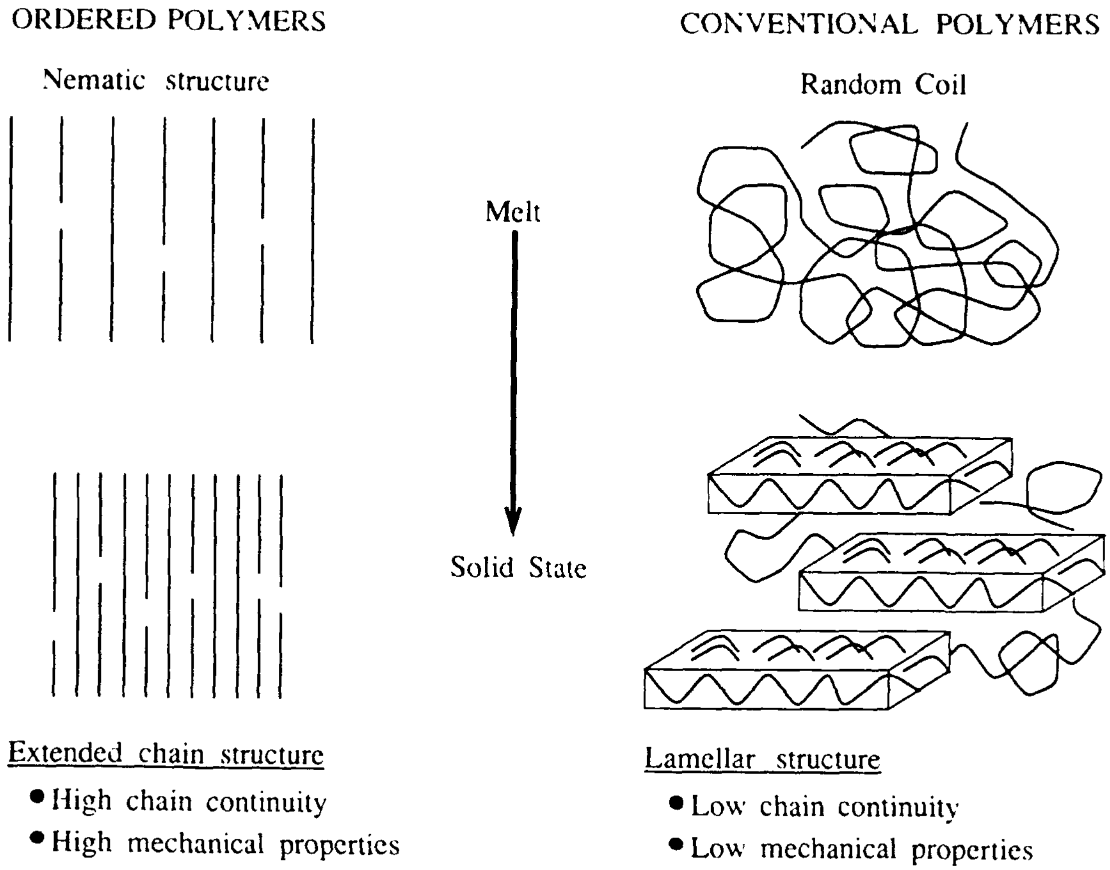


FIGURE 35-6 Ordered polymers versus conventional polymers. Adapted from Canundann and Jaffe, 1982.

reinforcement would allow increased flexibility in design, processing, and fabrication of complex structural shapes. Inorganic host matrices could also be combined with these reinforcements, giving rise to new hybrid materials. Armor for the individual soldier will be a major beneficiary of this technology. For example, an early demonstration of the potential for this class of materials is the 33 percent weight reduction in the standard helmet (from 3.5 to 2 lbs.).

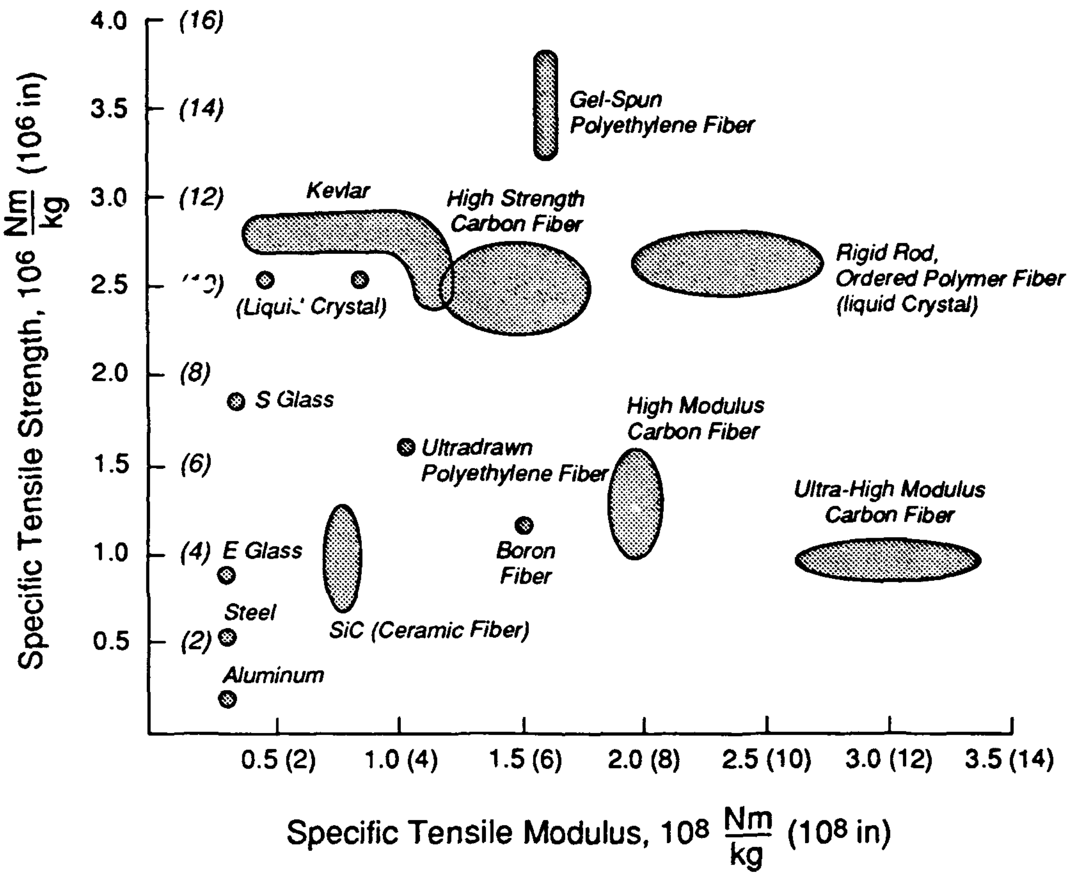


FIGURE 35-7 Strength versus modulus of ordered polymers. Adapted from Pigliacampi, 1987.

ADVANCED PROCESSING METHODS FOR ORGANIC-MATRIX COMPOSITES

Advanced organic-matrix composites have been the subject of materials and mechanics research, primarily so that these materials could be used for high-performance structures. However, if high performance is to be achieved, proper processing is just as important as selecting the proper materials. Conventional processing involves the application of heat and pressure, primarily through isothermal processes inside an autoclave. This process is limited to heat transfer into and out of the component being processed.

Optimization of the processing parameters for a given composite material relies on algorithms specific to a material and its nominal physical and chemical properties. In small-quantity aerospace applications, slow, empirically driven, processing cycles can be tolerated to ensure optimum composite properties. However, the economic and performance benefits inherent in the use of composite materials for structural applications can be obtained only through development of new processing methods, coupled with advances in reducing subassemblies and the increased use of low-cost tooling.

For example, electromagnetic (EM) curing of polymers and polymer-matrix composites can be accomplished with a high degree of efficiency and selectivity. EM radiation in the microwave region interacts with the pendant dipoles present on structural thermosetting polymers. The dipole coupling with the EM radiation causes immediate heat generation throughout the material without relying on conduction and convection mechanisms to transfer heat from the material's surface (Figure 35-8). Thus, heating of polymers and polymer composites can be accomplished in a matter of minutes instead of hours. Although the fundamental reaction mechanisms and kinetics are unchanged, the energy transfer throughout the material allows the processing cycle to be completed in much less time. Compositional tailoring of the molecular structure of a polymer, such as the addition of pendant groups, can achieve high coupling of the composite to a specific EM frequency.

In addition to the use of microwaves, other options for nonconventional processing of organic-matrix composites include the use of photo-initiated polymerization using optical, x-ray, or ultraviolet lasers (Figure 35-9) or electron-beam technology.

Nonconventional processing methods stand to benefit from synergy with parallel advances in sensor technology and artificial intelligence. The development of in-situ sensors, capable of being placed within a composite without disrupting its mechanical characteristics, offers the possibility of reducing manufacturing variability and increasing production efficiency. (See next section on "Smart Composites.")

Integration of new composite materials into transport and combat vehicles is important for achieving the highest combination of performance

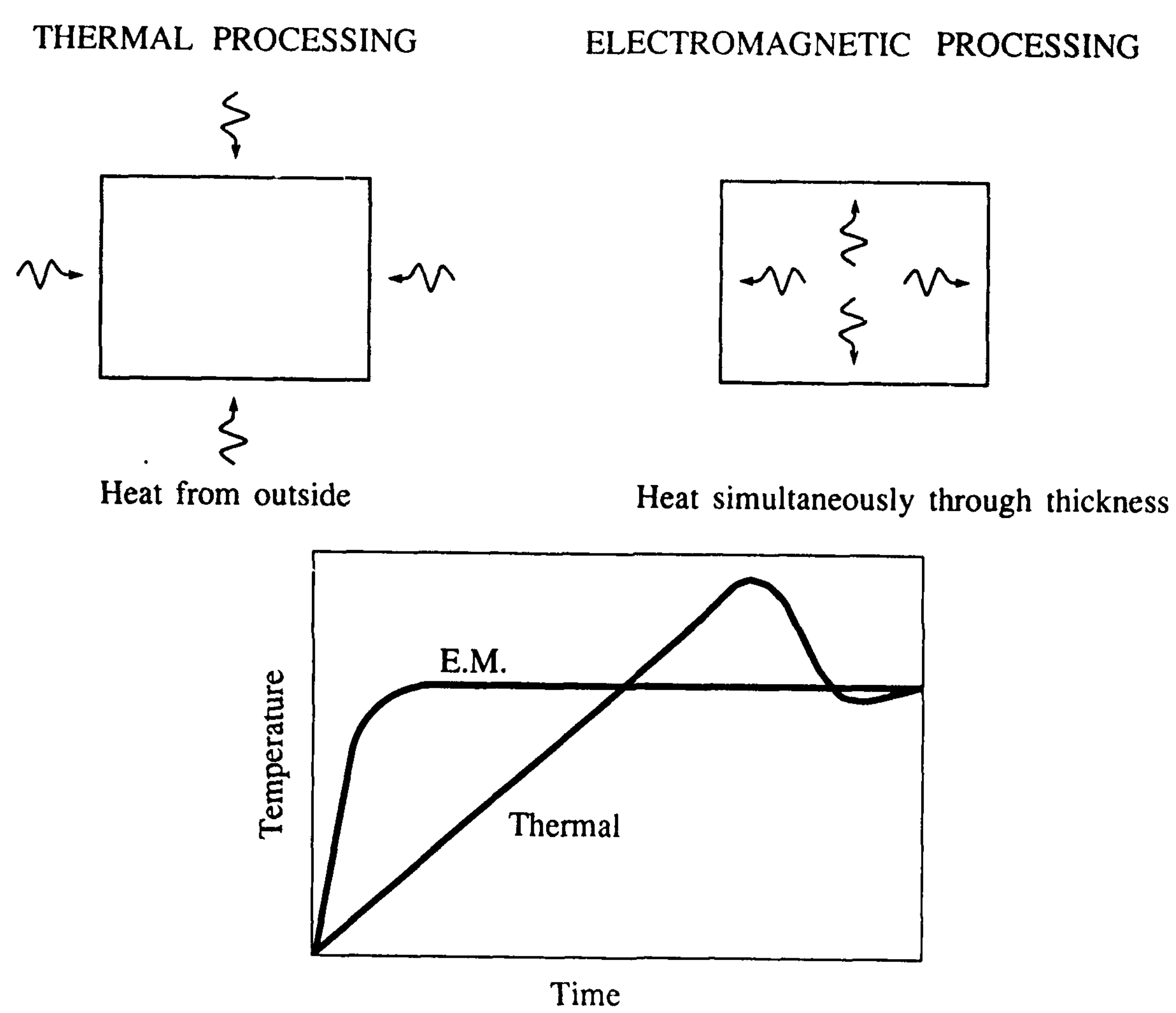


FIGURE 35-8 Thermal versus electromagnetic (EM) processing. Adapted from Asmussen et al., 1990.

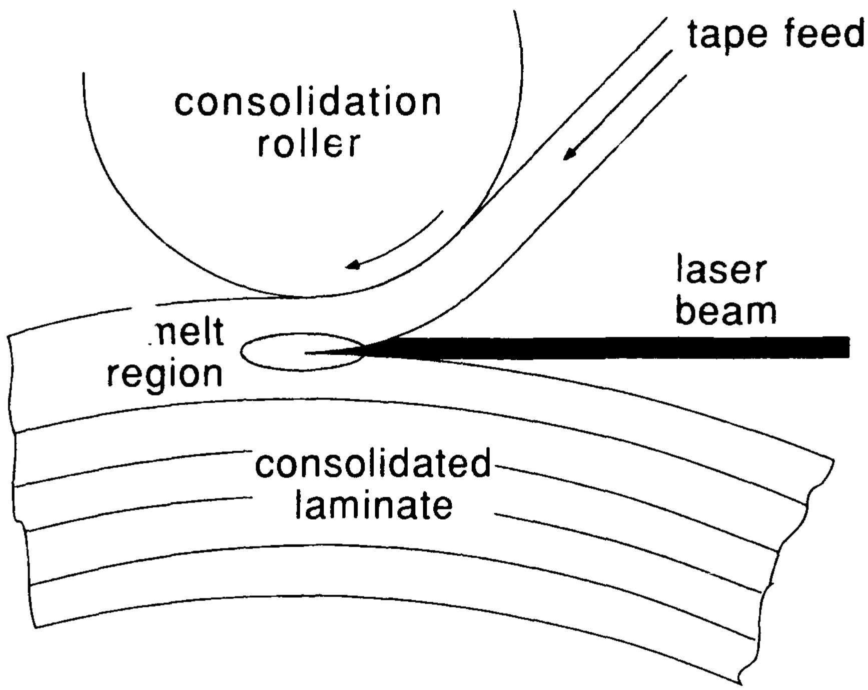


FIGURE 35-9 Schematic description of laser-assisted composite tape composition. Source: Beyeler et al., 1988. Copyright © Technomic Publishing Co., Inc.

and cost-effectiveness for the Army of the future. Reliance on conventional thermal-processing methods limits the potential gain. Nonconventional processing methods offer the opportunity to prepare and process thick composites as well as those with variable cross section. The benefits will also extend to fabrication. Organic-matrix composites produced through advanced processing methods will allow complex parts to be made in one operation. Low-cost tooling can be used to reduce finishing costs. In addition, the precise control of temperatures and chemical reactions inherent in these process methods will provide more consistent materials properties and behavior, both point-to-point within a component and from one component to another. This consistency will significantly enhance the reliability of future Army systems.

SMART COMPOSITES

Composite materials, because they are already heterogeneous, can contain in-situ sensors, conductive fibers, and other active or passive elements that are small enough to preclude a negative effect on the mechanical performance of the material but potentially capable of enhancing material performance. For example, the use of optical fibers implanted parallel to existing reinforcements would make it possible to detect local and distributed temperature, pressure, and stress levels. In the future, molecular interrogation of material for chemical reactions and the presence of moisture will also be achieved through the use of in-situ sensors. These are examples of passive elements in a smart composite.

In-situ sensors can also be active in the sense of causing structural composites to change their physical properties and shapes with mission requirements. For example, electrorheological fluids and shape-memory elements have already been incorporated into composite materials. In the case of the fluids, the vibration damping of composite beams can be altered by running current through them, thereby changing the viscosity of the fluids confined within the beams (Figure 35-10). Changes in shape are possible with proper design of the active and passive elements in a given structure.

When a smart composite is being formed, closed-loop feedback of the changes in material properties and local conditions can be relayed to the control system to optimize composite processing. Variations in the physical and chemical properties of materials at the start of the processing cycle can be accommodated by the system.

The utility of in-situ sensors does not end with the completion of manufacturing. Material interrogation during the structural lifetime of the composite can be used to provide data on deterioration of performance due to ambient and imposed environments. Advanced optical computing could be used to collect the outputs of in-situ fiber-optic sensors and compare them with design criteria in real time. Then, damage detection and assessment could be made instantaneously.

The impact of smart composite materials will be felt most strongly in the enhanced performance and increased reliability and durability of Army vehicles. In air or ground vehicles, in-situ passive sensors can monitor operational properties, while active sensors alter material properties in response to performance requirement. For example, electrorheological fluids could be embedded within a helicopter rotor to increase damping or stiffness as conditions warrant. Sensors could also detect combat damage, permitting actions to compensate for structural limitations inferred from the damage. Battlefield repair could quickly and effectively restore vehicle operational capabilities (Figure 35-11). Self-repair modes could also be activated, when required after battle damage has been detected and assessed. For example, smart materials in the compressor section of gas turbine engines could provide

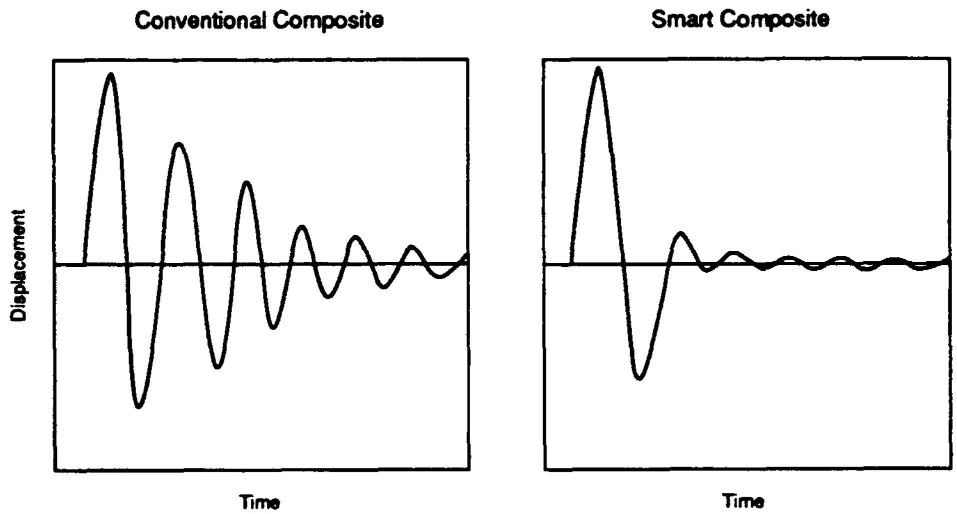


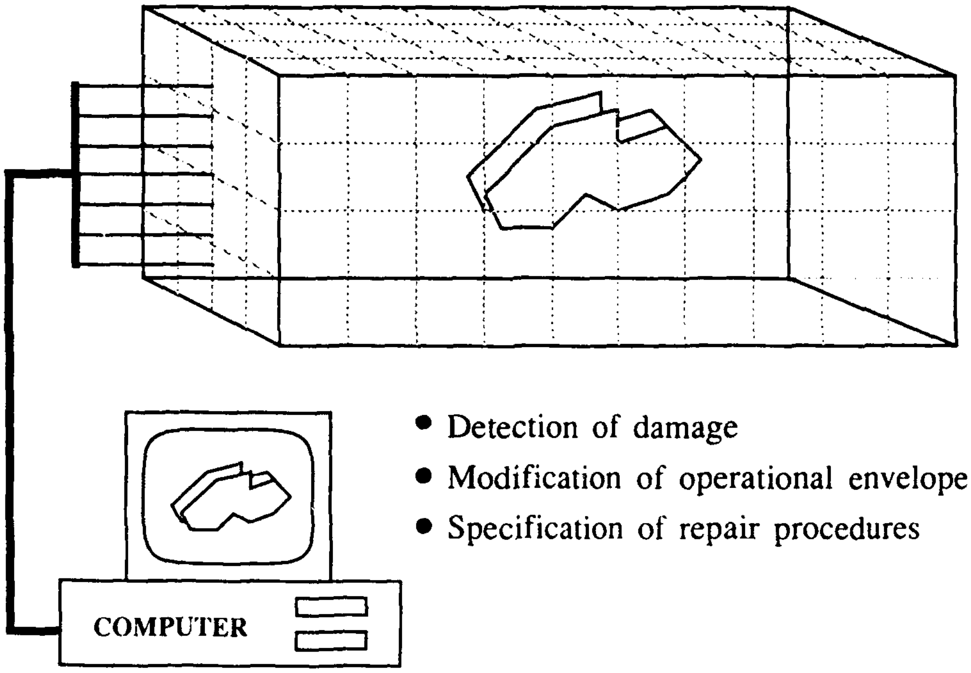
FIGURE 35-10 Contrast between vibration damping in a normal material and in a "smart" material in which active control of embedded elements alters the response.

variable geometry, allowing the compressor section to reconfigure itself (within limits) to correct for wear, damage, altitude, and mission requirements. In other words, this could be an "adaptive" engine.

BONDING OF STRUCTURAL MATERIALS

Structural use of organic-matrix composites will rarely result in the design of a structure made from a single piece. Structural pieces of the same or different composition must be joined together. Metal-to-metal, metal-to-polymer, ceramic-to-polymer, and polymer-to-polymer joining will be necessary. There will be permanent joints, which are not expected to be disassembled during the structure's lifetime, and mechanical joints specifically designed for disassembly when desired.

Permanent joining of organic-matrix composites will rely on adhesive bonding technology for thermoset organic matrices and local fusion of



- Detection of damage
- Modification of operational envelope
- Specification of repair procedures

FIGURE 35-11 Smart materials for detection and repair of battle damage.

thermoplastic matrices. Surface preparation, adhesive selection, and choice of processing methods will depend on the chemical composition of the organic matrices. Although progress has been made in adhesion and adhesive bonding, current technology depends on identifying the adherent and selecting the adhesive and processing conditions from a data base of validated empirical studies. For failures of cohesion *within* the adhesive layer, a lifetime predictive methodology can be based on material property and environmental exposure. However, interfacial failure cannot be predicted by the same means. Future research should advance adhesive bonding technology so that a lifetime predictive methodology that incorporates adhesive as well as cohesive failure becomes feasible.

Adhesive bonding of structural components distributes the stresses over a large area, so adhesive bonding is an inherently stronger and more reliable fastening method. Stress concentrations from holes and fasteners are avoided; corrosion at fastening holes is eliminated. Impact energies can be distributed over a large area, keeping the energy density below damage initiation levels.

Fatigue performance can be enhanced, resulting in longer lifetimes for the structure. Proof testing of a full-scale structure fabricated with mechanical fasteners versus the same structure joined with adhesive bonding showed that the adhesively bonded structure has a design lifetime four times longer than that of a mechanically fastened structure (Shannon et al., 1978).

Advances in adhesive bonding have potential benefits for battlefield repair of structures. Understanding of fundamental mechanisms of interfacial failure can lead to the development of repair kits and methods that are fast and effective enough to reduce the turnaround time for repair of damaged vehicles. Vehicle survivability and utility would benefit greatly.

36

Ceramics

REACTION-FORMED CERAMICS

Two key factors motivate the development of reaction-formed ceramics:

1. Fiber-reinforced ceramics, which promise so many property improvements, are not easily processed by traditional sintering technology.
2. Ceramics that can be fabricated to near-net shape and near-net dimensions, thus bypassing many shaping and finishing operations, offer distinct cost advantages.

Reaction-forming processes are conveniently classified according to their intrinsic rate, as depicted in Figure 36-1. Those processes at the extreme slow end of the spectrum, such as chemical vapor infiltration and conventional reaction-bonded silicon nitride (RBSN), have inherent limitations. First, processing times range from tens to hundreds of hours. Second, fully dense materials are obviated by the need to maintain continuous gas transport paths throughout processing. On the other hand, dimensional and shape tolerances are excellent (e.g., 0.1 percent tolerance for RBSN), and the naturally porous materials that result can have outstanding specific properties.

At the extremely fast end of the spectrum are the self-propagating high-temperature synthesis (SHS) processes, which are virtually explosive (Figure 36-2). The principal advantages of SHS processing are low energy input and the ability to synthesize highly refractory compounds at greatly reduced temperatures. The primary drawback of SHS is that the direct fabrication of monolithic components can be difficult if the reaction rate is not adequately controlled. Successes in this area have been achieved by applying pressure for consolidation before the reaction heat is dissipated. Examples include research at the Army Materials Technology Laboratory on SHS synthesis of TiB_2 armor, where hot-pressing was employed during the reaction to form large-scale monoliths (Katz, 1989).

The intermediate range of reactions is exemplified by reaction-bonded silicon carbide (RBSC), RBSN from monodispersed silicon powders, and solid–solid exchange reactions (e.g., the zircon–mullite reaction to form alumina–zirconia composites) or solid–liquid exchange reactions (e.g., zirconium metal reaction with B_4C to form $Zr/ZrB_2/ZrC$ composites, a process developed at Lanxide Corporation). All have the potential to both shorten processing times while retaining the integrity of the formed

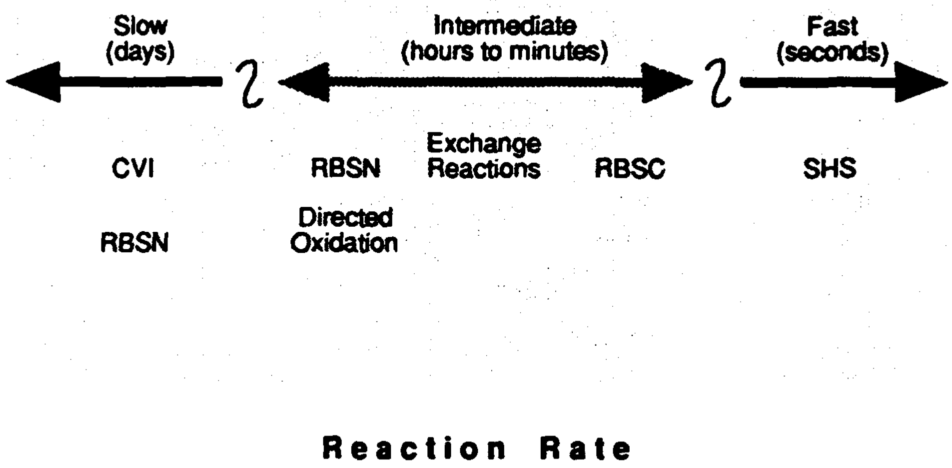


FIGURE 36-1 Relative rates of reaction-forming processes. CVI is chemical vapor infiltration; RBSC, reaction-bonded silicon carbide; RBSN, reaction-bonded silicon nitride; SHS, self-propagating, high-temperature synthesis.

component. For the manufacture of complex-shaped components, reactions in this range seem most promising.

For the near term (to 15 years out), the most important issue for reaction-based processing is the control of reaction rate. This concern is especially severe for the very fast (SHS) and very slow (gas-phase reaction bonding) processes, but it is also a major consideration in process feasibility of intermediate-rate reactions. This Technology Group anticipates that much basic research on reaction mechanisms and rates will occur and will result in a greatly enlarged data base. With this understanding, the properties

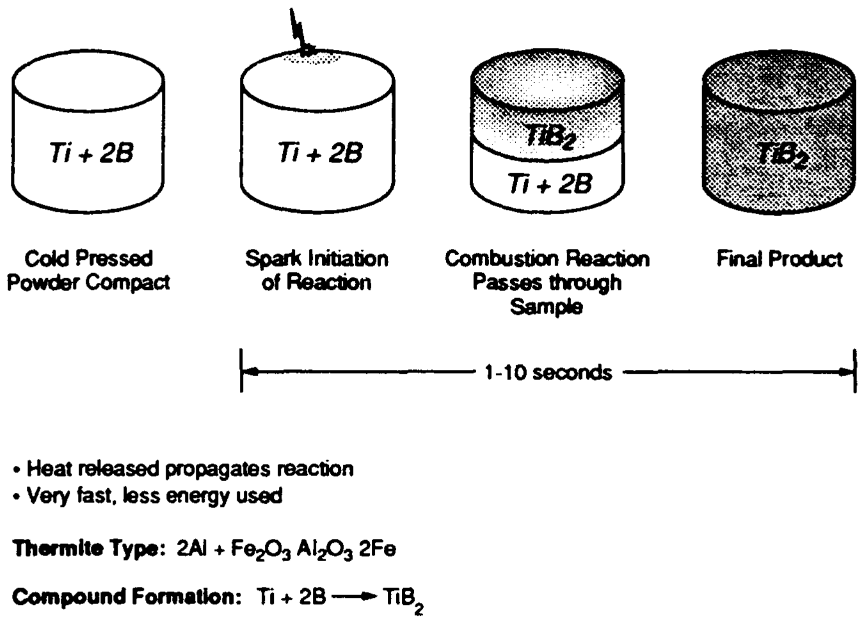


FIGURE 36-2 Self-propagating high-temperature synthesis (SHS). Courtesy of U.S. Army Materials Technology Laboratory.

(e.g., strength) will improve and the size limit for reaction-processed components will increase, as depicted in Figure 36-3. SHS will increasingly be used as a fabrication method for monolithic components while also being developed into a useful technique for powder synthesis. Reaction-processed monolithic and composite (fiber-reinforced) ceramic components of complex shape will begin to enter the marketplace.

In the far term (30 years out), reaction-based processes will begin to replace conventional sintering technology even for well-established, low-cost components. Manufacturing facilities for large-scale reaction-formed components will resemble present metallurgical foundries. The principal military impacts of these technologies will come in the following areas:

- armor;
- propulsion and power;
- gun barrels;
- missile guidance (thermal beacons); and
- heat sinks for electronic packaging.

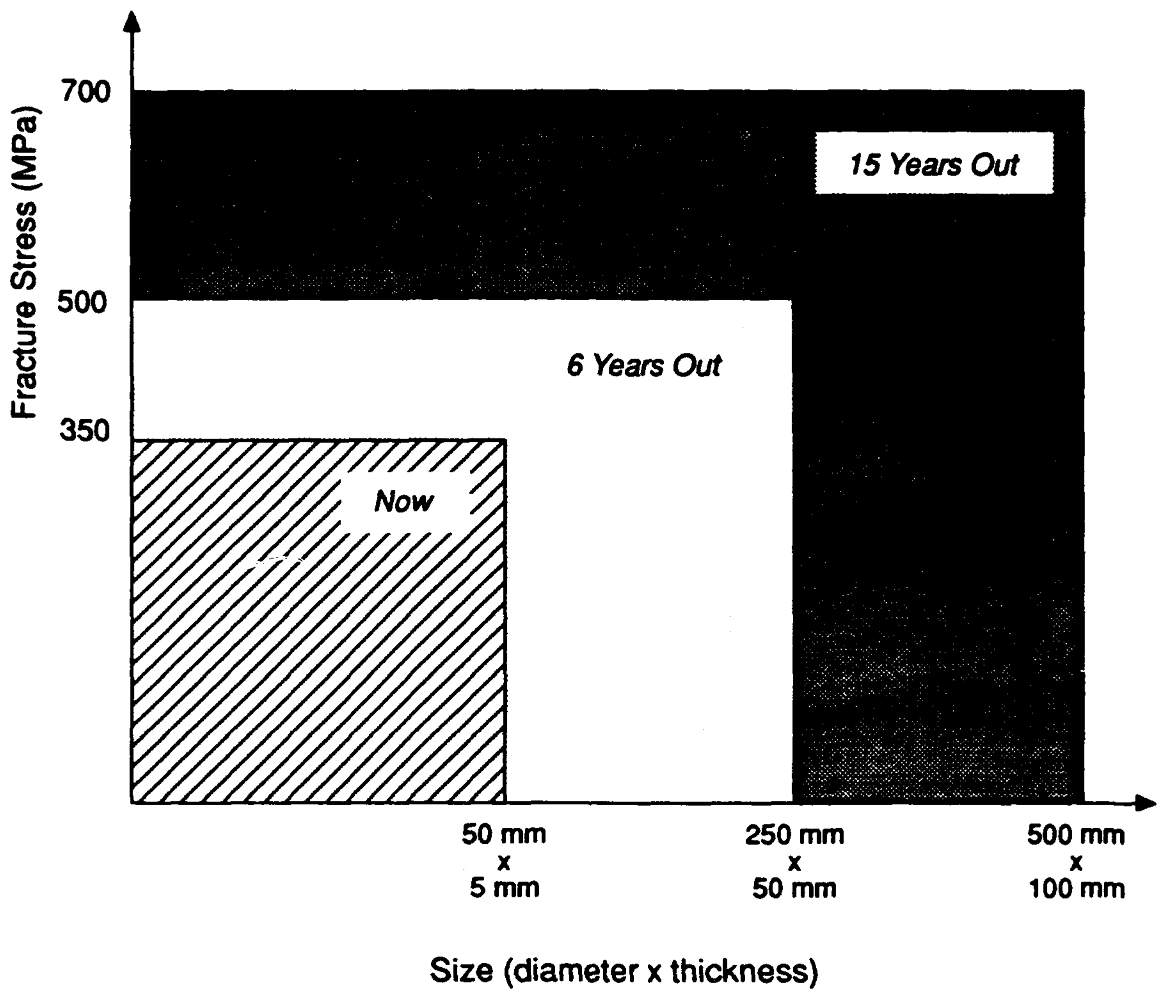


FIGURE 36-3 Projection of strengths available in reaction-formed ceramics compared to maximum size of a component with consistent and reproducible properties.

CELLULAR CERAMICS

The obvious motivation for use of cellular structures is the potential for increased *specific* properties because the macroscopic density is reduced. Based on the results of modeling and experimentation, it is generally thought that the specific properties (modulus, fracture toughness, mechanical and electrical strength) of a cellular material are always less (because of the nature of the mixing rules) than those of the pure, fully dense component.

However, the comparison of interest for cellular ceramics is not with their pure monolithic counterparts but rather with other materials systems (e.g., polymers or metals). For instance, a ceramic foam may provide a higher specific modulus than a bulk structural polymer and yet be useful at far higher temperatures or with greater chemical inertness. Furthermore, there are known cases in which the predictions are not correct, where a cellular material in fact has better specific properties than its monolithic counterpart. One example is the RBSN synthesized at Massachusetts Institute of Technology from laser-processed monodispersed silicon powders. This RBSN is a cellular material whose relatively porous (25 percent) but very highly controlled microstructure has higher specific strength than its corresponding dense monolith because of the reduction in flaw size (Haggerty et al., 1986).

Few high-performance cellular ceramics are under development at this time. Useful examples are the RBSNs mentioned above and silicon carbide composites formed by chemical vapor infiltration, which were developed in France and are now under development in the United States. Refractories and structural-foamed glasses are examples of older cellular ceramics. However, the research community is interested in both modeling and processing. A July 1989 Department of Energy workshop on the properties and processing of "interpenetrating phase microstructures" included extensive discussion of cellular materials (Clarke, 1992).

In the near future (to 15 years out), this Technology Group expects to see the following developments:

- a better fundamental theoretical understanding of the relationship between cellular material topology and properties (i.e., how to design a cellular material for optimum properties);
- a much more extensive data base on model cellular ceramics;
- development of processes and ceramic systems in which the cellular microstructure is highly engineered;
- development of coatings for cellular ceramics; and
- initial implementation of tailored cellular ceramics in structural and electronic applications.

In the far term (30 years out), cellular ceramics will replace many dense structural ceramics and metals for land-based as well as space applications, because of their greater specific strength and modulus. This will apply to ambient as well as high-temperature applications. They will see increasing roles in electronics packaging because of their low dielectric constants. Potential applications are wide ranging and include the following:

- heat shields in engines;
- catalyst applications;
- high-temperature sandwiched-foam structural materials;

- spacecraft structures;
- filters for biological agents;
- structures for support;
- thermal management of high-power electronics system; and
- possibly a role in low-observables technology.

DUCTILE-PHASE-TOUGHENED CERAMICS

Recently, there has been widespread renewed interest in the class of ceramics (often referred to as "cermets") that are toughened by the inclusion of a dispersed ductile phase (Figure 36-4). This interest has been stimulated in part by the advent of some novel processing methods that inherently result

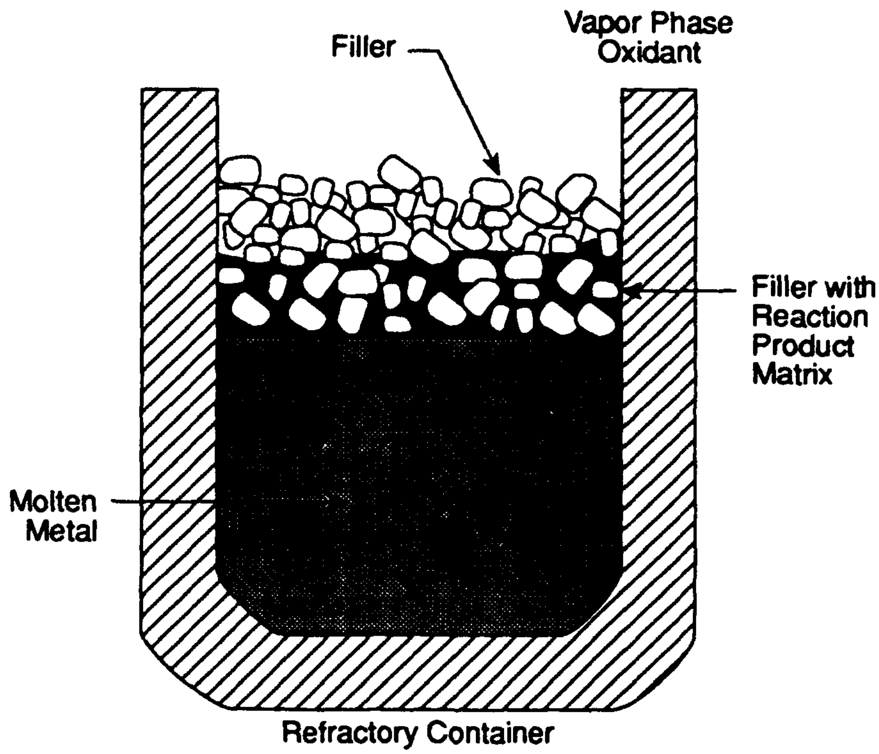


FIGURE 36-4 Schematic of the formation of a ceramic composite by the outward growth of a ceramic–metal reaction product matrix through a mass of filler material. Source: Newkirk et al., 1986.

in polyphase metal–ceramic microstructures. Examples are the composites made by directed oxidation and by various exchange-reaction processes. Examples of ductile-phase-toughened ceramic systems include: Al/Al_2O_3, Al/AlN, WC/Co, Zr/ZrB_2-ZrC, B_4C/Al, and $Ag/YBa_2Cu_3O_7$. Table 36-1 depicts the properties of some of these materials. Note the fracture toughness (K_{Ic}) of the composites compared with the monolithic ceramics.

TABLE 36-1 Measured and Calculated Properties of Ceramic–Metal Composites

Matrix	Filler	f Metal Fraction	K_{Ic} (Ceramic) ($MPa \bullet m^{1/2}$) Literature	K_{Ic} (Composite) ($MPa \bullet m^{1/2}$) Measured
Al_2O_3 + Al	None	0.25	4	7.8
Al_2O_3 + Al	SiC	0.08	4	5.6
WC + Co	None	0.10	8	11.8
WC + Co	None	0.30	8	17.3

Source: Andersson and Aghajanian, 1988.

At present, the degree of toughening that will ultimately be achievable in these ceramics is not clear. However, the perception of processing and manufacturing ease in these processes (compared with conventional sintering and hot-pressing), as well as the plethora of systems to which this toughening approach can be applied, makes ductile-phase-toughened ceramics a very attractive area for future development. In contrast, the transformation-toughened ceramics are predominantly based on a single system: ZrO_2. Development and implementation of these materials in the commercial arena is under way.

Low-temperature applications are natural for these systems. In the next decade, the extent to which toughening is possible by the incorporation of ductile phases will become clear. Progress will be made on the application of this toughening mechanism to higher-temperature systems. In this regard, the use of more refractory, nonmetallic ductile phases, such as the Si phase in SiC/Si composites or the $MoSi_2$ phase in $SiC/MoSi_2$ composites, may be a useful approach to extending the application's temperature range upward. Unfortunately, many of these phases are brittle at lower temperatures. Thus, a combination of low- and high-temperature toughening mechanisms for low and high temperatures may be optimum.

The far term (30 years out) will see widespread implementation of ductile-phase-toughened ceramics in large-scale structural components. Materials systems for more difficult high-temperature applications will be developed, although the properties of these materials are limited by the generally lower melting point of the ductile phase.

The Army will be interested in these ceramics because of their potential for scaleup, low-cost manufacturing, light weight, and unique properties. Specific applications of ductile-phase-toughened ceramics are likely to come in the following areas:

- armor;
- gun tubes;
- space structures;
- structures for high-power electronics;
- moderate-temperature engine components; and
- wear parts.

FIBER-REINFORCED CERAMICS

Fiber-reinforced ceramic composites are a class of materials in which fibers (generally ceramic or carbon) are incorporated in a ceramic matrix to improve the strength, fracture toughness, modulus, or thermomechanical properties of the matrix material. State-of-the-art examples include the following:

- SiC whisker-reinforced Al_2O_3;
- Carbon and SiC fiber-reinforced glasses and glass-ceramics;
- SiC whisker-reinforced glasses;
- SiC filament-reinforced RBSN; and
- SiC fiber-reinforced silicon carbide by chemical vapor infiltration.

At present, the key advantages of these composite systems over their monolithic counterparts are improved damage tolerance and strength. This is often expressed as "work-of-fracture" rather than fracture toughness because the failure modes of the composites are often "graceful" (that is, noncatastrophic in failure), unlike the monoliths (Lamicq et al., 1986). Figure 36-5 shows work of fracture versus crack extension. In certain of the low-density systems such as glass and glass–ceramic matrix composites, significant improvements in specific modulus and specific strength are also achieved (Prewo et al., 1986).

The key limitations of these materials are the absence of economical processing methods and their poor stability in high-temperature environments. Pressureless sintering is infeasible at virtually all fiber fractions of interest, so

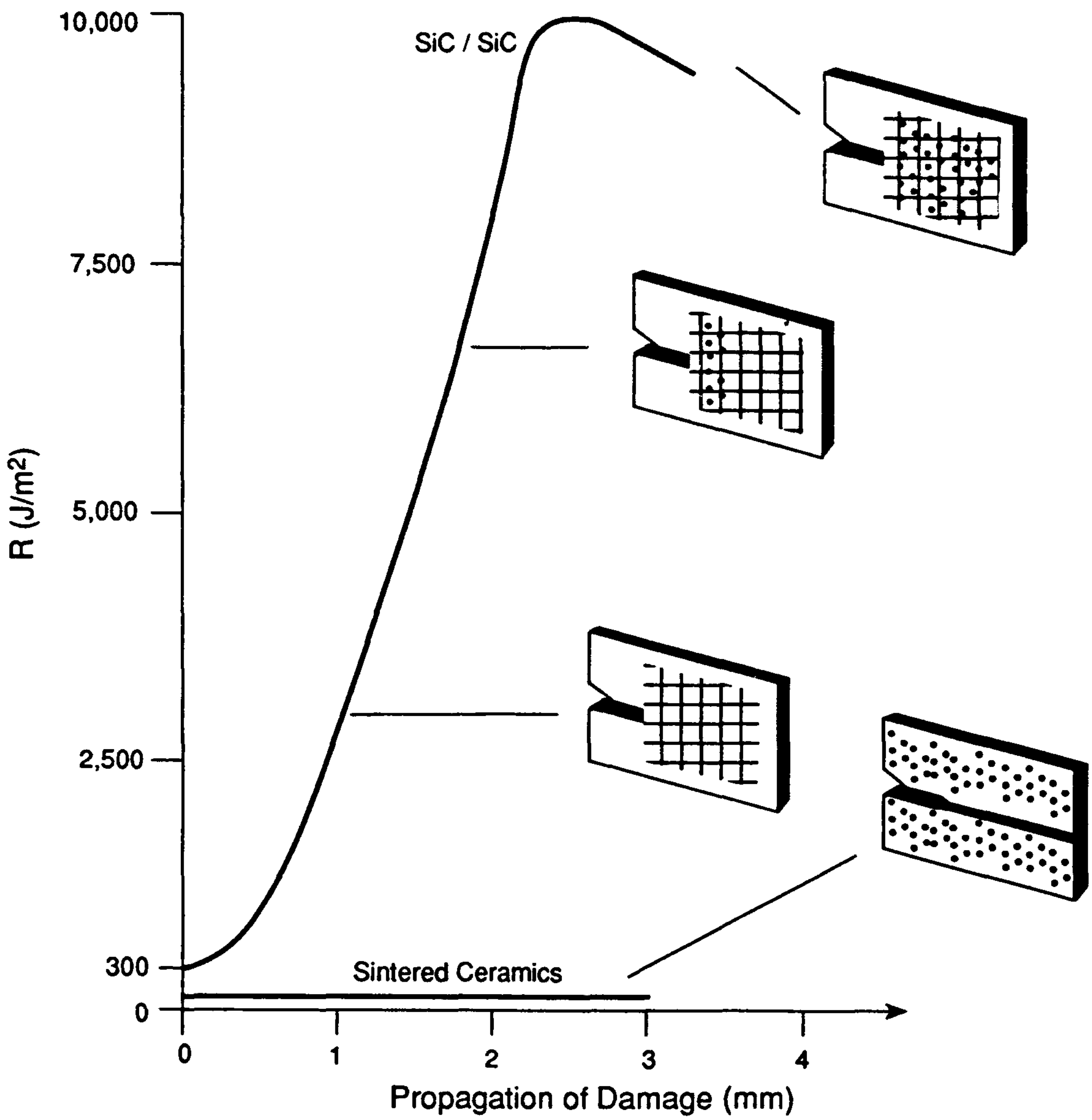


FIGURE 36-5 Comparison of SiC/SiC composite with sintered ceramics in slow crack-growth test. Source: Lamicq et al., 1986.

pressure-densification (Figure 36-6) or reaction-forming methods are necessary to fabricate these materials. In addition, both the fibers and the interface regions have poor oxidation resistance at high temperatures.

In the near future (to 15 years out), this Technology Group expects to see the implementation of glass and glass–ceramic matrix composites in moderate-temperature applications (<800°C) in oxidizing environments. Processing limitations will keep component size relatively small (less than 5 cm x 1 m^2). Anticipated developments that will expand the applications for these materials include:

- development of high-strength, high-modulus, small-diameter, continuous fibers that are stable to both temperature and oxidizing environments;
- low-cost single-crystal oxide and non-oxide whiskers, particularly for high-temperature applications; and

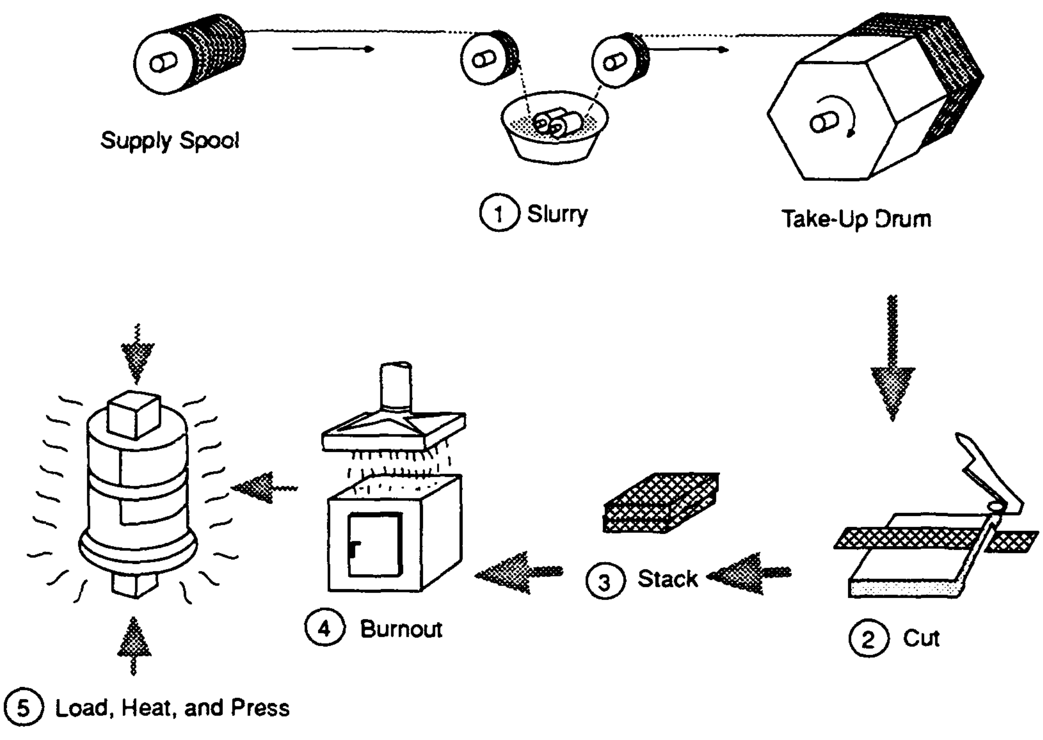


FIGURE 36-6 Steps in tape lay-up processing of glass matrix composites. Figure adapted from Prewo et al., 1986.

- coatings for fibers and whiskers, for the purposes of tailoring interfacial mechanical properties and environmental protection at high temperatures under oxidizing environments.
- multidirectional fiber reinforcement architectures (three-dimensional weaves);

In the far term (30 years out), larger-scale structures will become feasible because of improvements in processing and joining. Higher temperature applications (>1000°C) in oxidizing environments will occur. Key improvements will include the following:

- processing methods that can form in-situ matrices of reasonably high density, at temperatures and times that do not damage fiber reinforcements;
- near-net-shape processing methods (since cutting, grinding, and finishing operations are even more difficult for ceramic composites than they are for monolithic ceramics); and
- joining of composites (especially important for directionally reinforced systems).

The impacts of these materials will be felt in the following military systems:

- armor;
- propulsion and power;
- tools for metal cutting and forming;
- gun-barrel technology; and
- spacecraft structures.

DIAMOND AND DIAMONDLIKE COATINGS

Of all crystalline solids, diamond holds a special position because of its extreme properties (e.g., exceptional hardness, thermal conductivity, high dielectric breakdown, strength, and infrared transparency). Until 1977, parameters for synthesizing diamond, such as temperature and pressure, had also been extreme, which limited the ability to exploit the many desirable properties of this material. Since then, diamond and related "diamondlike" materials have been produced at practical growth rates under a remarkably wide variety of experimental conditions and at reasonable cost (NRC, 1990).

Films of these materials are grown by chemical vapor deposition processes, using a low-pressure gas that consists of atomic hydrogen and one or more hydrocarbons (e.g., methane). The material can be deposited on a variety of substrates. For the diamond films, which are crystalline and exhibit many of the properties of high-temperature, high-pressure diamond, the substrate temperature must be on the order of 500°C or greater. This temperature requirement, which limits the applications of diamond films, is considerably relaxed for the diamondlike films that can be deposited on plastics. Properties of the diamondlike coatings, such as hardness, are less extreme than for the diamond films, because they are amorphous and may contain considerable hydrogen. Nonetheless, they can provide extremely good abrasion and wear-resistant coatings.

Several university centers have been formed with joint government and industry funding to bring this technology to the marketplace. It is expected that these efforts could lead to a number of innovative applications of benefit to future Army needs, such as:

- abrasion-resistant coatings for infrared windows and for a variety of other optical equipment;
- high-power transistors and optically activated switches for high-power microwave and millimeter-wave sources;
- wear-resistant coatings for bearings and journals used, for example, in helicopters and cruise missiles;
- blue-light-emitting diodes and solid-state lasers for full-color flat displays and other display applications;
- substrates and insulating films for high-power electronics;
- ultra-inert and wear-resistant coatings for medical implants;
- highly efficient heat sinks for electronic circuits, allowing denser packaging for smart missiles and other applications;
- abrasion-resistant coatings for fibers used in fiber-optic guided systems (e.g., FOG-M);
- impervious coatings for storage containers that are used to hold highly reactive, corrosive chemicals;
- hard coatings for magnetic disks to prevent head crashes in field equipment;
- efficient electron emitters for micrometer-sized vacuum tubes with power and frequency performance far superior to that of conventional semiconductor devices; and
- high-efficiency thermal radiators for satellites.

37

Metals

STEELS

High-Strength Steels

Structural materials must possess adequate combinations of strength, ductility, static and dynamic fracture toughness, and wear resistance for reliable and reproducible use in critical components and structures. The properties of ferrous materials can be manipulated and improved through melting, processing, and microstructural alteration. Although basic research and development in the steel industry has drastically declined over the years, major developments in property improvement and optimization are both possible and essential.

The large tonnage of material that will continue to be used in structural applications indicates the continuing importance of ferrous materials. Figure 37-1 illustrates the tensile strength and elongation values for a variety of conventional steels and for new, fine-grained, ultrahigh-carbon (UHC) steels. Improvement in these properties increases the specific strength of the material; structures composed of such materials can be designed to take advantage of the considerable weight savings afforded by this increase in strength.

The advances shown in Figure 37-1 resulted from research into the relationship between understanding structure and property as well as advances in processing from the melting and casting stage through thermomechanical treatments. Similar improvements are being achieved as a result of improved understanding of the factors controlling fracture toughness. The primary variables controlling toughness at a given strength level are related to the microstructure and the spacing of sulfide inclusions. Advances in processing techniques, including vacuum-arc remelting and ladle refining, permit production of low-sulfur steels. This limits the number of sulfide inclusions, and thereby increases their spacing. Areas for further improvement will require research into the effects of microstructural variations and alloying additions on the mechanisms of failure occurring ahead of a crack tip. Very recent work has indicated that increasing the bond strength between inclusions and the matrix through alloying additions may further increase toughness. In this case, for a material with a strength of 180 kpsi, toughness was increased from 250 to 500 kpsi$\cdot$(in.)$^{1/2}$.

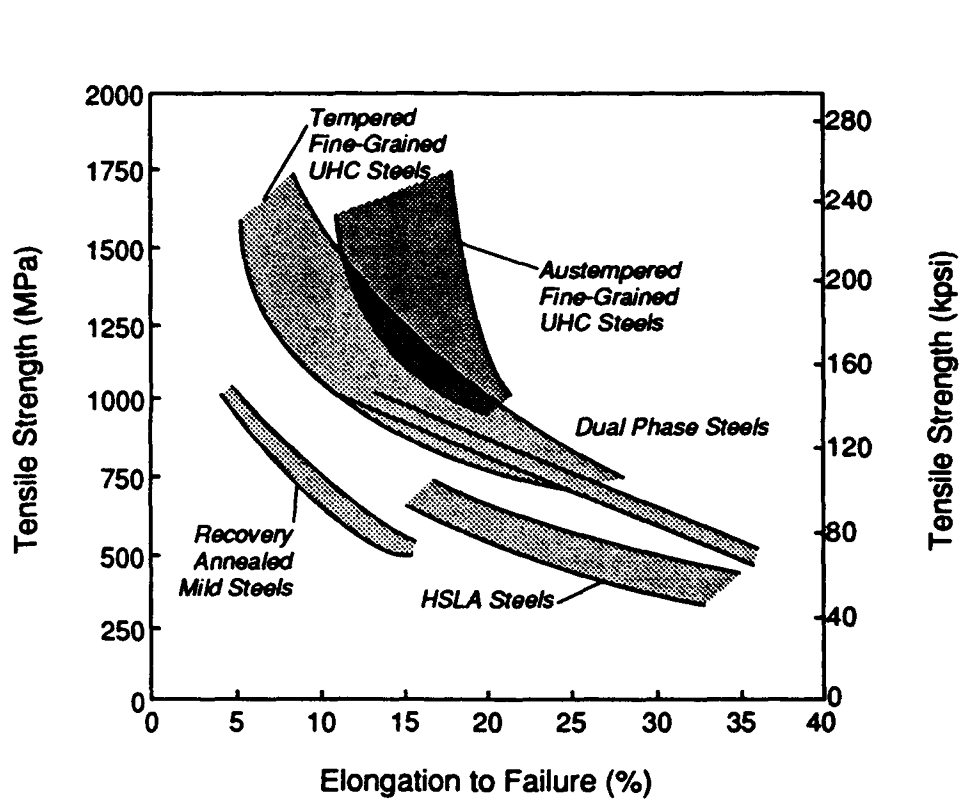


FIGURE 37-1 Effects of alloy composition on tensile strength and elongation to failure. UHC is ultrahigh carbon; HSLA is high-strength, low-alloy. Source: Sherby et al., 1985. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 37, No. 6, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

New compositions, refined melting, and processing techniques such as vacuum melting or rapid solidification technology will allow steel with strengths of 300 to 350 kpsi to be used structurally with higher toughness and less susceptibility to hydrogen embrittlement. Gear and bearing steels will be developed for higher loads and for use at higher temperatures. In the longer term, surface treatments such as ion implantation will be available to increase wear resistance and reduce corrosion.

Increases in the properties such as strength, ductility, and wear resistance will continue to have a major impact for structures where reliable, reproducible properties are required. Structures such as helicopters, ground vehicles, missiles, and weapons continue to be the most likely candidates for these materials. Gun barrels should also continue to be an application requiring the use of a highly wear-resistant material.

Laminated Structures

The toughness of the highest-strength steels is often curtailed by the limited ability of the material to absorb energy in the presence of a propagating crack. Thus, while strength levels approaching 500 kpsi may be achieved, it is highly desirable for such a material to also possess adequate toughness. The possibility of combining the high wear-resistance and strength of UHC material with the high impact-resistance of lower-carbon steels, or other materials, exists through the use of laminated structures, as depicted in Figure 37-2. Crack propagation in such a structure will bifurcate at the interface, provided the interface has suitable properties.

The low-strength component may also promote superplastic behavior in the laminated structure, thereby enhancing the formability of the material for

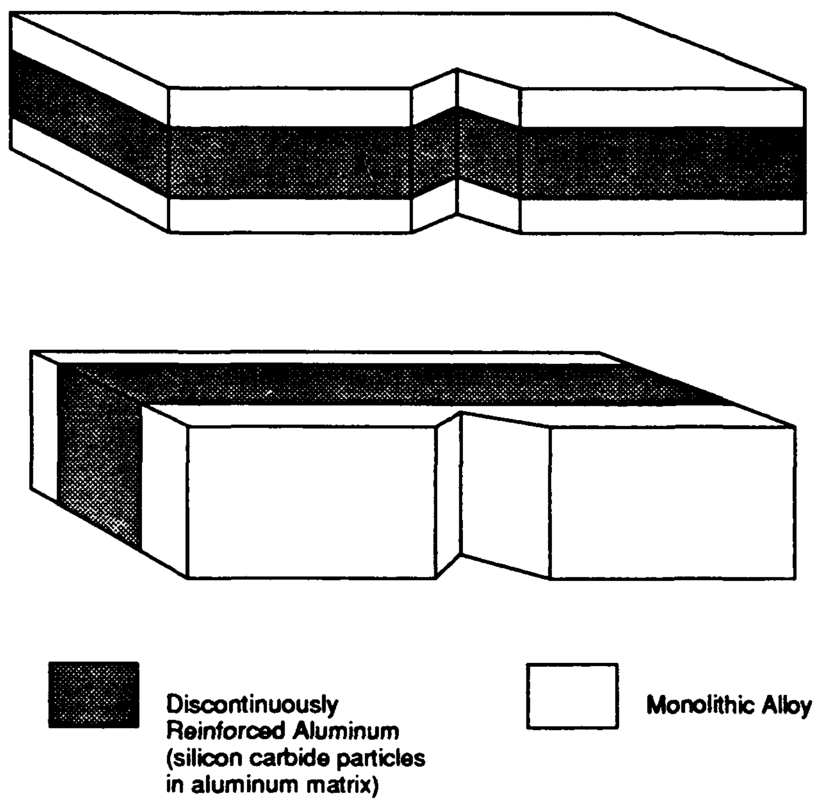


FIGURE 37-2 Laminated structures provide the potential for increasing the impact performance and toughness of low-carbon steels and other materials. Source: Hunt et al., 1993. Reprinted with permission from JOM (formerly Journal of Metals), vol 45, no. 1, p. 33, a publication of the Minerals, Metals & Materials Society, Warrendale, PA 15086.

use in advanced structures. Recent work has demonstrated that significant improvements in impact toughness may be achieved by use of laminated structure, as depicted in Figure 37-3. Solid-state bonding techniques have attained exceptional impact strengths in UHC steels bonded to other ferrous materials. UHC steels can be processed to contain exceptionally fine microstructures made up of fine spheroidized carbides and fine ferrite grains; this permits superplastic forming and superplastic bonding of UHC steels, either to themselves or to other ferrous materials, at relatively low temperatures. The significance of such a result is that ferrous laminated composites can be prepared at relatively low temperatures, which will not destroy the desired fine structure in the UHC steel. The resulting laminated structure combines the high strength and ability for superplastic forming of the UHC material with the higher impact toughness of the second material in the laminate. Furthermore, the laminated structure may enable heat-treating of the material so that the UHC steel has high strength, hardness, and wear resistance, while the other component in the laminated structure imparts toughening.

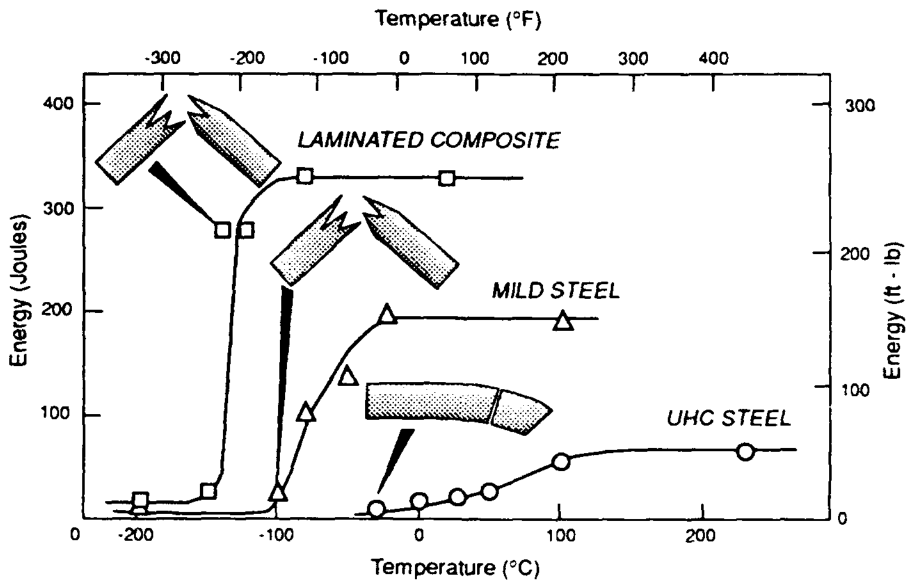


FIGURE 37-3 Influence of temperature on the impact properties of a laminated composite of UHC steel and mild steel compared with the component materials making up the composite. Source: Sherby et al., 1985. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 37, No. 6, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

Laminated steels offer the possibility of combining excellent surface properties (strength, wear resistance) with toughness not achievable in monolithic materials. Ballistic protection and other structural components are continuing areas of application for materials.

Steel-Based Composites

Bearing surfaces and other applications where metal contact is inevitable will require the use of materials with high wear-resistance. In conventional steels, microstructural variations can significantly improve both the hardness and wear resistance, as shown in Figure 37-4, for monolithic materials. The potential ways of increasing wear resistance for monolithic materials are shown in Figure 37-5. Increased wear resistance will ensure more reliable behavior of the bearing surface, whether it occurs in gears, gun barrels, or other load-bearing applications. As the action of the metal in contact with metal also increases the temperature locally, it is important that the steel exhibit resistance to softening (i.e., loss of strength) at modest and high temperatures (Advanced Materials and Processes, 1989).

Although little work has been conducted in the areas of discontinuous steel composites, one potential way to increase both the wear resistance and tolerance of high temperature involves the use of a composite approach. Particulates of TiC, TiN, or other materials could be introduced into the steel, thereby increasing the wear resistance by providing another hard phase. The strength provided by dispersion of particulates also will improve the high-temperature strength. This approach has little effect on the stiffness of ferrous materials. The effects that these additions will have on other properties (e.g., strength, toughness, fatigue) are not known. Little work has focused on the effects of such additions on high-temperature properties such as strength or creep resistance. Current strength limitations at high temperatures are shown in Figure 37-6 for a variety of steels in which improvements have been realized by a combination of fine grain size, substructure, and precipitation hardening. The introduction of particulates may significantly increase the temperature limits.

Steel-based composites will be of primary importance in applications characterized by high wear, elevated temperatures, or both. At elevated temperatures, these composites will have increased resistance to both wear and softening, compared with conventional materials. The performance of such materials under high-velocity ballistic impact may also be better than that of monolithic matrices, because the particulates may act as fragmentation sites, thereby providing another energy-absorbing medium. High-temperature oxidation-resistant materials such as stainless steels may be significantly strengthened by the addition of reinforcement. The structure produced will thus combine the oxidation and corrosion resistance of an austenitic stainless

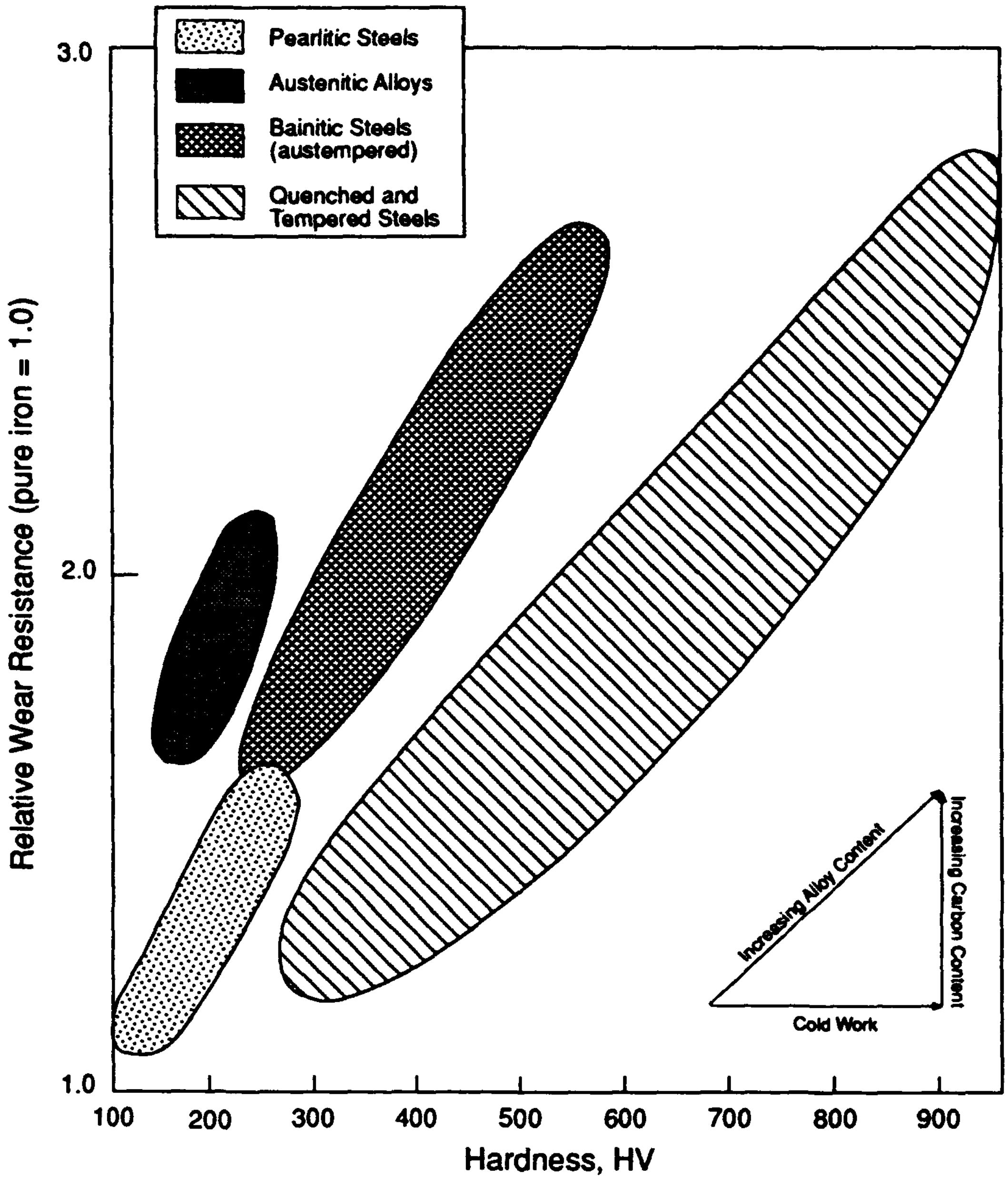


FIGURE 37-4 Microstructural variations may significantly improve both hardness and wear resistance. Source: Advanced Materials and Processes, 1989. Copyright © ASM International.

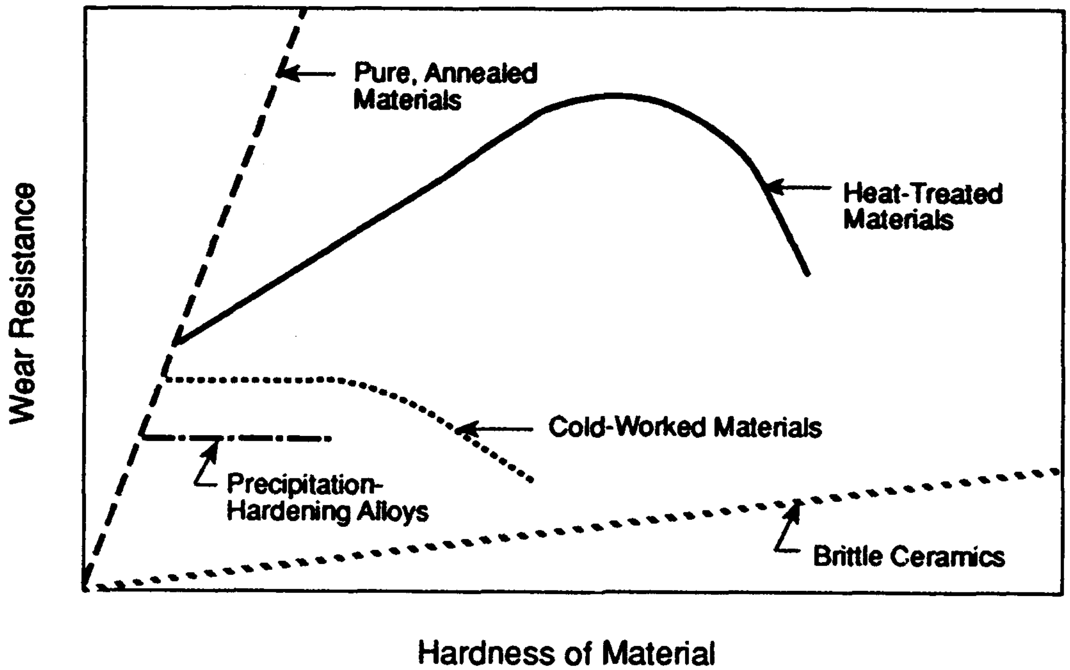


FIGURE 37-5 Ways of increasing wear resistance. Source: Advanced Materials and Processes, 1989. Copyright © ASM International.

steel with the wear resistance and high-temperature strength imparted by the particulates.

Major impacts on Army systems are expected to be in the following areas:

- gas turbine engine components, especially the main shaft;
- transmission housings; and
- advanced gun systems (e.g., gun tubes and howitzer carriages).

LIGHT METALS

Aluminum-Lithium Alloys

Several classes of new metallic materials promise to improve the baseline performance of monolithic materials. These improvements allow them to compete with engineered materials, such as composites, for advanced systems and hardware. Their commercial feasibility depends on techniques for

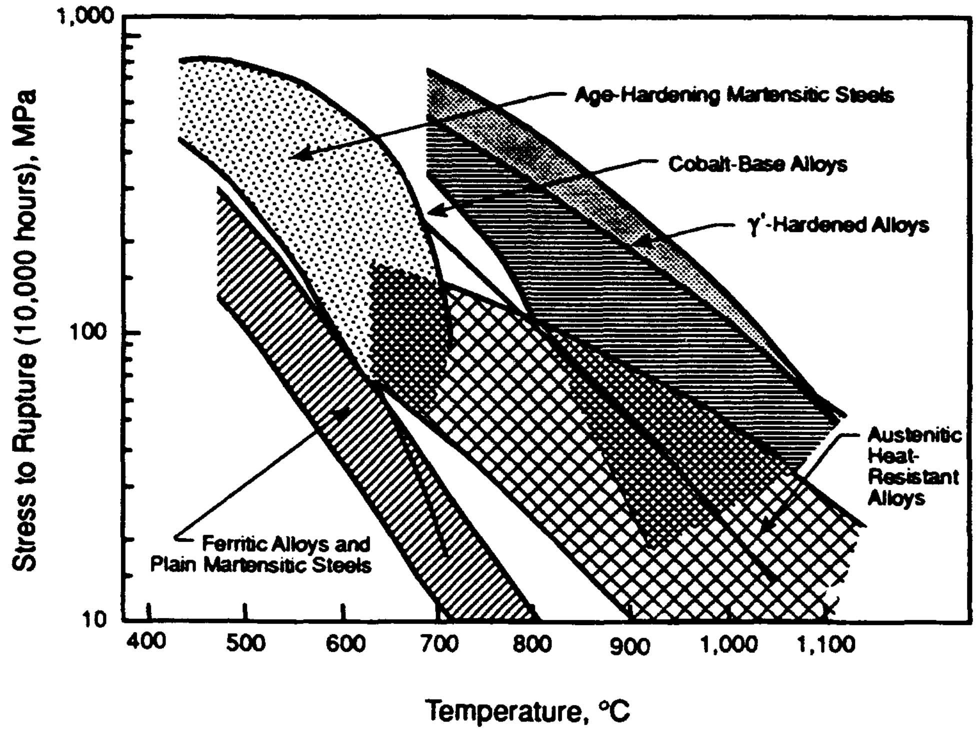


FIGURE 37-6 Current strength limitations at high temperature. Source: Advanced Materials and Processes, 1989. Copyright © ASM International.

materials processing. Rapid solidification processes, atomization of powders, thermomechanical processing, mechanical alloying, and advanced powder metallurgy techniques are but a few of the processing innovations that are leading to improved and new alloy systems.

Aluminum-lithium (Al-Li) alloys represent an innovative new basis for high-strength light metals. The specific strength and stiffness of these alloys, which are superior to those of other aluminum alloys, provide attract: 'e characteristics for advanced lightweight structural materials. These alloys have been under development for a decade, and first-generation commercial alloys are under large-scale evaluation. Increased understanding of the role of alloying elements and the physical metallurgy of the Al-Li system open the way to significantly extend the performance of first-generation commercial alloys, through continuing alloy development and study of their microstructure and properties. Recent work has demonstrated yield strengths greater than 100 kpsi in these materials (Figure 37-7) (Pickens et al., 1989). Considerable

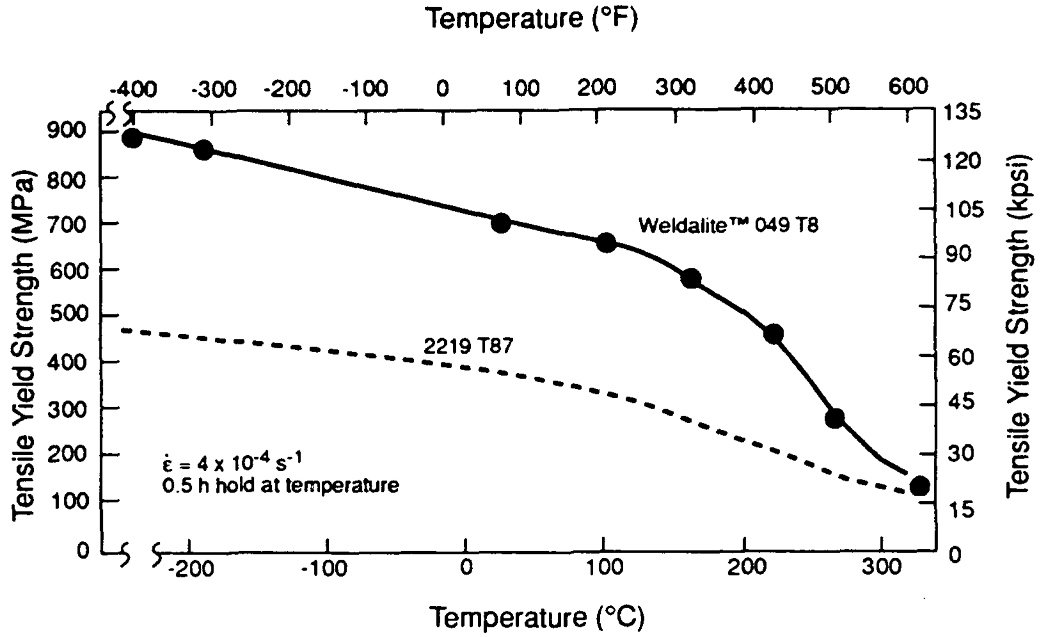


FIGURE 37-7 Tensile yield strength of Weldalite™, a new aluminum-lithium alloy, compared with alloy 2219. Source: Pickens et al., 1989. Copyright © Materials and Component Engineering Publications Ltd.

weight savings are possible by using variants of these alloys to replace conventional aluminum alloys (Figure 37-8).

The advantages of Al-Li alloys having specific strengths and moduli greater than steel will have major impacts in the following areas:

- armored vehicle hulls;
- helicopter structures and panels; and
- missile components (e.g., fins and cryotanks).

High-Temperature Aluminum Alloys

The ability to produce clean, rapidly solidified (RS) powders from alloys containing high-melting solutes has led to the development of new aluminum alloys that cannot be produced by conventional ingot metallurgy methods. As a result, there has emerged a series of powder-metallurgy (PM) aluminum

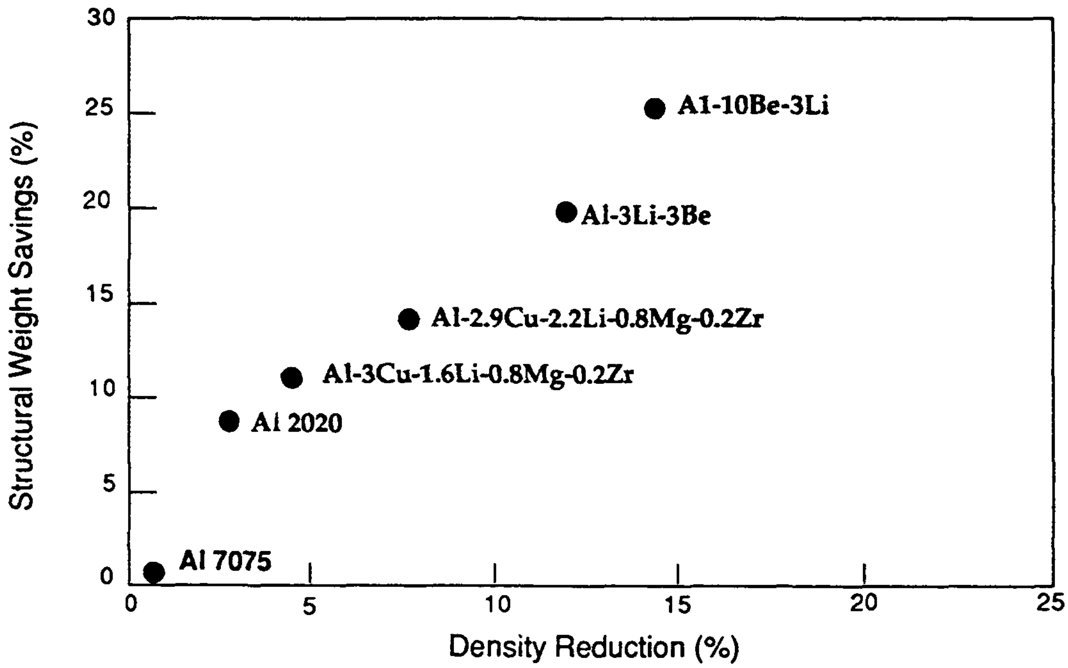


FIGURE 37-8 Effect of alloy content on density reduction and structural weight savings in Al-Li alloys. Source: Froes and Wadsworth, 1989. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 41, No. 5, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

alloys that retain their strength to considerably higher temperatures than conventionally produced alloys; they also offer the potential of higher elastic moduli (Froes and Wadsworth, 1989). These new materials may compete with wrought titanium alloys for lightening the force. Advanced thermomechanical processing sequences provide opportunities to tailor the microstructure of these PM aluminum alloys for further property improvements. Figure 37-9 illustrates the high-temperature strength of conventional aluminum alloys and the range achievable in materials produced from RS powders, in comparison with goals set by an Air Force program. Areas for further development include increasing the high-temperature capability of RS powder alloys and improving their resistance to fatigue and corrosion.

Continued refinements in the processing of RS materials will result in increased usage of these materials in the long term, provided that issues of fracture toughness and resistance to corrosion and fatigue are adequately resolved. Light metals in general will find major uses in structural applications where specific strength and stiffness are important. Applications for engines and robots are the most likely areas for future uses.

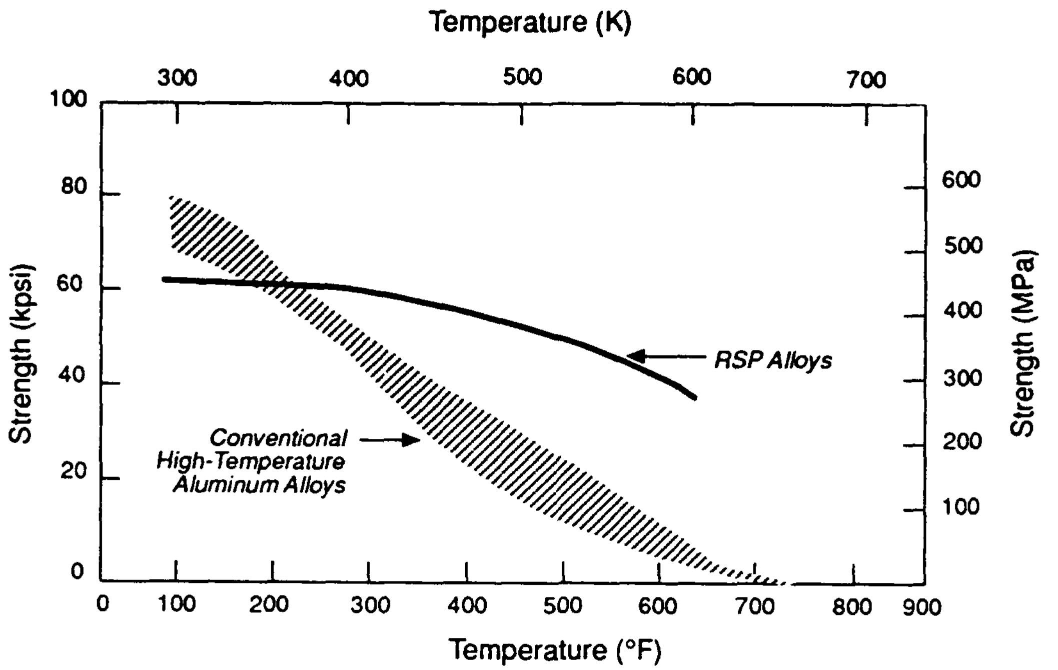


FIGURE 37-9 High-temperature strength of aluminum alloys. RSP, rapidly solidified powder. Source: Froes and Wadsworth, 1989. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 41, No. 5, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

Magnesium Alloys

Traditionally, magnesium-based alloys have suffered from low strength, limited ductility, and poor corrosion resistance. However, low density and very high specific stiffness and strength (shown in Figure 37-10) make alloys based on magnesium extremely attractive for aerospace applications. The poor corrosion resistance of magnesium arises from its position in the electromotive series; it is the most active of all structural metals and is therefore sacrificial to other metals in dissimilar-metal assemblies. Thus, proper design and coating techniques are necessary in environments such as salt water. Even when magnesium is not in contact with any other metal, general corrosion can occur on exposure to seawater environments because of the presence of undesirable metallic impurities, particularly nickel, iron, copper, and silicon. This finding has spurred the development of high-purity corrosion-resistant magnesium alloys (Froes and Wadsworth, 1989).

For magnesium-based systems, the possibility of powder metallurgy and rapid solidification (PM/RS) can lead to improvements in properties similar to those described above for aluminum alloys. By use of PM/RS, magnesium

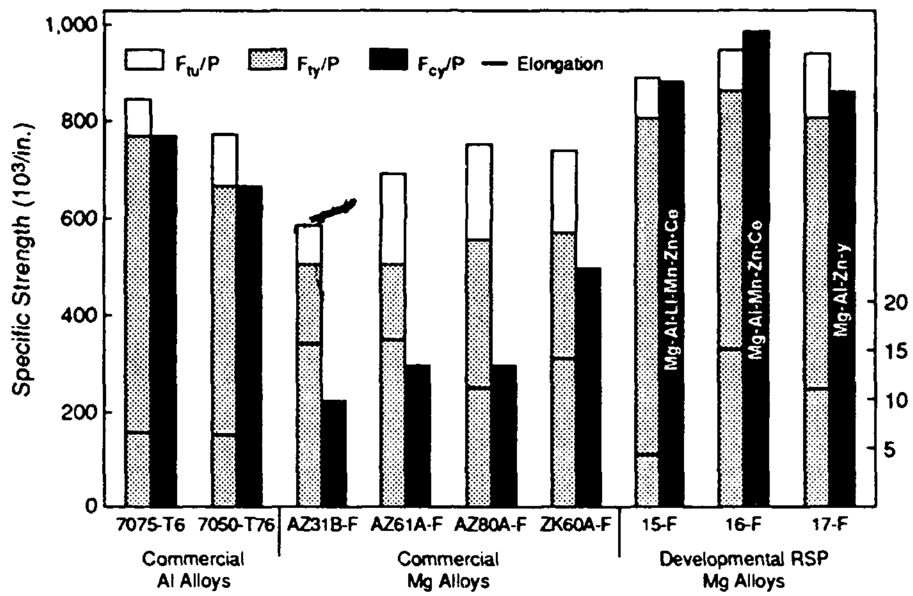


FIGURE 37-10 Magnesium alloys possess low density and very high specific stiffness and strength. Sources: Froes and Wadsworth, 1989. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 41, No. 5, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

alloys that contain rare-earth additions have been developed that have strength and ductility combinations equivalent to those of high-strength aluminum alloys. They are also more corrosion resistant than most corrosion-resistant conventional magnesium alloys. Figure 37-11 illustrates the corrosion resistance of the new magnesium alloys. If continued improvements in corrosion resistance and strength can be realized, there will be many applications for the improved materials. The possibility of increasing strength and stiffness through a composite approach is described in the next section ("Metal-Matrix Composites").

As with the other light metals, the use of such materials will be limited to airborne and ground-vehicle mobility systems where high specific strength and stiffness are required. Applications such as structural members in helicopters and other lightweight vehicles would appear to be the major uses.

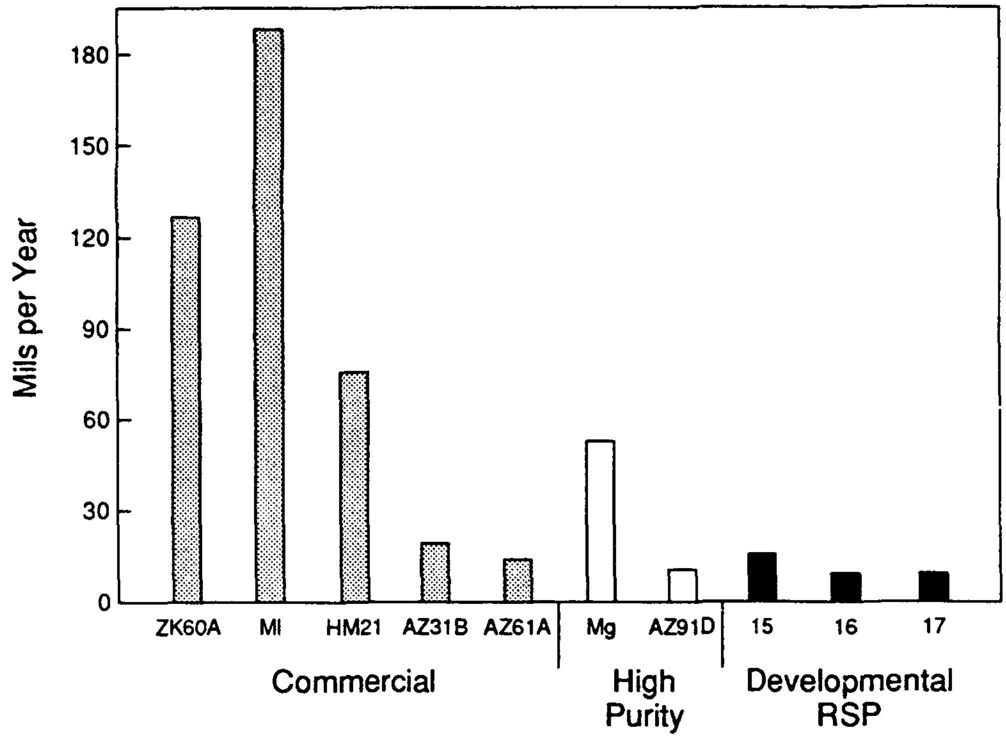


FIGURE 37-11 Corrosion resistance of new magnesium alloys. RSP, rapidly solidified powder. Source: Froes and Wadsworth, 1989. Reprinted with permission from JOM (formerly Journal of Metals) Vol. 41, No. 5, a publication of The Minerals, Metals & Materials Society, Warrendale, Pennsylvania 15086.

METAL-MATRIX COMPOSITES

Aluminum-Based Composites

The field of metal-matrix composites has most recently focused on aluminum-based systems with discontinuous reinforcements in the form of particulates or whiskers. Figure 37-12 shows that the introduction of reinforcement produces significant increases in the modulus (stiffness) and accompanying reductions in the coefficient of thermal expansion and thermal conductivity, shown in Figures 37-13 and 37-14, respectively. The introduction of ceramic particulates has also been shown to increase wear resistance significantly. Aluminum-based metal-matrix composites with the modulus of titanium are currently projected, as shown in Figure 37-15.

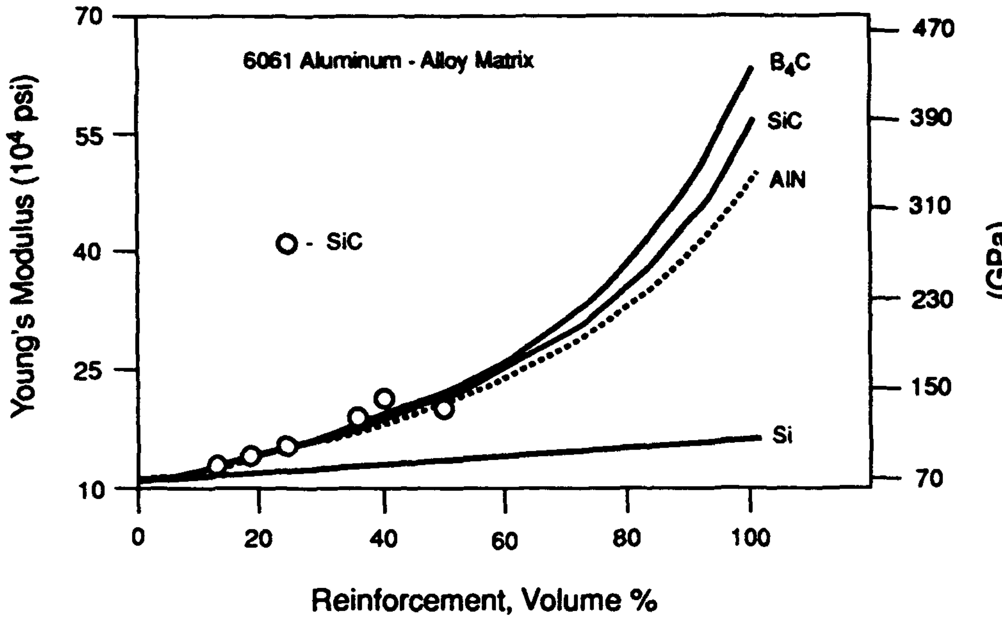


FIGURE 37-12 Effect of reinforcement volume fraction on Young's modulus (i.e., stiffness) of 6061 aluminum alloy. Source: Geiger and Jackson, 1989. Copyright © ASM International.

The high specific stiffness and wear resistance of these materials is attractive for a variety of structural applications, as well as for uses requiring a high degree of dimensional stability in changing-temperature environments. Critical aspects that require additional attention include toughness, fatigue, forming, and ballistic behavior, as well as the development of other reinforcements. The potential for expanding the composite approach to other systems is also extremely desirable and provides an attractive approach to improving the performance of gun barrels, tank or helicopter engine hot sections, and missile components. Figure 37-16 shows the potential benefits that such a composite approach confers on extending the useful operating temperature regimes of conventional monolithic aluminum and titanium alloys.

In the future, the ductility of aluminum metal-matrix composites will improve with advances in processing techniques and in the understanding of the mechanism's controlling fracture initiation and growth. Processes such as squeeze casting, spray deposition, and PM techniques have recently produced improved microstructures in the areas of reinforcement distribution and

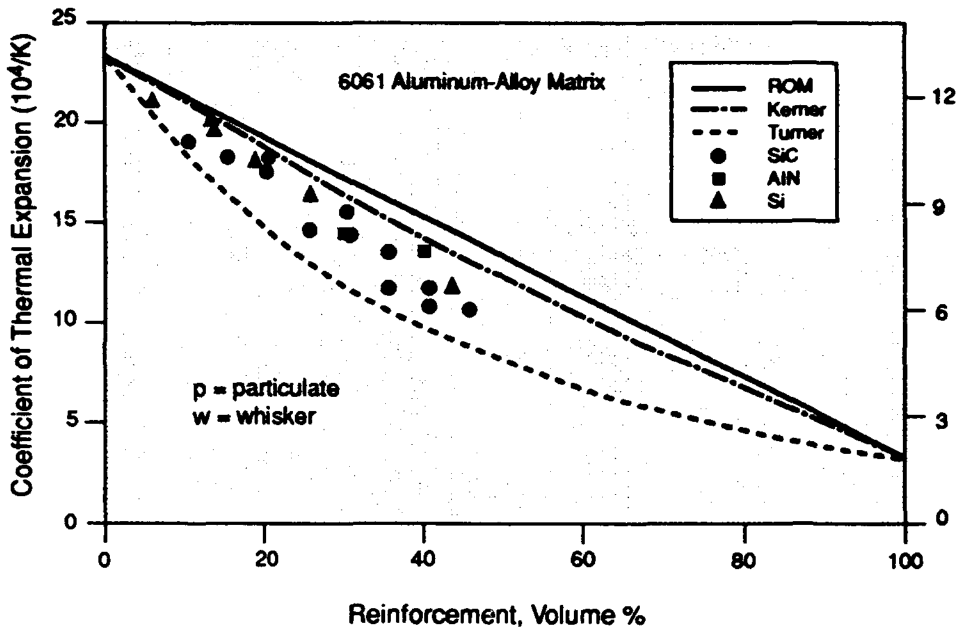


FIGURE 37-13 Effect of reinforcement volume fraction on the coefficient of thermal expansion of 6061 aluminum alloy. Source: Geiger and Jackson, 1989. Copyright © ASM International.

segregation. Emphasis on increasing the static toughness and flaw tolerance of such materials is critical.

Recent work indicates that significant increases in toughness of particulate-reinforced composite materials may be achieved by control of the microstructure, as shown in Figure 37-17. Areas that are likely to produce significant increases in the damage tolerance of such materials include suitable selection of particle size and limited clustering, the details of the interfacial regions and their modification, and selection of the matrix alloy and its microstructure (Lewandowski, 1989; Lewandowski et al., 1989). The increased specific strength and stiffness is particularly important for rotating parts, where the modulus and density control performance. Al-Li components may provide additional benefits because the addition of lithium decreases the density while increasing the modulus. Further enhancement of properties in the Al-Li system may be possible with incorporation of ceramic particulates.

In addition to the relative lack of information on the static toughness of such materials, little information is available in the open literature regarding

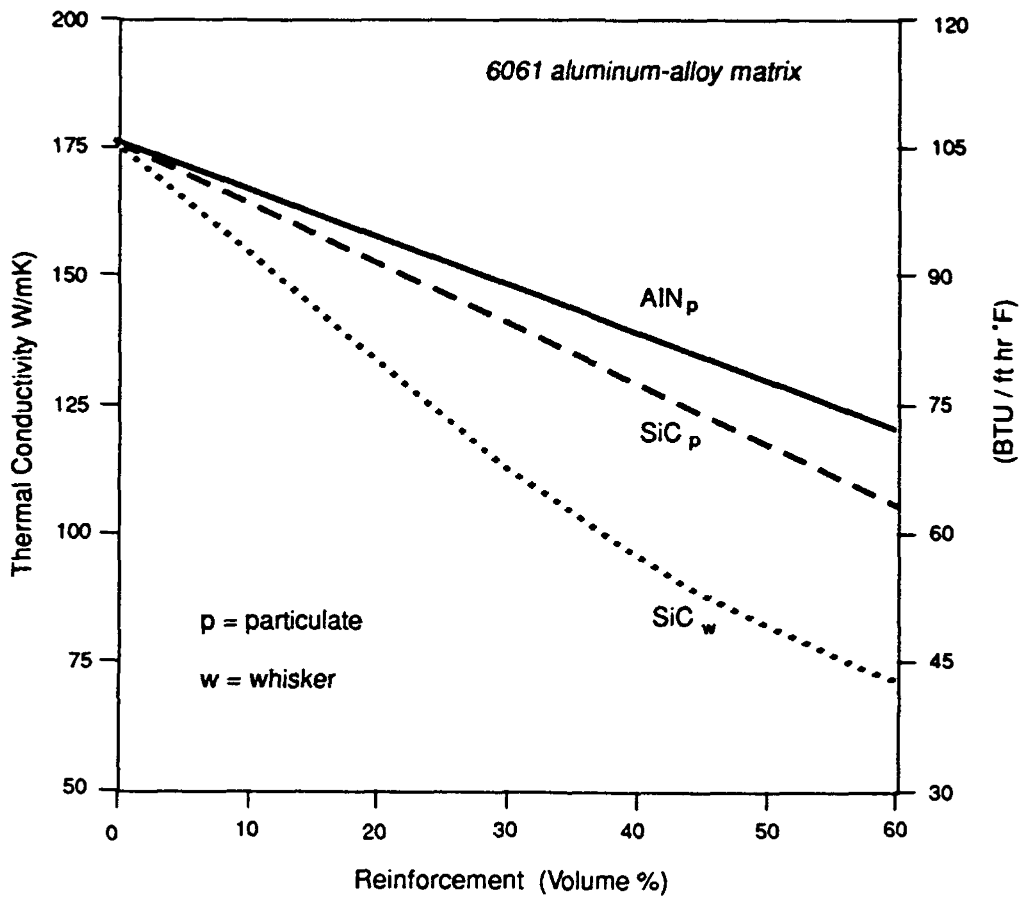


FIGURE 37-14 Effect of reinforcement volume fraction on the coefficient of thermal conductivity in 6061 aluminum alloy. Source: Geiger and Jackson, 1989. Copyright © ASM International.

the dynamic behavior (i.e., high strain rate) of these materials. Although some information exists concerning the effects of high strain rate on monolithic metals and alloys, much less work appears to have been conducted on composites. Studies of static and dynamic strengths and toughness on identically processed materials are not available. Suitable modification of the size, spacing, and volume fraction of reinforcement may produce significant differences in both the static and dynamic behavior. It is not clear what role microstructural modifications may have in increasing the toughness under dynamic conditions. Additionally, it may also be possible to tailor the composite microstructure so that the surface of the composite material exhibits good life-cycle dynamic properties.

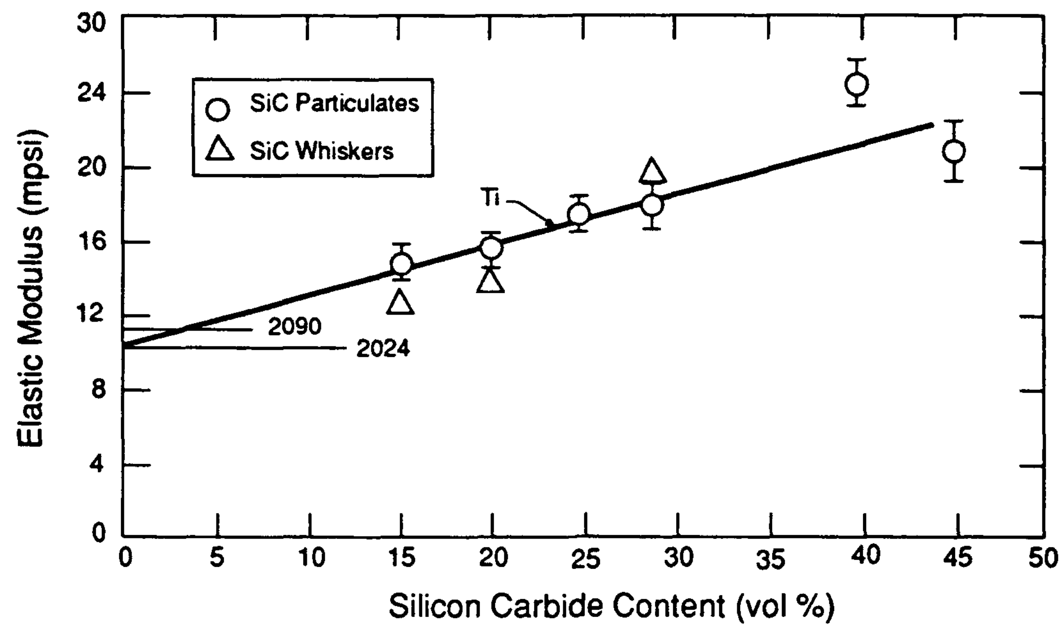


FIGURE 37-15 Aluminum-based metal-matrix composites with the modulus of titanium—as currently projected.

The benefits of metal-matrix composites, based on either aluminum or other matrix metals, lie in their increased specific strength, stiffness, damping characteristics, and decreased coefficients of thermal conductivity and thermal expansion. Continuous improvements in cost, reliability, and the ability to incorporate higher levels of reinforcement will further increase their specific strengths and stiffness. These advances will provide lightweight structures, gun systems, engine parts, and other parts for heavy-wear conditions over the design life cycle of such systems.

Other Metal-Matrix Composites

Several current and proposed advanced systems are dependent upon the development of new lightweight, high-performance materials. This need has stimulated a renewed interest in metal-matrix composites. While long-fiber continuously reinforced materials offer significant payoff in terms of specific performance, exploitation of this class of materials has been limited because of the cost of suitable fibers and fabrication processes, which are often specific to each alloy or composite system. By comparison, discontinuously reinforced metal-matrix composites also offer significant performance improvements

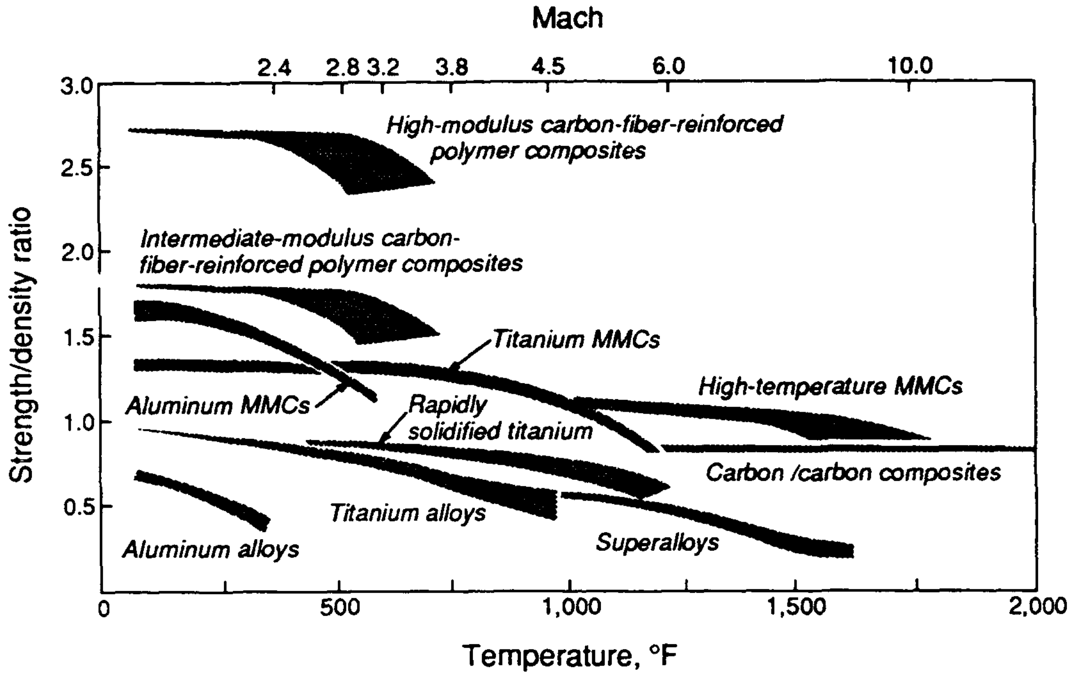


FIGURE 37-16 Potential benefits of a composite approach on extending the useful operating-temperature regimes of conventional monolithic aluminum and titanium alloys. Source: Advanced Materials and Processes, 1989. Copyright © ASM International.

relative to conventional engineering materials but have the additional process and cost benefits associated with traditional metal working.

Although R&D efforts to date have focused on aluminum-based metal-matrix composites, the potential for other matrix metals is enormous. For instance, the XD™ process provides a means to introduce a wide range (with respect to both chemistry and volume percent) of discontinuous ceramic reinforcement into virtually any metallic or intermetallic matrix (Christodoulou et al., 1988). Examples of these composites systems include carbide, nitride, and boride reinforcement in matrices of titanium aluminide (TiAl), nickel aluminide (NiAl), aluminum, or copper.

In addition to direct benefits such as strength and creep resistance, XD-reinforced alloys are characterized by a stable, refined grain size that improves the ductility of these intermetallic composites. (The differences in grain size can be seen by comparing Figures 37-18 and 37-19.) Substantial progress has been made in the use of this process to produce and evaluate composites of titanium diboride (TiB_2) in titanium aluminides. Such materials offer greatly improved specific properties relative to the currently used superalloys, which are based on nickel and iron. Substitution for these materials by XD titanium aluminides can lead to a direct 50-percent weight reduction of a component. In addition to strength, other attributes of these

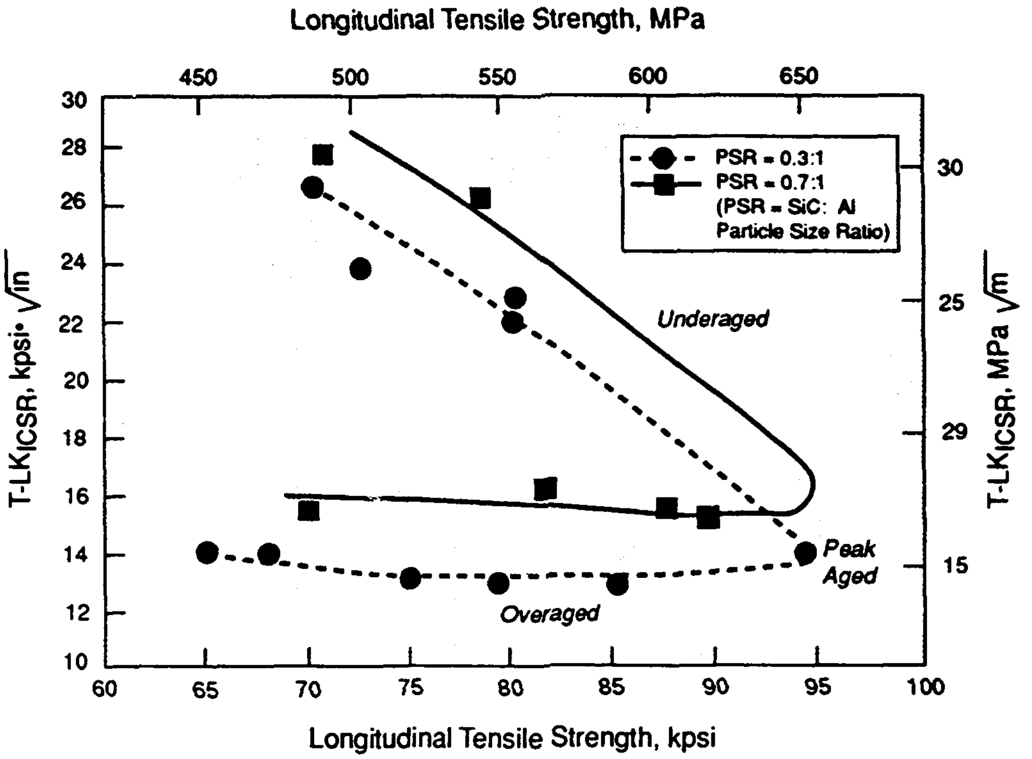
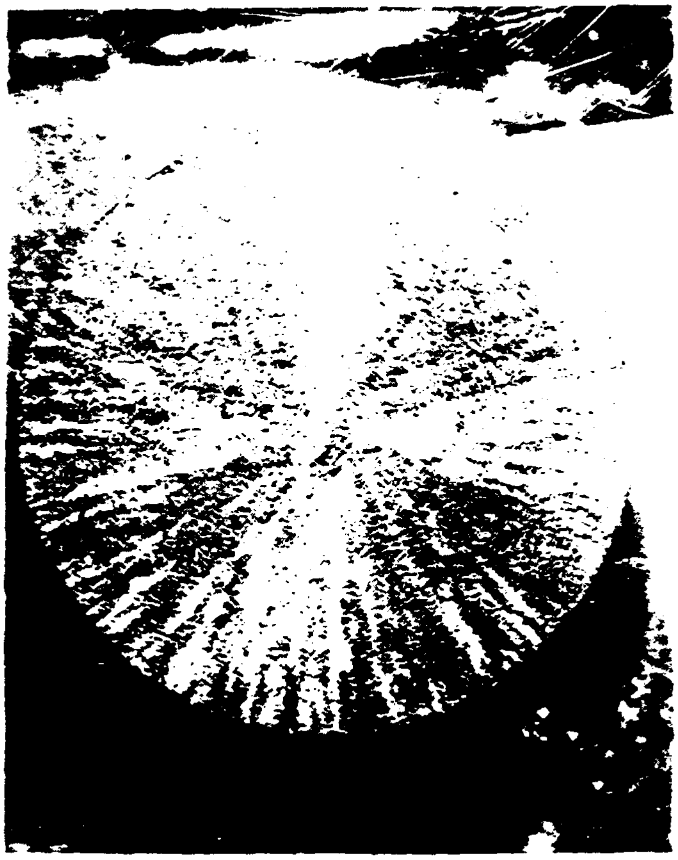


FIGURE 37-17 Effect of particle size and matrix-aging condition on the fracture toughness of an aluminum alloy composite. Source: Lewandowski, 1989. Copyright © The Society for the Advancement of Materials and Process Engineering. Reprinted by permission.

alloys include: modulus improvements (26,000 kpsi), good fracture toughness (as high as 23 MPa-m), and good resistance to wear and hot erosion. In the latter regard, these intermetallic-based composites have been investment cast into relatively complex near-net-shape components, forged, extruded, and atomized into powder form. Similarly, copper-based XD composites have been shown to have superior strength and stability, as well as lower densities, relative to NARloy-Z (a copper-based alloy used in the nozzles of the space shuttle's main engines). At the same time these composites exhibit thermal conductivities approaching that of pure copper.

XD titanium aluminides show promise for near-term applications that can benefit from incorporation of a lightweight, strong, high-modulus material. Maximum benefits will be in high-temperature applications. Initial



FIGL . 37-18 Ti–48Al–2Nb–2Mn (Magnified 5×). Photo courtesy of Martin Marietta Laboratories, Baltimore, Maryland.

applications for these alloys will probably be on systems that do not carry crews (non-man-rated) such as missile fins (subsonic and hypersonic), missile housings, and as components in disposable turbines. Other applications may include lightweight armor, especially at very high ceramic reinforcement levels (≥50 percent).

In the far term, ceramic-reinforced metal-matrix composites will be incorporated as key structural components on both non-man-rated and man-rated systems. Incorporation of soft phases within the microstructure, in addition to the ceramic reinforcement, will boost toughness and damage tolerance of these materials to produce lightweight armor with high impact resistance. Other areas of application include:

- missile components (e.g., fins, housings);
- rotating components;

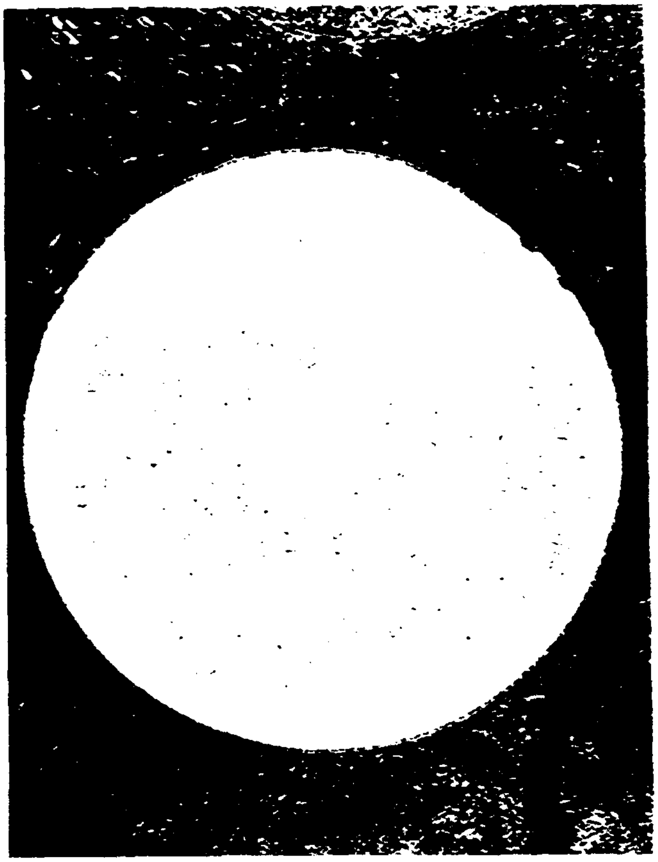


FIGURE 37-19 Ti–48Al–2Nb–2Mn + 7 volume percent TiB_2 (Magnified 5×). Photo courtesy of Martin Marietta Laboratories, Baltimore, Maryland.

- gun tubes and barrels; and
- electrically energized guns.

Advanced Forming Techniques

The ability to form advanced materials into physical components will continue to be a major area of importance, particularly for materials such as composites. The introduction of the reinforcement into the matrix may significantly change the ability and techniques necessary to successfully form these materials into advanced components. Superplastic forming of aluminum-based composite materials has been recently demonstrated at high temperatures (e.g., 500°C) and relatively high strain rates (Advanced Materials and Processes, 1989). Figure 37-20 shows a schematic of superplastic forming, where the conditions are defined such that extremely high

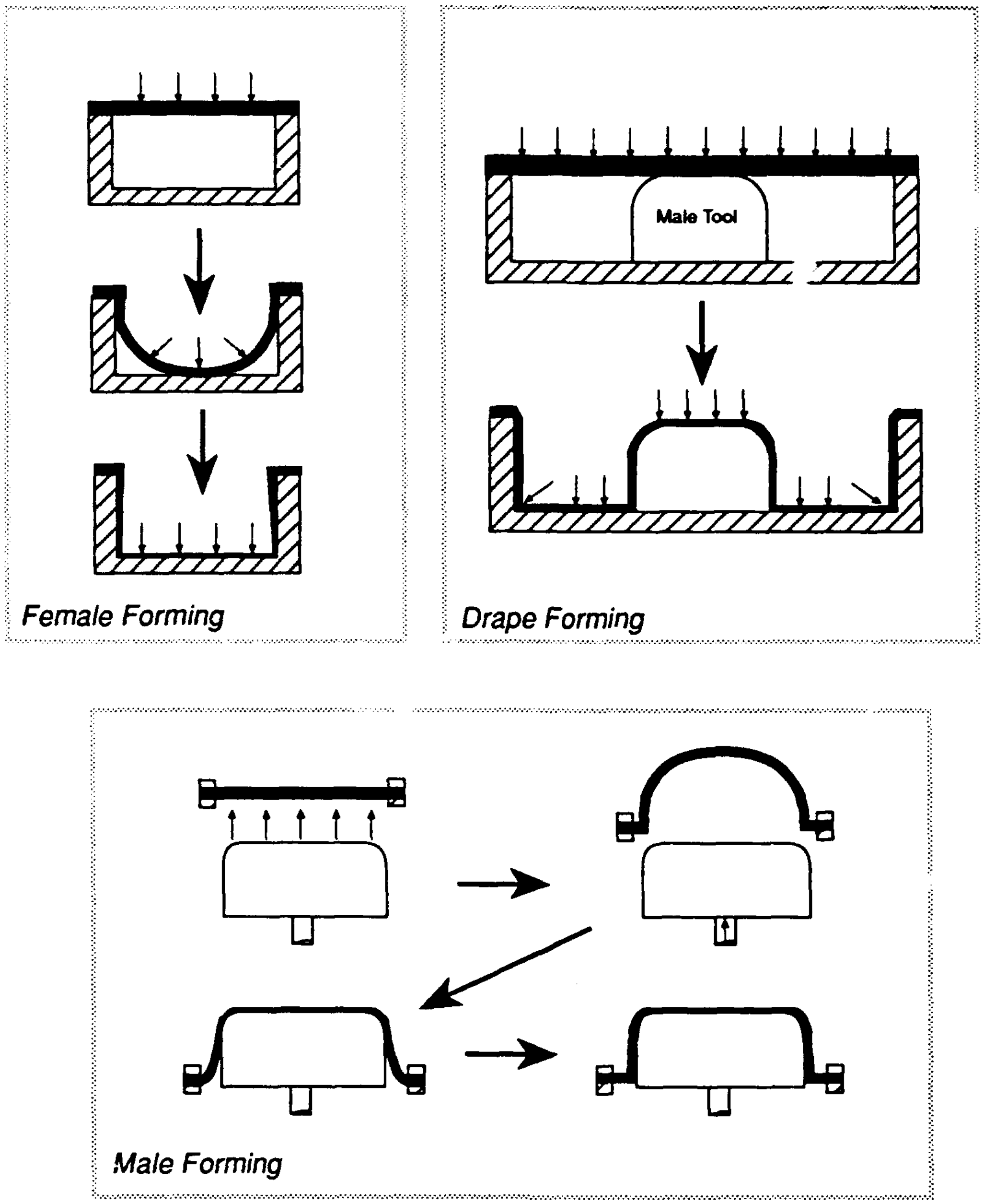


FIGURE 37-20 Superplastic forming. Source: Tuegel et al., 1989. Copyright © ASM International.

elongations (> 100 percent) are possible, thereby permitting the forming of complex shapes.

The fine grain size associated with these metal-matrix composites appears to be beneficial in imparting superplastic behavior. Significant advances may be achieved if these composites could be made superplastic at even lower temperatures. The potential for superplastic behavior of other, higher-temperature alloys (e.g., titanium alloys and composites or aluminum composites) will make these alloys competitive in both cost and weight with conventionally fabricated aluminum components. The fundamental microstructural features controlling the ability to achieve superplastic behavior will continue to be an area of active research.

The ability to form materials into components reproducibly and at low cost will be significant for all advanced materials with uses in structural components. It may be possible to reduce considerably the amount of material wasted as a result of more conventional component manufacturing techniques, such as machining. The beneficial properties that could result from these advanced forming techniques will affect the following areas:

- air frame and vehicle panels with integral stringers;
- warhead enclosures;
- cryogenic storage tanks; and
- shaped-charge liners (discussed further below).

HEAVY METALS

Tantalum Warhead Devices

Modern warhead devices use high-density materials to achieve the level of performance required to defeat modern armor targets. Some of these devices contain a carefully tailored explosive charge, which surrounds a liner that is hollow, conical, or hemispherical. When the warhead senses that it is in the proximity of the target and detonates, the detonation wave deforms the liner into a long slender supersonic penetrator jet (Figure 37-21). Similarly, the penetrators produced from explosively formed projectile (EFP) warheads originate from a saucer-like disc that explosively collapses to form an aerostable penetrator also travelling at supersonic speeds. In some applications, the penetrator must fly a few hundred meters to its target, while in other applications the flight path traversed by the EFP penetrator is considerably shorter. For EFP warheads, the aerostability requirement is more critical as the flight path increases in length. In both shaped-charge and EFP applications, it is important to optimize the energy transfer between the explosive and the liner to produce coherent jets and penetrators.

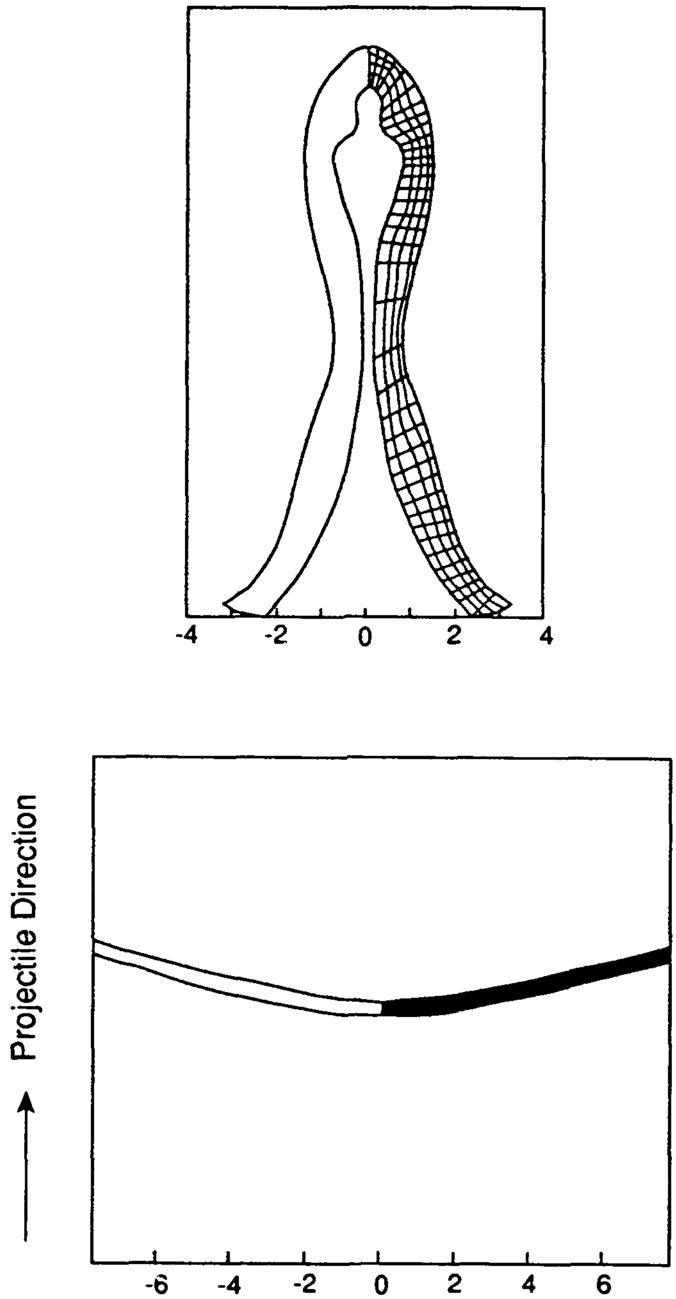


FIGURE 37-21 Explosively formed projectile. Representation of initial configuration (bottom) and subsequent deformation (top).

The penetrators produced from the collapse of shaped-charge and EFP warhead devices contain material that continues to stretch as it flies to the target. If the stretching is too extreme, the device can break up into smaller pieces, which can tumble and degrade the penetrator capability of the warhead. Work with the tantalum materials has focused on metallurgical experiments that are designed to produce shaped-charge and EFP penetrators having the ability to stretch and not easily fail under the extreme plastic deformation processes that occur during explosive collapse of the warhead. These deformation processes require considerable mass movement of penetrator material. Thus, much effort has gone into developing a data base identifying the role of processing schedules and of impurities, chemistry, grain size, and crystallographic orientation of the polycrystalline material from which the penetrator was fabricated. These efforts aim to produce warheads that hold together under the stretching actions caused by the extreme deformation processes involved.

There is also a considerable data base obtained from tensile, compressive, and torsional shear experiments that were conducted at strain rates similar to those experienced by the explosively collapsing warhead device. Soft recovery experiments have produced specimens whose postmortem analyses have yielded information concerning the temperature rise and recrystallization kinetics of shaped-charge and EFP penetrators.

Code research groups are attempting to develop constitutive equations to model materials that experience strain rates similar to those for shaped-charge and EFP penetrators. These models attempt to account for such properties as the pressure and temperature dependence of the yield strength and shear modulus, work hardening, pressure dependence melting, strain-rate effects, and spall behavior. These workers attempt to provide a bridge between the microscopic results of metallurgy and the macroscopic experiments of shock-wave physics.

The current status of this developing technology consists of materials research and code development work to improve the understanding of how materials behave under high strain and of the high-strain-rate conditions that occur during and shortly after warhead detonation, as well as research to understand and exploit the physics of penetrator–target interactions. The materials work concerns itself with identifying the melting, processing, and rolling schedules that must be followed to produce warheads with consistent penetration capability. It also provides the code developers with more physically based constitutive models for the next generation of codes. The code developers are attempting to incorporate into their models more realistic expressions for the dynamic yield strength, the effect of massive dislocation generation, their interactions with each other, the effects of dislocation annihilation behavior, and more detailed descriptions of the detonation and deformation processes that occur when shaped-charge jetting devices and EFP penetrators are produced. There is also considerable interest in modeling the perforation of monolithic, complex, and nonpassive armor by both shaped-charge jets and EFPs.

Current shaped-charge and EFP technology produces penetrators that have a velocity gradient along their axis, which causes the stretching jet or penetrator to break up eventually. Experiments have recently been initiated to produce high-velocity projectiles with a uniform velocity distribution. Techniques to produce shaped-charge jets with tailored velocity distributions, such as high-speed jet tips followed by slower-traveling material, are also receiving attention. For example, a bimetallic liner can be fabricated that not only produces the desired velocity distribution but also conserves critical defense materials by the substitution of materials such as niobium for tantalum in selected regions of EFP liner. Such techniques would also provide significant cost savings.

In the far term, this R&D will lead to more effective warheads. High-speed impact tests using single crystals in various orientations have indicated that optimum penetration can be achieved when mushrooming of the impacting penetrator is controlled through a judicious choice of crystal orientation in the projectile. This test result can probably be further exploited by tailoring the processing schedule of tantalum shaped-charge and EFP devices to produce high-speed nonmushrooming projectiles.

Improved Depleted-Uranium Alloys

Depleted uranium (DU), a byproduct of nuclear fuel production, is a low cost and relatively available material. Consequently, industrial nonnuclear usage has increased steadily during recent years. From an engineering standpoint, the most important property of DU alloys is their great density, almost twice that of lead and nearly as great as those of pure gold and tungsten metals. DU alloys are much easier to fabricate than other dense metals, such as tungsten and rhenium, and are much less costly than metals such as gold and platinum. These qualities make DU alloys good candidates for objects that must be small yet very heavy. There are three principal nonnuclear uses of DU: radiation shielding; counterweights in airplanes, helicopters, and missiles; and kinetic-energy (KE) armor-piercing projectiles for military ordinance (Blasch et al., 1970; NRC, 1971). DU alloys are also being evaluated for vehicular armor and for selected warhead applications.

KE penetrators constitute by far the largest single use of DU alloys. In addition to high density, DU alloys offer high penetrator effectiveness against both monolithic and spaced armor, post-penetration pyrophoricity, ease of fabrication, abundant availability, and low cost. Two DU alloys, U-3/4 Ti and U-2 Mo, are used for most penetrator applications. These alloys are thermally processed to produce properties that will give the best possible ballistic performance as KE penetrators. Planned and actual usage includes 25-mm, 105-mm, and 120-mm long-rod projectiles. The Air Force also uses the U-3/4 Ti alloy in its GAU-8 projectile. U-2 Mo is the standard DU alloy for selected British munitions; it is also used by the Navy for its Phalanx Penetrator System.

DU is a highly anisotropic material. Properties can vary extensively, depending on fabrication history, thermal processing, impurity levels, and orientation with respect to the direction of working (Eckelmeyer, 1976). Tables 37-1 and 37-2 present typical mechanical properties for production-quality U-3/4 Ti and U-2 Mo alloys. A majority of the current DU R&D programs are aimed at improving the performance of the standard alloys by thermal or mechanical processing and by design innovations for the armor, warheads, or KE penetrator systems under development.

Future armor-antiarmor systems will require DU alloy materials with combinations of properties (density, strength, ductility, toughness, etc.) not available with current materials and procedures. Two promising areas are new alloy development and rapid solidification processing. In particular, rapid solidification processing offers the potential of tailoring DU alloys that, with further thermal or mechanical processing, will produce a variety of desired property combinations not currently available. Limited testing has shown that these materials offer the property improvements at a reasonable cost.

TABLE 37-1 Tensile Properties of U-3/4 Ti

Yield Strength		Tensile Strength		
MPa	kpsi	MPa	kpsi	Elongation (%)
Underaged				
700	101	1350	196	14
850	123	1450	210	13
1000	145	1525	221	7.5
Peak Aged				
1200	174	1650	239	2.5
Overaged				
1000	145	1450	210	3
850	123	1300	188	4
700	101	1175	170	7

Source: Eckelmeyer, 1976.

Table 37-2 Tensile Properties of U–2%Mo

Yield Strength		Tensile Strength		
MPa	kpsi	MPa	kpsi	Elongation (%)
Underaged				
700	101	1150	167	4
850	123	1200	174	4
1000	145	1250	181	2.5
1150	167	1350	196	1.5
Peak Aged				
1350	196	1600	232	1.5
Overaged				
1150	167	1375	199	1.5
1000	145	1400	203	3.5
850	123	1225	178	8
700	101	1125	163	17
550	80	925	134	24

Source: Eckelmeyer, 1976.

Tungsten Alloys

Tungsten alloys and DU alloys are two primary candidates for KE penetrator core materials. The U-3/4 Ti alloy has been the material of choice for U.S. large-caliber KE long-rod projectiles since the early 1970s, because it has demonstrated ballistic performance superior to that of comparable tungsten alloy projectiles against a spectrum of armor designs. In recent years, however, there has been a renewed interest in improving the properties of tungsten alloy projectiles.

Tungsten alloys are typically fabricated by liquid-phase sintering of mixed elemental powders (Figure 37-22). The resulting product is a composite that consists of interconnected tungsten grains with an interpenetrating solidified liquid phase. A typical composition is 90 to 97 percent tungsten, the remainder being nickel and iron in a ratio from 8:2 to 7:3. For KE projectile application, the main concerns are the strength, hardness, and toughness of the material. Usually the needed strength and hardness are created by selective deformation and heat treatment after sintering. In recent years, developmental work has concentrated on generating new compositions and employing advanced processing and working technologies to improve the mechanical properties of tungsten alloys. This work has been successful in

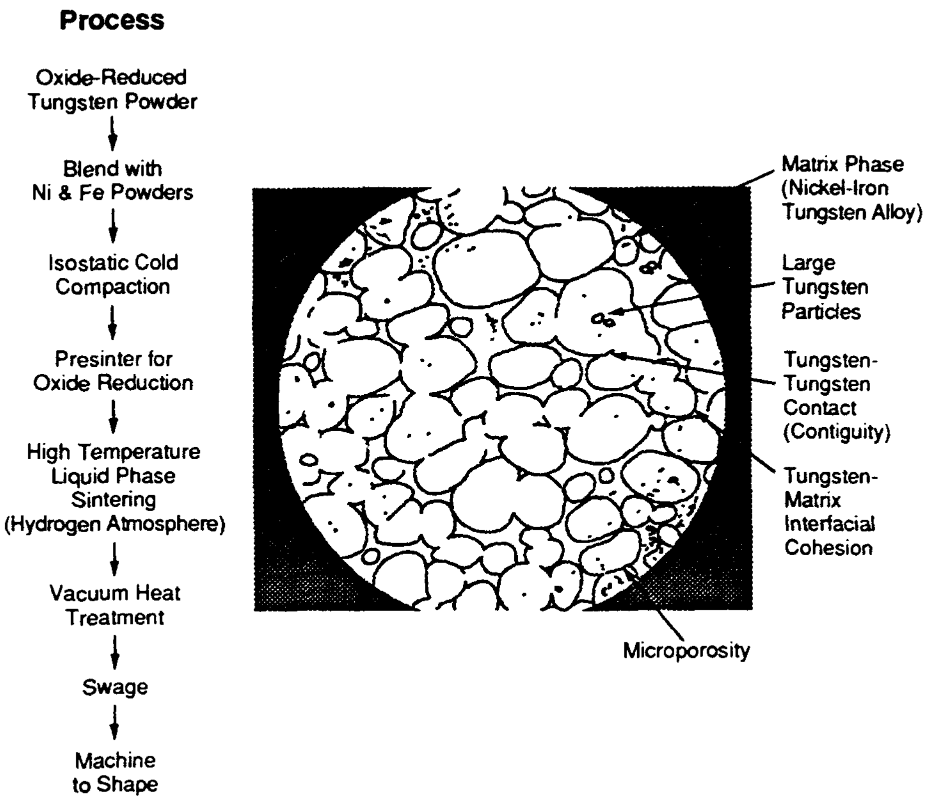


FIGURE 37-22 Microstructure of liquid-phase sintered material. Courtesy of U.S. Army Armament, Munitions, and Chemical Command.

improving mechanical properties, but no improvement in ballistic performance has yet been realized.

Mechanical properties are far less important in the ballistic performance of KE projectiles against heavy monolithic armors and ceramic-steel laminate armors. The penetration of heavy targets is to the first order a hydrodynamic process, and inertial forces play a diminishing role in the erosion of the projectile and the displacement of armor material. The density of penetrator material, therefore, is an important parameter and, in general, the ballistic performance improves with increasing alloy density. However, in laboratory tests DU alloys consistently outperform tungsten alloys of the same density against heavy monolithic targets (e.g., rolled homogeneous armor). Although several other explanations have been proposed, recent tests at the Ballistic Research Laboratories at Aberdeen suggest that it is the greater susceptibility of the tungsten alloy to localized adiabatic shear that leads to its poor performance. Under the high hydrostatic pressure operating at the penetrator–target interface, tungsten alloys undergo tremendous plastic strains and gross bulk deformation. The presence of a large mushroom head is routinely observed on the residual tungsten alloy penetrators.

However, the defeat of many armor systems is not simply a function of penetrator performance. As has been observed in the past, the resistance of the projectile to structural failures is an essential factor in the defeat of many complex armors.

Against light armors, especially high-hardness armor plate, plugging is often as important a part of the perforation process as is penetration. In this application, tungsten penetrators perform as well as their DU counterparts. In terms of basic penetration efficiency, however, the uranium alloy has clear advantages.

Future development of tungsten alloys will be directed toward inducing fundamental changes in the physical characteristics of these materials, to introduce localized shear failure that will improve terminal ballistic performance.

The principal benefits of these developmental efforts will derive from the availability of an alternative material to DU for armor-piercing applications. An improved material with ballistic performance at least as good as a DU penetrator is the primary goal of present developmental efforts. The use of tungsten alloys as large-caliber KE penetrators will mitigate problems posed by exclusive reliance on DU, with respect to both environmental issues and total life-cycle system cost.

38

Energetic Materials

SYNTHESIS OF NEW HIGH-PERFORMANCE ENERGETIC MOLECULES

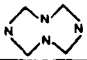
Energetic molecules form the basis for explosives; for missile, rocket, and gun propellants; and for pyrotechnics. They are the primary ingredient in all munitions. There are opportunities to increase the energy density of these materials, thus increasing performance or reducing volume. Increased energy density allows increased performance of antiarmor warheads and higher-velocity projectiles launched from gun tubes; it also allows increased range or reduced size of rockets and missiles.

Currently, HMX (cyclotetramethylene tetranitramine) is the energetic material used in explosives for high-performance antitank warheads and in missile and rocket propellants that require great range with minimum smoke. RDX (cyclotrimethylene trinitramine) is the current basis for high-performance gun propellants that are insensitive to fragments and effects of spall behind armor. Calculations indicate that cage explosives, such as those shown in Table 38-1, have the potential to increase the density of an energetic material by 30 percent (ARDEC, 1985–1989). Since the explosive output of an energetic material is proportional to the square of its density, these new molecules could significantly increase explosive output. Again, the higher energy, dense energetic materials will enable longer ranges to be achieved in missiles and rockets with equivalent volume, while keeping smoke output at a minimum.

The nitration of cage-type molecules has been under study for several years. Table 38-1 gives calculated performance parameters of some cage molecules with respect to HMX. The table shows several cage molecules with greater potential performance than HMX, as indicated by parameter P_{CJ} in the last column. The nitration of cubanes has made progress in the past several years: to date, four nitro groups have been placed on the cubane ring; the objective of fully nitrating this compound to octanitrocubane should be reached sometime in the 1990s. Because nitrocubanes are less sensitive than HMX and RDX, they are candidates for insensitive munitions (see "Insensitive Energetic Materials," below) as well as for increased performance. Further increases in energy density beyond nitrocubanes could be achieved by synthesizing heterocyclic cage molecules that contain carbon–nitro linkages. This work could carry through the time period from 2000 to 2010.

These new energetic materials, which will form the basis of explosives and propellants (solid, liquid, or gel) with higher energy densities, will

TABLE 38-1 Properties of Carbocyclic Cage Compounds with Nitro Content Optimized for Maximum Detonation Output, as Calculated by the Kamlet-Jacobs Simple Method

Parent Hydrocarbon Cage Compound	Composition of Polynitro Cage			Density	Heat of Formation	Strain Energy		Detonation Pressure
	C (no.)	H (no.)	NO_2 (no.)	ρ (g/cm^3)	ΔH°_f (kcal/mole)	Molecular (kcal/mole)	Avg. C–C Bond (kcal/mole)	P_{CJ} (kbar)
Tetrahedrane 	4	0	4	2.138	88.03	126	21.0	512
Triprismane 	6	0	6	2.138	80.03	137	15.2	493
Cubane 	8	0	8	2.098[a]	81.04	157	13.1	467
Homocubane 	9	1	9	2.094	30.08	122	9.4	453
1,3-Bishomocubane 	10	1	11	2.092	-33.83	82.6	5.9	431
Bishomopentaprismane 	12	2	12	2.057	-56.76	70.1	4.1	421
Trishomocubane 	11	2	12	2.063	-75.3	57.1	3.8	419
Diamantane 	14	5	15	2.048	-170.47	9.8	0.5	415
Adamantane 	10	5	11	1.959	-136.69	5.6	0.5	383
HMX[b] 	4[c]	8	4	1.903	17.4	0	0	382

[a] Modified by taking cubane as basis for calculation.
[b] Included for comparison.
[c] The two-dimensional ring contains four nitrogen atoms in addition.

Source: ARDEC, 1985–1989.

enhance the lethality of munitions and increase the velocity or range of projectiles, missiles, and rockets. Figure 38-1 shows improvements that might be achievable over current technology. Similar curves could be drawn for EFPs; Table 38-2 gives the calculations of expected increased velocities of EFPs.

TABLE 38-2 Potential Improvements in Velocity of Explosively Formed Projectiles[a]

		Velocity Increase[b]			
	LX-14 Velocity (%)	Octanitrocubane		Dinitrodiazatetrahedrane	
		(km/s)	(km/s)	(%)	(km/s)
KAMLET	2.5	2.59	20%	2.95	36%
TIGER	1.90	2.50	32%	2.93	54%

[a] DYNA2D calculations using gamma law.
[b] Increase = percentage increase in velocity to LX-14.
Source: ARDEC, 1985–1989.

INSENSITIVE ENERGETIC MATERIALS

The development of energetic materials for military applications faces conflicting requirements for both (1) increased performance and (2) insensitivity to uncontrolled stimuli, such as fire, bullet or fragment impact, shaped-charge jets, or the violent reactions of other nearby munitions. The performance of a munition depends, among other factors, on the amount of energy stored in the energetic molecules and the crystal lattice; the sensitivity of a munition is related to the ease with which the energetic material initiates and propagates sustained reaction.

Early attempts to reduce the sensitivity of energetic materials involved the addition of inert materials, such as wax or other binders, which also reduced performance. High-energy-density materials that are also insensitive will enhance the operational and logistic survivability of troops transported on weapon platforms or in close proximity to munitions.

Particle size, binder type, plasticizer, and energetic crystal interactions greatly influence sensitivity. Greater understanding of these facts has enabled formulation of explosives and propellants with reduced sensitivity while maintaining current performance. Research during the next 10 years will bring a clearer understanding of the factors underlying sensitivity. Within 20 years, advanced processing technology will allow smaller particle sizes and increased

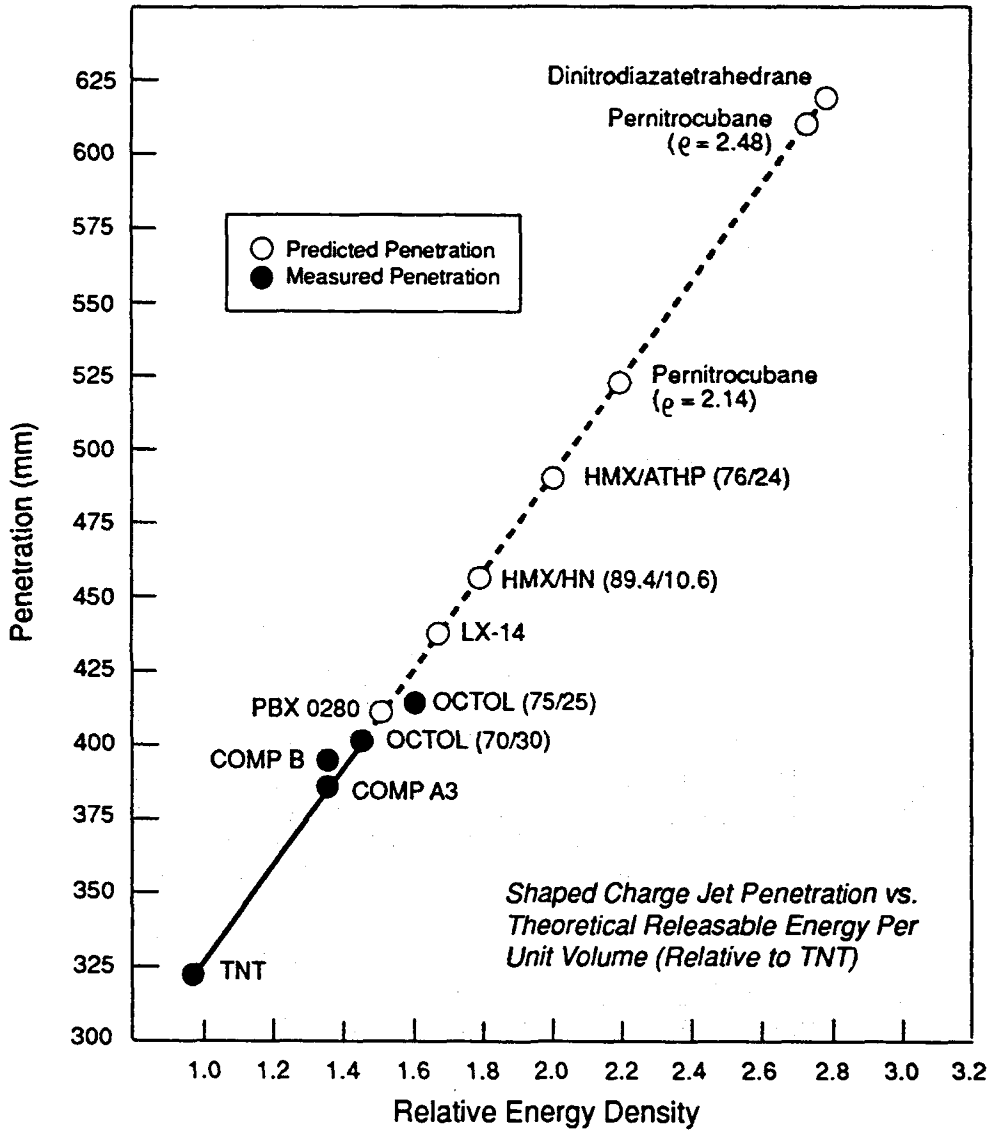


FIGURE 38-1 An idealized curve that shows potential achievement in explosives performance over current technology. Source: ARDEC 1988–1989. Courtesy of U.S. Army Armament, Munitions, and Chemical Command.

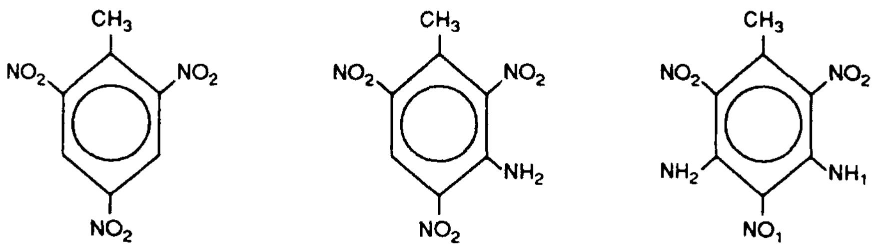
energetic crystal interaction with binders and plasticizers in a very controlled matrix. These advances will further reduce sensitivity.

Recent advances in computational techniques and experimental reaction kinetics have also shown that increased performance in a system is possible at reduced vulnerability. Figure 38-2 shows a molecule of 1,3,5-trinitrotoluene (TNT) and two modifications of this molecule by addition of amino groups to the ring. Molecular-orbital calculations show that the $C{-}NO_2$ bond (a determinant of initiation) is much stronger in the 3,5-amino-TNT than in TNT or 3-amino-TNT. When these explosive molecules were synthesized and detonated, the 3,5-amino-TNT proved to be about 75 percent less sensitive than TNT, yet had a measured detonation pressure 30 percent higher than TNT. In this figure, impact height is a measure of sensitivity (higher values represent less sensitive material), while the P_{CJ} pressure and detonation velocity indicate the performance of an explosive. Modeling and computational techniques have thus proven themselves to be useful in developing energetic molecules with less sensitivity and greater performance.

Future advances in measurement techniques and increases in computer capability will allow calculation of the sensitivity and explosive yield of potential explosives from first principles. This will allow the design of insensitive, high-energy-density materials on the computer before going into the laboratory to synthesize the materials. The principal benefits for the Army will be in munition survivability and the potential to save lives and weapon platforms. This modeling capacity will also aid in reducing resupply, because of lower vehicle and munition loss in combat areas. Less sensitive but energy-dense materials also offer greater mobility or increased payloads, since less ammunition is likely to be destroyed during a combat operation, allowing the supply tail to be reduced.

PROCESSING AND LOADING OF ENERGETIC MATERIALS

The current methods for processing, manufacturing, and loading of energetic materials uses methods that are based for the most part on World War II technology. These outdated methods are labor-intensive and generate considerable pollution. In fact, the domestic manufacture of TNT has been curtailed because of the pollution it generates. The potential of biotechnology to develop means of biodegrading hazardous materials has not been fully exploited; the reverse process of using biotechnology to synthesize energetic molecules also offers potential. For example, the DNA bases synthesized by living organisms—adenine, uracil, cytosine, guanine, thymine, and 5-methyl



TNT (Trinitrotoluene) | 3-amino-TNT | 3,5-diamino-TNT

	Sensitivity	Yield	
	Impact Height (cm)	C-J Pressure (Kbars)	Detonation Velocity (km/s)
TNT	61	180	6.942
3-amino-TNT	174	220	7.44
3,5-diamino-TNT	239	254	7.78

FIGURE 38-2 Molecular modification of explosive behavior. Courtesy of U.S. Army Armament, Munitions, and Chemical Command.

cytosine—are potential feedstocks for bioconversion to nitramine compounds. An enzyme isolated from the crown vetch plant converts uracil to nitramines.[1]

Improved processing technology can also lead to improved performance and reduced sensitivity. For example, if it were possible to reproducibly make a layered gun propellant, in which each layer has a very controlled solid oxidant (amount and particle size), binder, and plasticizer matrix and a very controlled burning rate, it would be possible to keep the pressure on the base of the projectile higher than is currently possible. This would result in higher projectile muzzle velocities and therefore greater lethality. This kind of control would also lead to greater insensitivity, since it would be possible to better shield the more sensitive materials in the material matrix with the less sensitive binders and plasticizers. Similar arguments for increased

[1] Briefings to the Advanced Materials Technology Group of the STAR Science and Technology Subcommittee by Joseph A. Lannon, U.S. Army Armament, Munitions, and Chemical Command. Picatinny Arsenal, New Jersey.

performance and reduced sensitivity could be made for missile propellants and explosives.

Recent advances in biotechnology indicate that pollution problems from energetic materials can be handled in an efficient and economic manner; current work in Europe shows that TNT and nitroglycerin can be biodegraded (Lannon, 1989). Biotechnology is also being used to synthesize new energetic molecules; some recent work indicates that it is possible to convert glycerin to nitroglycerin using enzymes (Lannon, 1989). New processing techniques that use turn-screw mixing and extrusion are much less labor-intensive and offer the potential for producing a more uniform product.

Within the next 15 years, improved synthesis processes that generate less pollution are possible. Some of these may make use of biotechnology, which could reduce costs, improve safety, and enable synthesis of new materials. Waste streams can be cleaned up by biotechnology or other improved process controls.

The Technology Group believes that, within 30 years, it will be possible to process extremely small particle energetics (submicron size) on a large scale by introducing more computer control into the process. Programmed layered energetic materials will enable the user to have munitions with uniform and improved performance and reduced sensitivity. Improved processing and loading of energetic materials will enable the Army to improve the lethality and survivability of its missiles, rockets, and munitions in the field. Performance will be enhanced by the ability to control the initiation, detonation, and burn characteristics of energetic materials far better than with today's technology. Pollution will be eliminated from the manufacturing process, which will be capable of producing energetics for small conflicts or expanding quickly to allow surge productions for larger conflicts.

DEVELOPMENT OF A NEW CLASS OF MORE LETHAL WARHEADS

Known chemical reactions could potentially release much greater amounts of energy than conventional organic explosives. The problem for military applications is to release this energy fast enough to produce a lethal warhead or jet. The aim is to fabricate these energetic materials with barrier layers separating the reactants, in a manner similar to that used for multilayer composites in the micron range. Initiation of these composites could make use of slapper detonator technology.

Figure 38-3 illustrates this concept. Alternating thin layers of reacting chemicals, separated by some physical barriers, are prepared on hard substrates by advanced-material preparation methods, such as controlled vapor deposition or epitaxy. The barriers could be designed to provide a great deal of insensitivity in the munition. Initiating shocks and propagation events break the barrier between the reacting chemicals, whose reaction generates large

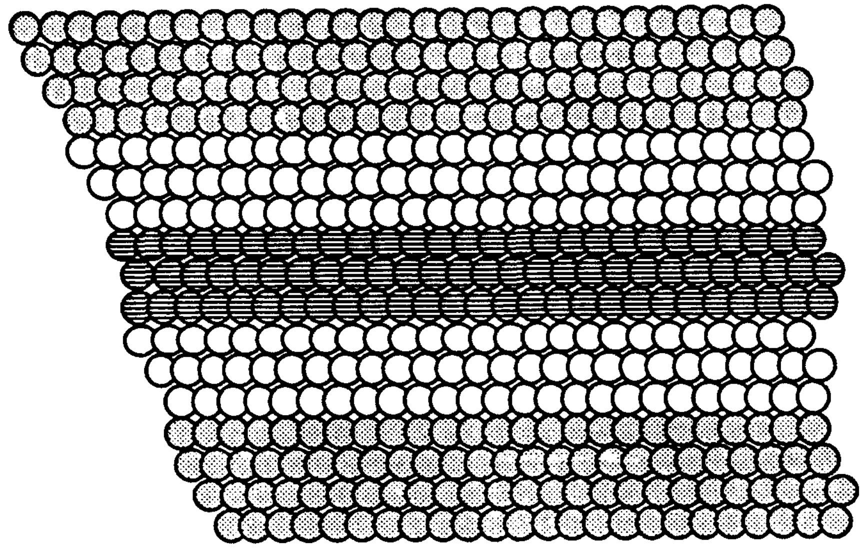


FIGURE 38-3 Schematic representation of energetic reactants separated by barrier layers. Thickness of each layer would be in the micrometer range. Courtesy of U.S. Army Armament, Munitions, and Chemical Command.

amounts of energy. Chemicals considered for this role include high-burning boron compounds, high-energy thermite reactions, and others. For increased lethality, the energy released by the reaction could be coupled to a metal liner, as in an EFP warhead. This new explosive concept would enable the development of a new class of warheads, especially antiarmor warheads with greatly improved performance and reduced sensitivity.

Although suitable metastable mixtures that react to give a high energy release are already known, further R&D is needed to determine the practicality of this concept. Fabrication techniques for multilayer composites in the micron range are known but have not been applied to layering of reactive materials. The coupling of the energy released by these classes of reactions to the metal in a warhead in the proper time frame is yet to be demonstrated. However, further research appears justified by the potential advantages; if successfully demonstrated, this concept could lead to extremely compact or greatly enhanced munitions and to warheads that would be extremely effective against hard targets.

39

Armor Materials

Advanced materials are a key technology in the multilayered, multiconstituent armor systems that are required to protect against the wide spectrum of threats on the modern battlefield. This spectrum includes shaped charges, high-velocity KE penetrators, fragmenting munitions, and directed energy threats. While much current work on armor systems is focused on nonpassive concepts such as reactive armors, it is clear that all projected forms of armor will require a passive backup layer that has high ballistic efficiency. Advanced armor materials that combine ballistic efficiency, ease of manufacture, and low cost will remain a key Army requirement over the time period covered by this study.

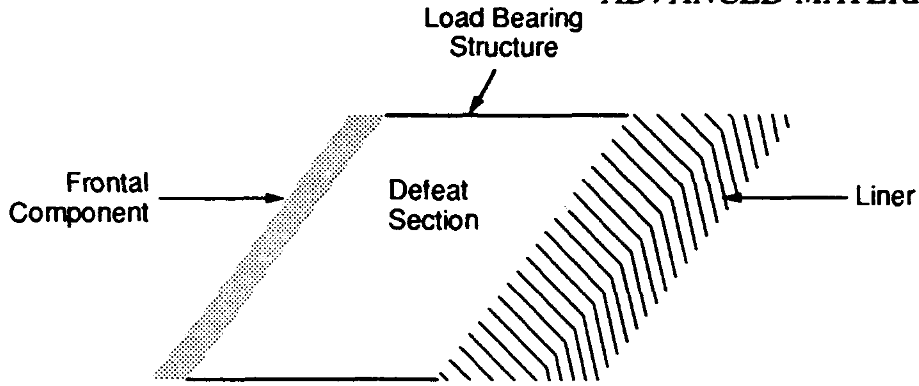
At present, the Army has three major applications for armor systems and materials:

1. protection of the individual soldier;
2. protection of aircrew and critical aircraft components; and
3. protection of combat vehicles.

Each of these applications has its own trade-offs with respect to mission value per pound, volumetric efficiency versus cost, and so on. However, generalizations can be made. For personnel and aircraft armor materials, high mass efficiency is critical. Thus, Kevlar helmets and helicopter seats of boron carbide and Kevlar are the current state of the art. In the case of ground-based vehicles, weight has not been viewed as critical until now; conventional materials such as steel and aluminum have been the dominant armor materials. For light-armored vehicles such as armored personnel carriers and infantry fighting vehicles, aluminum armor is the main structural element; add-on steel armor (perhaps perforated) might be the frontal or outer component, and a Kevlar spall shield might constitute the liner (Figure 39-1). For tanks, steel would constitute the outer and structural armor, but there may be various types of "special" armor arrays in the defeat section.

In the near future (to 15 years out), projections of technology demonstrated at the laboratory level indicate that systems designers can count on the following technology:

- Advanced ceramics processing and packaging technology will develop to the point where ceramic armor will be cost-effective as well as ballistically efficient (Figure 39-2).



Approaches

Conventional
- Rolled Homogeneous Armor
- Structural Aluminum
- Dual Hardness Steels
- Reinforced Plastics

Unconventional
- Ceramics
- Ceramic Composites
- Novel Steel Laminates
- Reactive Systems

FIGURE 39-1 Armor systems. Courtesy of U.S. Army Materials Technology Laboratory.

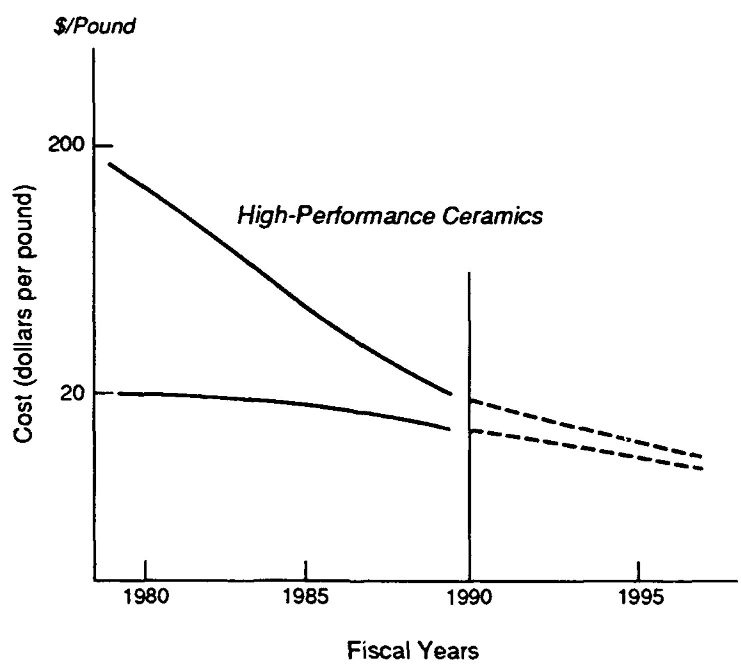


FIGURE 39-2 Cost trends for ceramic armor materials. Courtesy of U.S. Army Materials Technology Laboratory.

- Ballistically efficient thick-section graphite-reinforced plastic will continue to improve in performance (Figure 39-3) and will provide reductions in manufacturing and maintenance costs.
- Advanced aluminum alloys (especially Al-Li) and Al-matrix ceramic particulate composites will increase performance and reduce weight of armor for light-armored vehicles.
- High-performance glasses such as oxynitride glasses will be available as improved transparent armor and dilatent armor for the defeat of shaped charges.
- Microstructural texturing has been shown capable of increasing the ballistic performance of steel. This approach will lead to other enhanced metallic armors (Figure 39-4).
- Improved polymeric fibers such as spectra fibers, which are derived from an oriented sol-gel, will provide enhanced protection to the individual soldier (Figure 39-5).

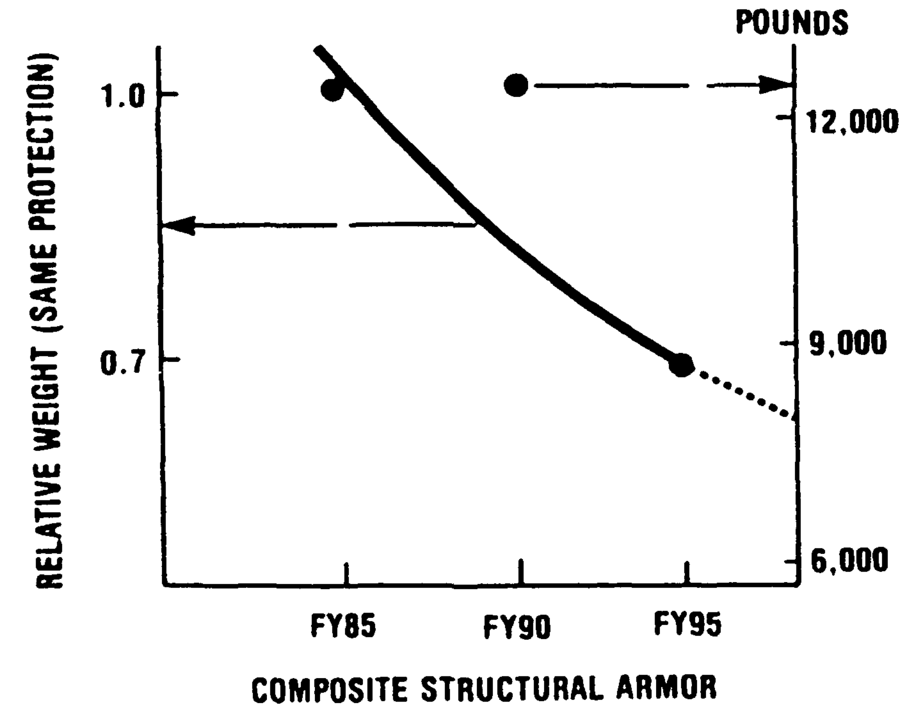


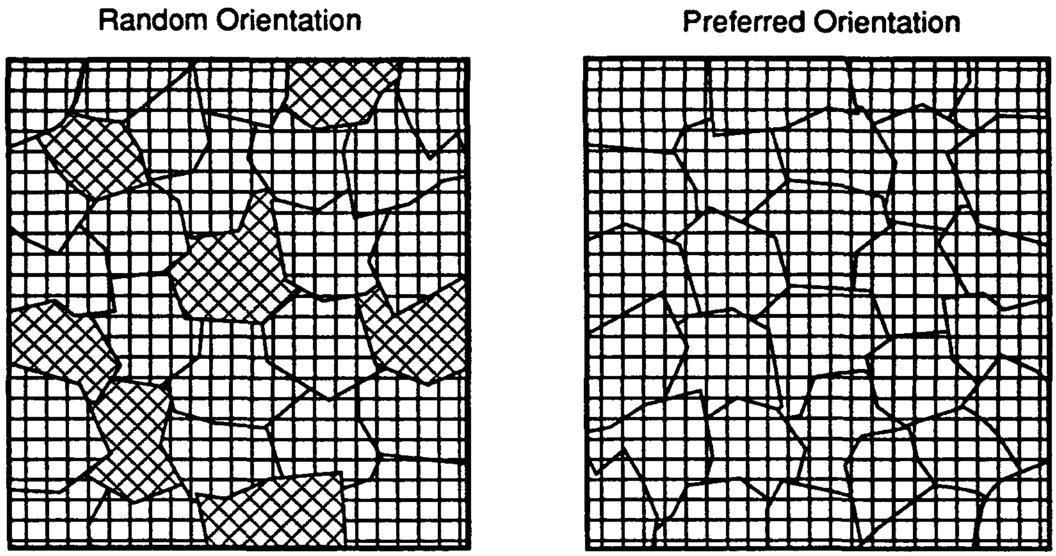
FIGURE 39-3 Hull and armor weight for combat vehicles. Courtesy of U.S. Army Materials Technology Laboratory.

In 30 years, there will be further improvements in all of the above areas and the emergence of real capability in the following:

- multifunctional armor structures (e.g., protection against ballistic attack and chemical, biological, and nuclear threats; reduced signature in multisensor signal domains; and materials hardened to electromagnetic pulse).
- biologically engineered fibers, with the possibility for exceptional strength-to-weight ratios, for uses such as body armor (see "Part V, Biotechnology and Biochemistry," Chapter 27, section on "Novel Materials for New Capabilities");
- models for nonlinear dynamic systems that will lead to major design improvements in ballistically tolerant materials; and
- electrically enhanced armor.

The above advances will have significant impacts on the following Army systems:

- armored vehicle design and survivability;
- aerial vehicle design and survivability;
- protection of the individual soldier; and
- maintenance and logistics.



Process Control

↓

Oriented Polycrystals

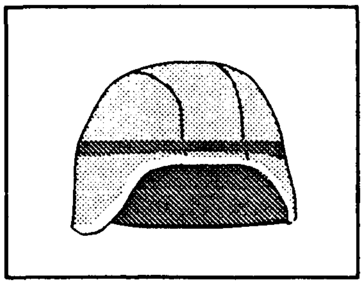
↓

15–20% Improvement Over High Hard Steel

- Current Technology
  - 5% Ni - 0.38% C - 0.6% Mn - 0.5% Mo Steel
- Future Technology
  - Textured aluminum alloys, titanium alloys, ceramics

FIGURE 39-4 Crystallographically textured armor. Courtesy of U.S. Army Materials Technology Laboratory.

SPECTRA 1000 2-lb Helmet



Properties

	SPECTRA 1000	KEVLAR
• Density (g/cm^3)	0.97	1.44
• Strength (psi)	400,000	400,000
• Modulus (psi)	17×10^6	12×10^6

Future Army Applications

• Helmets	Demonstrated	↓1/3 wt.
• Vests	Feasibility Demonstrated	↓1/3 wt.
• Helicopter Seat Back-Up	Potential	↓5–10% wt.
• Spall Liner	Not Suitable (flammability issue) vis-a-vis Shaped Charge	

Technology

- SOL-GEL spinning of polyethylene yields 70% crystalline fiber versus 60% crystalline in normal polyethylene fiber
- Process commercialized by Allied Corporation as SPECTRA 1000 fiber in the U.S. and by DSM as DYNEEMA-SK60 in Europe

FIGURE 39-5 Advanced polymer processing can lighten the soldier's load. Courtesy of U.S. Army Materials Technology Laboratory.

References

Advanced Materials and Processes. 1989. Advanced Materials and Processes: 1989 Guide to Selected Engineering Materials. 4(1) June.

Andersson, C.A. and M.K. Aghajanian. 1988. The fracture toughening mechanism of ceramic composites containing adherent ductile metal phases. Ceramic Engineering and Science Proceedings. 9(7–8):621–626 [check volume and pages; volume 9 also cited for same article.]

ARDEC. 1985-1989. Proceedings of Working Group Meetings on Synthesis of High Energy Density Energetic Materials. 1985, 1986, 1987, 1988, and 1989. U. S. Army Armament Research, Development, and Engineering Center. Picatinny Arsenal, N.J.

Asmussen, J., M.C. Hawley, and L.T. Drzal. 1990. Electromagnetic Coupling Systems and Materials for Materials Processing. Final Report for Contract No. DAAG 46-85-K-0006. Army Materiel Command, Watertown, Mass.

Beyeler, E., W. Phillips, and S.I. Güçeri. 1988. Experimental investigation of laser-assisted thermoplastic tape consolidation. Journal of Thermoplastic Composite Materials. 1:107–121.

Blasch, E.G., G.L. Stukenbroeker, R.J. Lusky, C.F. Bonilla, and H. Berger 1970. The use of uranium as a shielding material. Nuclear Engineering and Design. 13:146–182.

Canundann, G.W., and M. Jaffe. 1987. Anisotropic polymers: Their synthesis and properties. Chapter 7 in Proceedings of the Robert A. Welch Conferences on Polymer Research, 26th Conference, Synthetic Polymers. Houston, Texas: Robert A. Welch Foundation. (November):247–291.

Christodoulou, L., P.A. Parrish, and C.R. Crowe. 1988. XD titanium aluminide composites. Pp. 29–34 in Materials Research Society Proceedings, vol. 120, F.D. Lemkey, S.G. Fishman, A.G. Evans, and J.R. Strife, eds. Pittsburgh, Pa.: Materials Research Society.

Clarke, D.R. 1992. Interpenetrating phase composites. Journal of the American Ceramic Society. 75:739–758.

Eberhart, M.E., K.S. Kumar, and J.H. MacLaren. [1990]. An electronic model for the DO_{22} to $L1_2$ transformation of the Group IVA trialuminides. Philosophical Magazine B 61(6):943–956.

Eckelmeyer, K.H. 1976. Aging phenomena in dilute uranium alloys. Physical Metallurgy of Uranium Alloys. Pp. 463-509 in Proceedings of the Third Army Materials Technology Conference (Vail, Colo., 1974), 2nd ed., J.J. Burke, D.A. Colling, A.E. Gorum, and J. Greenspan, eds. Columbus, Ohio: Metals and Ceramics Information Center, and Chestnut Hill, Mass.: Brooke Hill Publishing Co.

Froes, F.H., and J. Wadsworth. 1989. Developments in metallic materials. Journal of Metals 41(5):12–19.

Garrison, W.M., and N.R. Moody. 1987. Ductile fracture. Journal of Physical and Chemical Solids 48(11):1035–1074.

Geiger, A.L., and M. Jackson. 1989. Low-expansion MMCs boost avionics. Advanced Materials and Processes. 136(1) July:23-30.

Haggerty, J.S., J.H. Flint, G.J. Garvey, J-M. Lihrman, and J.E. Ritter. 1986. High strength, oxidation resistant reaction-bonded silicon nitride from laser-synthesized silicon powder. Pp. 147–154 in Ceramic Materials and Components for Engines, W. Bunk and H. Hauser, eds. Verlag Deutsche Keramische Gesellschaft.

Hunt, W.H. Jr., T.M. Osman, and J.J. Lewandowski. 1993. Micro- and macrostructural factors in DRA fracture resistance. Journal of Metals. 45(1)30-35.

Lamicq, P.J., G.A. Bernhardt, M.M. Dauchier, and J.G. Mace. 1986. SiC/SiC composite ceramics. American Ceramic Society Bulletin 65(2):336–338.

Lewandowski, J.J. 1989. Processing and mechanical properties of lightweight structural composites. SAMPE Quarterly 20(2):33–37.

Lewandowski, J.J., C. Liu, and W.H. Hunt, Jr. 1989. Effects of matrix microstructure and particle distribution on fracture of an aluminum metal matrix composite. Materials Science and Engineering A107:241–255.

Newkirk, M.S., H.D. Lesher, D.R. White, C.R. Kennedy, A.W. Urquhart, and T.D. Claar. 1987. Preparation of Lanxide™ ceramic matrix composites: matrix formation by the directed oxidation of molten metals. Ceramic Engineering and Science Proceedings. 8(7–8):879–885.

NRC. 1971. Trends in the Use of Depleted Uranium (NMAB-275). Report of the National Materials Advisory Board, National Academy of Sciences, Washington, D.C.: National Academy Press.

NRC. 1989. Research Opportunities for Materials with Ultrafine Microstructures (NMAB-454). Report of the National Materials Advisory Board, Washington, D.C.: National Academy Press.

NRC. 1990. Status and Applications of Diamond and Diamond-Like Materials: An Emerging Technology (NMAB-445). Report of the National Materials Advisory Board, National Research Council. Washington, D.C.: National Academy Press.

NRC. 1991. The Impact of Supercomputing Capability on U.S. Materials Science and Technology (NMAB-451). Report of the National Materials Advisory Board, National Research Council. Washington, D.C.: National Academy Press.

Pickens, J.R. F.H. Heubaum, T.J. Langan, and L.S. Kramer. 1989. Al–(4.5-6.3) Cu–1.3Li–0.4Ag–0.4Mg–0.14Zr. Pp. 1397–1414 in Aluminum-Lithium Alloys: Proceedings of the Fifth International Aluminum-Lithium Conference (Williamsburg, Va., Mar. 27–31, 1989), T.H. Sanders and E.A. Starke, eds. Birmingham, UK: Materials and Engineering Publications Ltd.

Pigliacampi, J.J. 1987. Organic fibers. Engineered Materials Handbook. Metals Park, Ohio: ASM International. 1:54–57.

Prewo, K.M., J.J. Brennan, and G.K. Layden. 1986. Fiber reinforced glasses and glass-ceramics for high performance applications. American Ceramic Society Bulletin. 65(2):305–322.

Shannon, R.W., P. Stifel, R. Beger, E.J. Hughes, and J.L. Rutherford. 1978. Primary Adhesively Bonded Structure Technology (PABST). U.S. Air Force Flight Dynamics Laboratory Technology Department, Report No. AFFDL-TR-77-107. September.

Sherby, O.D., D.W. Kum, T. Oyama, J. Wadsworth, and B. Walser. 1985. Ultrahigh carbon steels. Journal of Metals 37(6):50–56.

Tuegel, E.J., M.O. Pruitt, and L.D. Hefti. 1989. SPF/DB takes off. Advanced Materials and Processes. 136(1) July:36–42.

PART VII

PROPULSION, POWER, AND HIGH-POWER DIRECTED ENERGY

PROPULSION AND POWER TECHNOLOGY GROUP

Gerard W. Elverum, *Lead Expert*
W. James Sarjeant, *Vice Lead Expert*

40

Summary of Findings for Propulsion, Power, and High-Power Directed Energy

PROPULSION TECHNOLOGIES

For the highly mobile Army of the future, advances in various propulsion technologies will have a major influence on functionality, supportability, and survivability of many weapon systems and battle units. For missile propulsion the needed capabilities will be evasion in offensive systems and interception in defensive systems. Both liquid and gel propellant propulsion systems, and possibly liquid–solid hybrids, can be configured to support these thrust management requirements. Substantial increases in specific impulse of up to 20 percent are forecast over the next 30 years for both solid and gel rocket propellants. The evolution of solid and gel propellants is also expected to result in low-exhaust-smoke formulations, although these propellants may have somewhat lower specific-impulse values. In addition, solids should become less sensitive to various thermal and shock environments.

Army nonballistic missiles and air vehicles will benefit from expected *major improvements in gas-turbine engine developments*. The Technology Group forecasts a twofold increase in engine thrust/weight ratio, combined with up to a 40 percent decrease in specific fuel consumption (i.e., pounds of fuel per horsepower-hour). These gains could provide up to a 100 percent increase in range-payload factors. The Group suggests that use of beamed microwave energy to provide power to small remote-piloted air vehicles during the necessarily slow ascent to and descent from very high altitudes and to extend the operational time aloft.

For surface mobility applications, evolution and utilization of a methodology for total integrated propulsion system design can offer a multiplying effect on the expected improvements in various engine, transmission, cooling system, and control technologies. Hybrid electric-drive propulsion systems have potential to provide improvements in the total battle zone effectiveness of many vehicles. Gains could be made in overall primary energy efficiency and therefore also in attendant fuel logistics, in functional capabilities of various armored vehicles and mobile weapons, and in providing flexible alternatives for electric power availability under extended deployment. Technology improvements already achieved in the past 10 years in small primary turbine and diesel engines, electric motors and generators, solid-state power and conditioning elements, and electronic control systems provide a basis for near-term development of effective hybrid propulsion systems.

For the propulsion of projectiles from gun tubes, significant improvements are offered by liquid propellants and by electrically energized guns, which the Group forecasts will provide enhanced warfighting flexibility in the future. The electromagnetic (EM) gun has accelerated projectiles up to velocities of 7 km/s at total energies in the megajoule class. Both electrothermal-chemical and EM guns would derive overall system advantages if utilized with electrically driven ground platforms that incorporate electrical energy storage systems, such as those discussed in Chapter 43, "Electric Power Technology for Battle Zones."

ELECTRIC POWER TECHNOLOGIES

Future Army units of all types will become increasingly dependent on electric energy. Power levels will range from tens of watts for the needs of individual soldiers and various robotic surveillance devices; kilowatts for operation of command areas, radars, motors, and environment control; and up to megawatts for use in electric-drive propulsion, directed energy weapons, or electrified hypervelocity projectile launchers. To satisfy the high level of mobility and survivability demanded by the fluid battle zones of the future, electric power systems will need to be extremely compact, have high specific power and specific energy, and in many applications produce minimal signatures.

Major improvements in volume, weight, and efficiency for various continuous-power supply systems can be achieved by direct coupling (no gear box) of advanced turboshaft engines at 24,000 rpm to high-frequency generators (400 Hz), together with high-frequency power conditioning and distribution systems. Factors of two or more in the specific power of engines can be expected from the Integrated High-Performance Turbine Engine Technology Program, which is a joint program of the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) in cooperation with the aerospace industry. The Technology Group projects an order-of-magnitude increase in specific power when these engines are coupled to advanced high-frequency generators and solid-state power control technologies.

Similar order-of-magnitude increases in specific power should evolve out of new technologies for pulsed-power systems, which are necessary for radar; laser detection and ranging (LADAR); electronic countermeasures (ECM); and high-power microwave (HPM) weapons, antimine devices, and even antiarmor devices. Today, up to 80 percent of a pulsed-power system's total weight and nearly all of the risks reside in the power conditioning units. Properly nurtured by the Army, technology development of molecularly tailored solid-state materials and new thermal management concepts could provide systems that not only have specific power higher by a factor of 10 but also exhibit graceful degradation, so that a critical level of capability is always available.

The Army of the future will have many applications requiring energy storage with electric power output. Improvements in primary and secondary batteries appear to be quite limited, achieving perhaps a factor of 3 or 4 over lead-acid technology, measured in watt-hours per kilogram. Technology development is required on fuel cells in which the hydrogen is supplied from JP-8 (aircraft fuel) or other storable compounds, on regenerative hydrogen–oxygen fuel cells, and on other concepts with the potential to deliver very high specific energy and specific power, such as flywheels made of ultrastrong composite materials.

HIGH-POWER DIRECTED ENERGY TECHNOLOGY

High-power electromagnetic energy beams can be used to upset, degrade, disable, or destroy various kinds of attacking weapons, weapon platforms, and surveillance/target designator systems. Four types of lasers currently in some phase of technology development have been identified for such applications: free-electron lasers (FELs), chemical lasers, solid-state ionic lasers, and solid-state diode lasers. The FEL would be used by the Army for strategic ballistic missile defense from major ground installations. Chemical lasers have potential battle-zone and support-zone uses for terminal-phase underlayer defense against (nonnuclear) theater/tactical ballistic missiles and for terminal-phase defense against all types of threats involving end-game maneuvering missiles.

Diode-array lasers of the future are projected to achieve up to tens of kilowatts of coherent continuous-wave power at 50 percent electric-energy efficiency. They would have battle-zone uses in antisensor and antipersonnel weapons. Arrays of diode lasers that are noncoherent would be used to pump solid-state ionic lasers. Ionic lasers produce coherent pulses in the near infrared or visible region. Crystalline-based ionic lasers are projected to achieve average powers of up to 500 watts per single aperture at pulse rates of up to 500 Hz. Glass-type ionic lasers could produce greater than 1 kilojoule per pulse at lower repetition rates (1–3 Hz). Coherent coupling of these ionic amplifiers could produce high-power laser arrays—perhaps as high as 50 kW at 20 percent efficiency. These lasers could severely damage optical systems even at long ranges.

Directed narrow beams of high-power millimeter-wave radiation (wavelengths from 1 to 10 mm) can create in-band upset or permanent damage to millimeter-wave radars and passive sensors. Target intensities are limited at longer ranges by atmospheric absorption in the higher frequencies and by practical antenna size at the lower frequencies.

HPM (wavelengths from 2 to 30 cm) beams could provide severe upsets to the electronic systems of all kinds of weapon platforms and many missiles. Coupling is out of band, via electromagnetic current pulses that are generated in the internal skin of the target. Intensities on target at given ranges are primarily limited the by peak power per pulse that can be obtained by coherently combining outputs from multiple microwave tubes and by practical overall diameters of phased-array antennas.

41

Introduction

SCOPE OF THIS TECHNOLOGY FORECAST

The Propulsion, Power, and High-Power Directed Energy Technology Group was one of nine such groups that constituted the Science and Technology Subcommittee of the STAR Study. These technology groups were intended to be a resource available to the eight systems panels as they formulated visions of potential future battle-zone scenarios and of system concepts that could provide the Army with superior capabilities to prevail in those scenarios. Each technology group consisted of several individuals who had broad expertise in the designated technical areas and were appointed by the National Research Council (NRC). These individuals were to respond to specific technology inquiries by the panels in the form of brief overviews and assessments of the future evolution of those technologies. These assessments would be based on published documents or information provided to the group by scientists and engineers at various government and industrial organizations.

During the first months of the STAR Study, the systems panels' efforts proceeded in such a way that only limited requests for specific technology forecasts were made. Because of this, and because the study's steering committee believed that the systems panels' work would benefit, the technology groups were requested to provide status descriptions of each technology category and their judgments regarding how those technology areas could realistically be expected to evolve over the next 30 years. The technology lead experts were also asked to select and provide more detailed concise forecast assessments for a few specific technology elements in each category that, in their opinion, could provide special advantages for future Army systems.

It should be noted here that the summaries of each technology category are not intended to be engineering tutorials but rather concise descriptions along with the current and projected future performance and the operating characteristics that would be useful and important to the engineers in the applicable systems panels. The technology groups then elected to provide specific technology forecast assessments (TFAs) for technology elements that were believed to have exceptional potential for improvement or those that could enable new ways of performing envisioned future missions. The projections and assessments in this report are the opinions of the members of the Propulsion, Power, and Directed Energy Technology Group, based on their personal expertise and information requested from various contributors.

They are not necessarily directly supported by extensive engineering analyses or quantitative data.

One additional point should be made clear. In selecting these few technology elements for TFAs, and in some cases making recommendations for more direct Army financial support, the group does not mean to imply that other technologies are necessarily of less importance or potential. Many of the other technologies identified in the summary for each category are of fundamental utility and will be further developed as a matter of course by the Army, other elements of DOD, NASA, or industry. In many of these cases, the Army can benefit most from the investments of others by expending its limited resources on systems analyses of how those potential technical advances could be applied in specific Army systems to satisfy future unique Army battle-zone needs.

ORGANIZATION OF THE STUDY

The Technology Group organized its work into three primary categories, which were further subdivided into nine specific technology topics as follows:

1. *Propulsion Technology*
   - missile propulsion,
   - surface mobility propulsion,
   - air vehicle propulsion, and
   - gun or tube projectile propulsion;
2. *Electric Power Technology for Battle Zones*
   - continuous electric power generators,
   - pulsed and short-duration power generators, and
   - energy storage and recovery for ultimate electric power output;

and

3. *High-Power Directed Energy Weapons Technology*
   - high-power lasers,
   - radio-frequency, high-power microwave, and millimeter-wave projection systems.

The following areas were addressed for each of the nine topics:

1. battle application areas for the topic;
2. current and near-term (approximately 10 years) characteristics of the technology; and
3. future characteristics (approximately 30 years).

In response to the request to provide a limited number of concise TFAs, the Technology Group defined a set of figures of merit to use as a framework for determining the relative value, as leverage on future Army battle-zone systems, of the predicted characteristics for each technology element. Each element was assigned an index from 1 to 5 (5 being best) for each of six general figures of merit that the group believed should be important to Army operations. These six are shown in Table 41-1 along with a representative set of specific factors the Group considered when evaluating technologies to assign figure-of-merit indices. In the example shown in Table 41-1, the factors relate to directed energy for high-power weapons. For each specific technology topic, the Group defined an applicable set of factors. Examples of applicable factors are presented for each of the three technology categories in this report. Relative indices for each figure of merit were assigned based on the Group's judgments regarding the composite set of factors.

The Technology Group concluded that many of the technologies to which it assigned high relative indices will be supported and evolved by the private sector or DOD in the normal course of events. Therefore, the technology elements selected for detailed forecast and assessment were not arrived at by any specific weighted summation of the six index values. Rather, the Group considered a range of selection criteria, including:

1. the potential for *significant improvement* in figures of merit (i.e., indices of 4 or 5 for the "Future" column of several key figures of merit);

2. unique enabling characteristics that seemed worthwhile to elucidate;

or

3. whether, in the Group's consensus opinion, special attention to that technology by the Army was essential if substantial progress was to be made or if characteristics specifically relevant to Army needs were to evolve.

In short, comparison of numerical values assigned to the figures of merit was one factor used by the Group in selecting technologies for detailed review, but not the only factor.

The following technologies were selected for detailed forecasts and assessments:

In Propulsion:

- gel-propellant rockets for missile systems,
- beamed microwave power for long-duration, unmanned air vehicles (UAVs),
- electric-drive propulsion for tracked and wheeled vehicles, and
- electrically energized gun systems;

Table 41-1 Figures of Merit and Technology-Specific Factors Used to Assess Directed Energy Weapons

Figures of Merit	Specific Factors for Directed Energy
Functionality	Lethality at target Range vs. lethal flux Repeat rate Beam control vs. scenarios
Mobility	Specific beam power, kW/ton Specific beam energy, kJ/ton Modularity
Supportability	Commonality of components Field service life and maintainability Reliability Environment maintenance
Survivability	Hardness to all threats Low signatures Autonomy
Manpower	Operating manpower level Support manpower level Force multiplier
Cost	Nonrecurring cost Recurring cost Life-cycle operating cost Replacement period

In *Electric Power*,

- turbogenerator units for continuous electric power,
- elements for pulsed short-duration power generators (capacitors, inverters, transformers, switches), and
- flywheel energy storage systems recovered as electric power output;

In *High-Power Directed Energy*,

- ionic solid-state laser arrays,
- coherent diode-laser arrays, and
- phase conjugation for high-energy lasers.

ACKNOWLEDGMENTS

The original Propulsion, Power, and High-Power Directed Energy Technology Group consisted of three members appointed by the NRC and one Army liaison person. Several months into the effort, one of the appointed members, Mr. John H. Clark from the U.S. Air Force Astronautics Laboratory, was unable to continue his participation. Because he had already provided information and forecast assessments in his area of expertise—solid propellant rocket propulsion—he was not replaced.

The Group wishes to acknowledge the valuable technology information summaries and program data provided by key contact individuals at a number of government organizations:

- Dr. Walter Bryzik, U.S. Army, Tank and Automotive Command (TACOM)
- Mr. Michael A. Barga, U.S. Air Force, Wright Research and Development Center
- Dr. George E. Checklich, U.S. Army, TACOM
- Dr. William Chew, U.S. Army, Missile Command
- Mr. Mark R. Dale, U.S. Air Force, Wright Research and Development Center

The Group also wishes to thank the following senior managers at TRW, Inc., for providing personnel to support coordination with various organizations, acquiring many of the reference documents, and helping in evaluating the pertinent information.

- Dr. Robert S. Bradford, Jr. (directed energy)
- Dr. Jack L. Blumenthal (electric power)
- Mr. Robert L. Sackheim (propulsion)

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Propulsion Technology

INTRODUCTION

Propulsion technology was divided into four specific topics:

1. missile propulsion;
2. surface mobility propulsion;
3. air vehicle propulsion; and
4. gun or tube projectile propulsion.

Within each of these specific topics, various technology elements were identified for initial consideration and assessment. These elements are shown in Table 42-1. Although this selection is quite comprehensive, it should not be viewed as inclusive, nor does it imply that other technologies in each topic area should not be pursued by the Army. The battle-zone applications and near-term characteristics of each technology element were reviewed and qualitatively assessed against a set of figures of merit, which had factors selected by the Technology Group as relevant for each topic. Table 42-2 shows a representative set of factors for missile propulsion. Various contributors to the report judged the improvements that could be anticipated for each element, given reasonable funding support, and how those improvements would change the figure-of-merit indices.

The Group believes that many of these technologies will be advanced over the next 30 years as a matter of course; by either commercial industry or DOD. Therefore, in response to the Study Chairman's request to prepare a very limited number of technology forecasts in propulsion, the Group selected four elements that appeared to offer either conceptually new or particularly advantageous ways of performing propulsion tasks in the future and that are of interest primarily to Army missions. The technology elements chosen were:

1. for smart missile propulsion, gel-propellant rockets;
2. for surface vehicle propulsion, electric drives;
3. for UAVs for surveillance, propellers driven by solar plus millimeter-wave beam-powered electric motors; and
4. for projectile propulsion from guns, electrically energized systems.

TABLE 42-1 Propulsion Technology Options

Missile Propulsion	Surface Mobility Propulsion	Air Vehicle Propulsion	Gun or Tube Propulsion
Solid rockets	Diesel engine	Gas turbine jet	Solid charge
Liquid rockets	Gas turbine engine	Propeller-driven	Traveling charges
Gel-propellant rockets	Transmission technology	Ramjets/scramjets	Liquid-propelled
Hybrid rockets	Electric drives	Solar powered	Electric energized
Turbine engines	Integrated systems	High-power microwaves	Electromagnetic
Ramjets/scramjets	Hybrid electric		Ramjet-distributed
Ducted/ air-augmented	Ground effect		

TABLE 42-2 Typical Factors Considered for Assessing Figures of Merit for Missile Propulsion Technologies

FUNCTIONALITY
- System response time
- Flyout time
- Payload/range
- Duty-cycle flexibility
- Kill probability

MOBILITY
- Volume/warhead-range
- Weight/warhead-range
- Low handling sensitivity
- Modularity
- Configuration flexibility

SUPPORTABILITY
- Component commonality
- Field service life/maintainability
- Reliability
- Critical resources availability
- System safety

SURVIVABILITY
- Ruggedness
- Low signature
- Hardness to all environments
- Autonomy
- Insensitive munitions criteria compliance
- Reaction time (dash)

MANPOWER
- Battlefield operations level
- Support level
- Main force multiplier

COST
- Nonrecurring
- Recurring per field unit
- Life-cycle operating

Technology forecasts are provided for three of these high-leverage technologies. For the gun technologies, only a general discussion was attempted of work needed to resolve inconsistencies in reported results and provide the data from which a forecast could be made.

MISSILE PROPULSION

The Group projects future Army requirements for missile systems to be used for air defense, tactical ballistic missile defense, battlefield offensive force projection, and ground-based antisatellite (ASAT) operations. In the future, ballistic missile defense in particular will become increasingly important in protecting rear echelon areas, as well as troops at the front. The Group's objective was to identify missile performance characteristics that will be demanded by Army operations in the 2020 time frame and to recommend missile propulsion technologies that could be of particular importance for the Army to invest in. The review was based on information from recently published studies on Army missile applications and future needs, data from many other sources, and discussions with knowledgeable people in the field.[1]

Battle-Zone Applications

Current Army missile applications can be grouped into five basic categories:

1. air defense (negation of all types of aircraft operations and their attack armaments);
2. battlefield support (antiarmor, deep attack, assault, fire support, antipersonnel, etc.);
3. strategic defense (intercontinental and submarine-launched ballistic missiles);
4. theater defense (theater ballistic and cruise-type missiles); and
5. ground-based ASAT.

The first two applications involve traditional Army battle missions. The last three involve missions that have been studied or have advanced-development status; no operational weapon systems designed specifically for these categories have been deployed to date. (The Patriot system used in Desert Shield/Desert Storm operations was adapted for limited anti-tactical-missile defense, but was designed for aircraft defense.) In the future, tactical ballistic

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[1] General references for this section are Anonymous, 1988; DOD, 1989; Dugger, 1969; Hesse and Mumford, 1964; Hosney, 1974; and Pretty, 1985-86.

missile defense in particular will become increasingly important in protecting rear echelon areas, as well as troops at the front.

Strategic intercontinental ballistic missile defense from the ground is the responsibility of the Army's Strategic Defense Command. The use of ground-based missiles for this mission involves exo-atmospheric mid-course and endo-atmospheric terminal intercepts of deployed subcarrier platforms and warheads. Those systems under development involve highly maneuverable systems such as the exo-atmospheric re-entry intercept systems (ERIS) and entail technologies that could be adapted to theater ballistic missile defense. The basic goal of zero-leakers through both strategic and theater ballistic missile defense systems is particularly stressing for the maneuvering end-game final missile stages. These areas are being pursued at levels consistent with long range plans of the Army and the Strategic Defense Initiative Organization (SDIO). The use of exo-atmospheric strategic defense missile systems for certain types of ASAT is clearly technically feasible.

When investing in various missile propulsion technologies, the Army should emphasize smart propulsion systems, which can be responsive to the demanding maneuverability and performance requirements of "smart-to-brilliant" missile systems. The robust, agile, and highly noncooperative advanced threats that these smart-to-brilliant missiles will be countering by the end of the 30-year forecast period will be extremely demanding in terms of altitude profiles, velocities, range, and rapid-maneuvering capability. Therefore, defensive smart missiles will have to be highly maneuverable and capable of extremes in energy management for increased range, targeting flexibility, and hit-to-kill accuracies. Advanced rocket and air-breathing propulsion technologies also must address safety, environmental, and reliability aspects of future operations.

Current and Near-Term (about 10 Years) Characteristics

Rocket Propulsion

The current or evolving concepts in missile propulsion systems listed in Table 42-1 can be divided into two categories: rocket systems and air-breathing systems. In rocket systems, all of the required fuel and oxidizer is carried as an integrated part of the propulsion system. Propellant systems generally applicable to Army missiles can be divided into four categories: solids, liquids, gels, and hybrids. Each of these propulsion concepts and its application to Army missiles is discussed briefly below.

Solid Propellants. Solid rocket propellants have proven to be relatively simple, moderately priced, and reliable for the current set of Army battle missions. They store well for long periods of time but must be protected from electrostatic discharge and other environmental shocks or extreme thermal conditions. Solid propellants use macroscopically homogeneous grains containing both the fuel and oxidizer constituents in a uniformly distributed matrix, usually CTPB/HTPB binder-fuel[2] with ammonium perchlorate oxidizer. Future solid motors (such as those currently under development by the Air Force for the small ICBM) are projected to make more use of nitrate ester plasticized polyethane (NEPE or Class 1.1) propellants to increase specific impulse, and may eventually make use of highly strained carbon bonds to add some extra energy of combustion. However, the exhaust signature problem for solid propellants of various types will still be significant as long as metal additives are used to control combustion instabilities and because the exhaust products contain carbon particles. For applications where exhaust signature is not critical but performance is, the metal additives will probably continue to be used.

Liquid Propellants. To date, the Army has used few liquid propulsion systems for its missile applications. One exception is the LANCE artillery missile, used for general battlefield fire support. Liquid propulsion systems offer the advantage of flexible on-demand energy management, which can permit multiple starts and stops, throttleability, and precise thrust termination on command. A number of liquid propellants provide higher chemical energy per pound of stored propellant than do the solid motors in use today. Advanced development work being conducted with high-energy storable propellants offers the potential to increase the specific impulse by 10 to 20 percent over today's prepackaged propulsion system used for the LANCE. A perceived drawback to the use of liquid propellants in the field has been concerns about handling leakage and toxicity.

Gel Propellant Systems. Gel propellant systems can be stored and handled leak-free, like solid propellants, but under high-pressure shear stress they convert to the operating flow characteristics of liquids. Gel propellant systems are generally considered to be less sensitive and safer to handle and store than either liquids or solids.

A gel propulsion system operates the same as a liquid propulsion system. That is, its energy can be managed to provide multiple starts and stops, proportional throttling, and so on. Gel propellants in which the fuel gel

[2] CTPB is carboxy-terminated polybutadiene; HTPB is hydroxy-terminated polybutadiene.

contains a high loading of aluminum have higher performance (especially density impulse) than ungelled storable liquids. They are also less sensitive than most solid propellants to shock, incendiary penetration, and electrostatic discharge because the gel fuel and the oxidizer are stored separately. In addition, for applications where signature minimization is a primary requirement, gels without aluminum loading can be utilized with some attendant reduction in specific impulse.

Hybrid Propellant Systems. Hybrid propellant systems make use of various combinations of solid and liquid propellants. Different designs have been tested; most common is a liquid oxidizer injected over a solid fuel. For Army missile applications, hybrid propulsion for tactical missiles must rely upon ambient storable liquid-side propellants. Most of the work done to date on hybrid rockets has been for target missiles and low-cost experimental tactical missile applications requiring some capability for stops and starts or variable thrust. Because hybrid systems are generally lower in performance than solids, liquids, or gels (specific impulse values between 170 and 220 seconds at sea level), they appear to offer little advantage for Army operational battle-zone missiles in the 2020 time frame.

Advanced Energetic-Propellant Rockets. A new class of high-energy-density matter envisioned for use as a propellant could provide a major advance in rocket propulsion. Conceptually, the energy content of a chemical propellant would be increased by preparing it under conditions that leave a substantial population of electrons in a long-lived excited-state. To date, most of the work done in excited-state high-energy-density matter systems relates to cryogenic fluids and has been theoretical research based on models run on supercomputers. However, the Army should monitor research on these concepts so that if field-storable, truly stable, very-high-performance propellants can be made, the Army could make timely use of them.

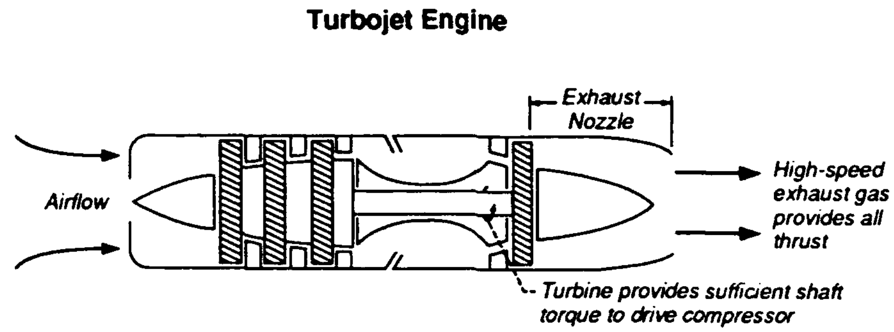
Air-Breathing Propulsion

This class of propulsion technology for missiles includes turbojets, turbofans, ramjets, dual-combustion ramjets, scramjets, air-turbo rockets, integral rocket-ramjets, pulsejets, and air-augmented rockets. The specific impulse of these air-breathing propulsion systems is from two to five times higher than that of rocket engines operating at similar pressure ratios because the oxidizer (air) is provided from the ambient environment (i.e., the air flow rate is not included in the calculation of specific impulse). For appropriate flightpaths, this high value of specific impulse for air-breathing engines, appropriately decreased for the large extra drags, can provide increased payload and range capability for a given missile launch weight. For medium-range to long-range (>50 km) sustained flight applications, air-breathing systems offer the potential for superior payload mass fraction performance over that of rocket engines and ballistic trajectories. However, the resulting lower-velocity flight profiles (less than Mach 6, approximately) will find application only to certain missions.

Turbojets. The turbojet engine has a mechanical compressor, so it is capable of increased performance in flight, relative to what could be achieved with ambient ram air (Figure 42-1). Because of limits in current turbine materials, only an air-rich mixture can be burned in the primary combustion chamber. Additional thrust can be obtained from the turbojet engine through the use of an afterburner in which additional fuel can be burned. Major near-term gains in the performance of turbine jet engines are expected from a program on high-performance turbine engine technology, jointly sponsored by DOD, NASA, and industry. This program, called Integrated High Performance Turbine Engine Technology (IHPTET), integrates nearly all of the government-sponsored technology development work on advanced aircraft and missile turbine engines. The program has a stated demonstration goal to "double propulsion system capability by the year 2000." This goal is to be met by increasing the thrust/weight ratio by a factor of 2 from a "current baseline engine." Additional demonstration goals for the year 2000 are decreases in specific fuel consumption of 15 percent for turbojet and turbofan engines, 40 percent for turboshaft engines, and 40 percent for expendable missile systems engines (Wright Aeronautical Laboratory, no date).

It should be recognized that a significant period will elapse between the demonstration of these ambitious goals and the actual introduction of engines with these performance levels into missile programs. The Technology Group estimates that actual engines available for operational use will provide around a 20 to 25 percent reduction in specific fuel consumption, an increase in thrust-to-airflow ratio of about 50 percent, and improvements in thrust-to-weight ratio of 60 percent, when compared with the state of the art in 1989.

Turbofan Engines. The turbofan engine is similar to the turbojet engine except that it incorporates a fan and a bypass duct in addition to the other engine elements described previously. The primary purpose of the fan is to provide a low-velocity, high-mass flow of exhaust gas, thereby increasing the propulsive energy efficiency of the engine. The lower velocity and lower temperature of the exhaust flow also reduce the acoustic and thermal signatures of the engine.



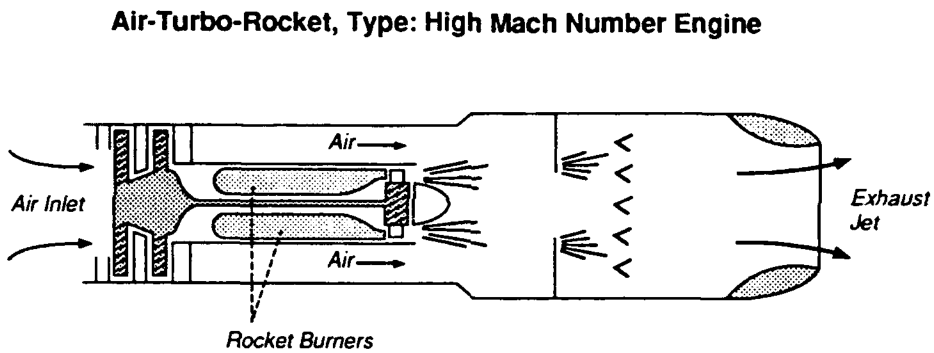


FIGURE 42-1 Turbojet and turborocket engine schematics. Turbojet engine diagram courtesy NASA (NASA, 1971). Air turborocket diagram adapted from Hesse and Mumford, 1964.

Ramjets. The simplest type of air-breathing jet engine is the ramjet, which makes use of an air inlet and diffuser to deliver air at a high head pressure to a simple combustion chamber, where fuel is mixed with the air and ignited. From this point the hot combustion gases are expanded through a nozzle to produce a net thrust. However, because of the need for high-velocity ram air, an auxiliary power plant (usually a booster rocket), must be provided to accelerate the vehicle to a speed where the ramjet can provide useful thrust.

The integral rocket-ramjet (IRR) is designed for this purpose (Figure 42-2). It combines the principles of the rocket and the ramjet, so that the two elements operate sequentially using a common combustion chamber. This

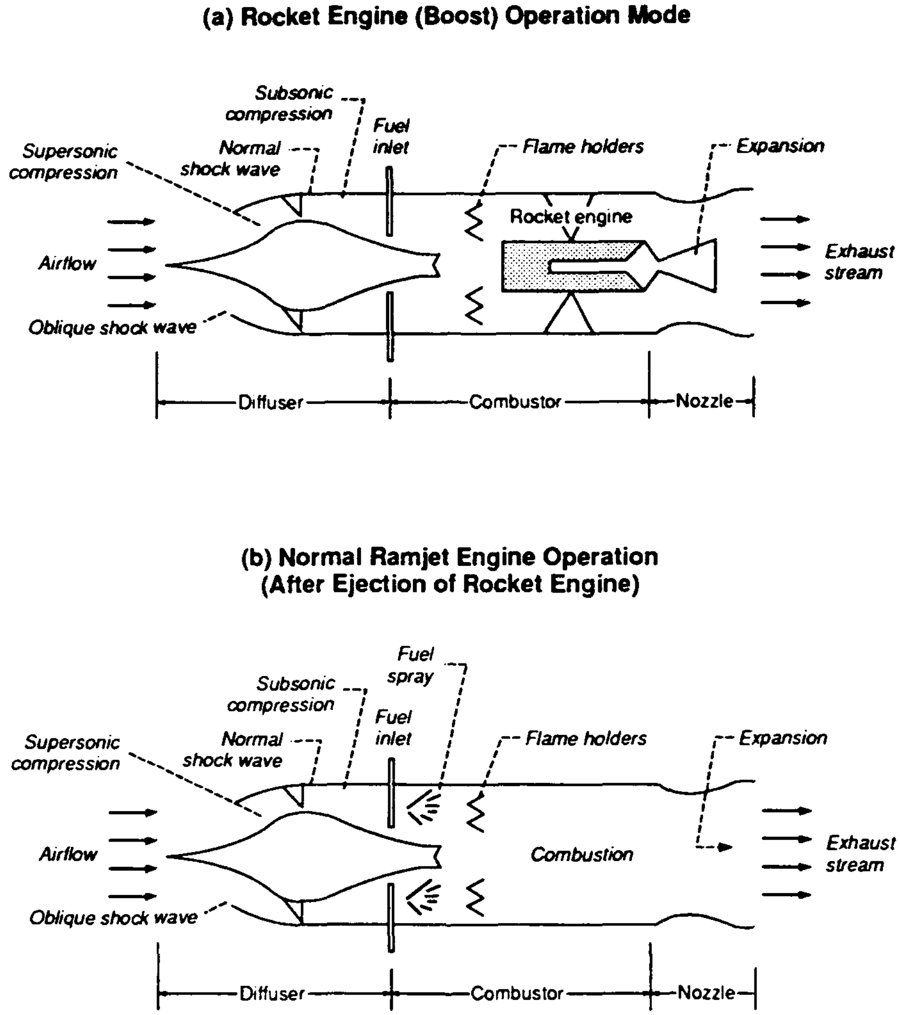


FIGURE 42-2 The integral rocket ramjet (IRR) engine. Source: NASA, 1971.

low-volume propulsion device is particularly attractive for high-speed air-launched missiles.

Scramjets. The supersonic combustion ramjet (scramjet), because of the nature of its operating characteristics, has less applicability to Army tactical missiles than do conventional ramjets.

Ducted or Air-Augmented Rockets. An air-augmented rocket produces higher specific impulse than a rocket engine when operating inside the earth's atmosphere. Usually, the term "air-augmented" applies specifically to the mixing of air with a fuel-rich rocket exhaust in a region below the nozzle throat. In contrast, a "ducted" rocket is more like a ramjet, in that it is boosted by its rocket engine to high operating speeds and then uses the rocket as a combination fuel-rich gas generator (liquid, solid, or hybrid) and air-ejector pump to augment the ram air. Work is being done in these propulsion technology areas under the sponsorship of other government agencies.

Air Turborockets. The air turborocket is similar in principle to the IRR in that it is a combination of rocket and an air-breathing (gas turbine) engine. For this device, the power for driving the turbine-compressor unit comes from a rocket-type combustion chamber (gas generator) that operates fuel-rich. Additional fuel is then injected into the combustion products, and the entire mixture is burned with the air coming from the mechanical compressor (see Figure 42-1). The primary advantages of this combined-cycle engine are (1) its high thrust-to-weight ratio and high thrust-to-frontal-area ratio, compared with that of a turbojet engine; and (2) its specific impulse, which is higher than that of a rocket engine.

Future Characteristics and Figures of Merit

Table 42-3 presents the Group's composite figure-of-merit indices for each missile propulsion concept, first for the near term (the year 2000) and then for a future time frame out to about 2020. As can be seen from Table 42-3, several concepts have significant potential for improvement during the next 30 years: solid-propellant and gel-propellant rockets, turbine air-breathing engines, and ducted or air-augmented rockets. Of these, the Group believes that the solid-propellant rocket systems and turbine air-breathing engines will enjoy continuous advanced development support as a matter of course in various programs among all three of the military services.

The solid propulsion system elements that have the greatest potential for improvement are the propellant systems themselves and the associated case and nozzle technology. The Technology Group believes that the Army should actively support the development of the high-energy solid-propellant systems such as NEPE and gluycidal azides (GAP), together with safe, reliable production processes and facilities for these propellants. Concomitant with the development of the higher-energy systems, the Army should support investigations of smoke elimination and alternative signature characteristics, with the objective of improving the trade-off between detectability and performance. Similar support should be provided for development of advanced composites such as carbon and carbon-matrix materials and metal/fiber overwrap designs, for motor-case structures and for nozzles and insulation.

TABLE 42-3 Assessed Figures of Merit for Missile Propulsion Technologies for Years 2000 and 2020

System Concept	Figures of Merit: Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Solid Rockets	3	5	3	4	3	4	2	4	3	4	4	4
Liquid Rockets	3	4	2	3	3	4	3	3	2	3	2	3
Gel Propellant Propulsion System	3	5	3	4	3	4	3	4	2	4	2	3
Hybrid Rockets	2	3	2	3	2	4	2	3	2	3	2	3
Energetic Propellants	?	?	?	?	?	?	?	?	?	?	?	?
Turbojets	3	5	3	4	3	4	3	4	3	3	3	3
Turbofans	3	3	2	3	2	4	2	4	3	3	3	3
Ramjets	1	3	3	4	2	3	4	4	4	4	3	4
Scramjets	1	3	3	4	2	3	4	4	4	4	2	3
Ducted or Air-Augmented Rockets	3	5	3	4	2	3	3	4	2	4	2	4
Integral Rocket Ramjets	2	4	2	4	2	3	2	4	2	3	2	3
Air Turborockets	2	3	2	3	1	3	2	3	2	3	1	3

Index Values: 1 (minimal) through 5 (excellent).

The Technology Group anticipates that the cost of the advanced solid-propellant propulsion systems in the 2020 time frame will be reduced through use of fully automated mass production techniques and facilities for the propellants. Similarly, the costs for advanced materials, such as composites, will fall significantly because of increased production experience, automated production procedures, and process evolution. Table 42-4 summarizes some of the improvements that are forecast for solid-propellant rocket systems both for the near term and by 2020.

Air-breathing missile engines by the year 2020 will have been able to take full advantage of the technology advances made possible by the IHPTET initiative. Engines will be approaching inherent physical limits at about a 45 percent reduction in specific fuel consumption from the 1980s, the ability to operate with turbine inlet temperature increases of 1400 F°, and increases in thrust-to-airflow ratio of 100 percent compared with the current state of the art. Compressors will be made of nonmetallic material such as ceramics, to handle the increased temperatures associated with the high pressure ratios. The combustor, nozzles, and turbines will be uncooled to maximize performance and will utilize materials such as ceramics and carbon/carbon composites. The exhaust nozzle as well as the turbine will utilize materials such as carbon/carbon composites. High-temperature solid lube bearings will be used, as well as air journal bearings in the hot section, to decrease or eliminate the need for cooling. Improved control sensors, automated diagnostics using microminiaturized digital electronics, and advanced algorithms will enable self fault identification and correction and highly reliable engine operation at high performance conditions.

The Army of the future will depend heavily on smart missiles for defensive and offensive missions. To fully exploit the great advances in electro-operated seekers, guidance technology, and computerized real-time controls, these advanced missiles will require high-performance propulsion capable of a broad range of thrust management. However, with solid-propellant rocket motors, it is difficult to manage flexible deliverable thrust profiles with multiple starts and shutdowns. Rocket motors using storable liquid propellants readily meet requirements for complete energy management, can be very low in exhaust smoke, and have quite high specific impulse, as shown in Table 42-5. Using current field-storable oxidizers, they are significantly lower in density impulse than solid propellants. They also seem to require more complex handling and logistic support than may be desired for the more fluid battle-zone operations expected in the future. Currently employed solid-and liquid-propellant rockets also generally fail to fully meet one or more of the safety requirements of Military Specification 2105, which sets criteria for toxicity, volatility, impact sensitivity, fast and slow cookoff properties, and so on, for insensitive munitions. However, that does not mean that they should not be considered "safe" from a military-risk perspective.

TABLE 42-4 Performance Characteristics for Solid-Propellant Rockets (Theoretical Equilibrium Flow)

Time Frame	Propellant System	Specific Impulse (I_{sp})[a] (s)		Density Impulse[a] (lb-s/in^3)		Propellant Mass Fraction, Propulsion Stage Only
		to 14.7 psia (ϵ = 10:1)	to Vacuum (ϵ = 54:1)	to 14.7 psia (ϵ = 10:1)	to Vacuum (ϵ = 54:1)	
Today	Aluminum-loaded HTPB, high smoke	264	297	16.8	18.9	0.92
1990s	Low-smoke formulations of HTPB	250	281	15.0	16.9	0.90
2000	NEPE	271	305	16.2	18.3	0.92
2000	Glycidal azides, low smoke	284	320	17.0	21.0	0.92
2020+	High-strain carbon-bond concepts	300–320 (?) (estimates)	340–360 (?) (estimates)	?	?	0.94

[a]Chamber pressure (P_c) = 1000 psia.

NOTE: ϵ = nozzle expansion ratio (exit area/throat area); HTPB = hydroxy-terminated polybutadiene; NEPE = nitrate ester plasticized polyethane.

TABLE 42-5 Performance Characteristics for Storable-Liquid-Propellant Rockets (Theoretical Equilibrium Flow)

			Specific Impulse (s)		Density Impulse[a] (lb-s/in^3)		
Time Frame	Propellant System	Oxidizer/ Fuel Ratio	to 14.7 psia (ϵ = 10:1)	to Vacuum (ϵ = 54:1)	to 14.7 psia (ϵ = 10:1)	to Vacuum (ϵ = 54:1)	Propellant Mass Fraction Propulsion Stage Only
Today	IRFNA/UDMH	3.13	272	333	12.4	15.2	0.87
1990s	IRFNA/MMH	2.6	274	342	12.6	15.7	0.88
2000 ↓ 2020	CLF_5/MMH	2.8	302	368	15.3	18.6	0.90

[a] Chamber pressure (P_c) = 1000 psia.
NOTE: ϵ = nozzle expansion ratio (exit area/throat area); IFRNA = inhibited red fuming nitric acid; MMH = monomethylhydrazine; ClF_5 = chlorine pentaflouride.

The Technology Group believes that gel-propellant rocket propulsion is an attractive evolving technology that could provide system advantages for many of the Army's smart missile applications of the future. Metal-loaded formulations of gel propellants can provide density impulse performance that is competitive with that of solid propellants, while being capable of flexible thrust management. These gel propellants also satisfy the Military Specification 2105 criteria for insensitive munitions. Because of these unique characteristics and future growth potential, gel-propellant propulsion was selected for a technology forecast.

Technology Forecast: Gel-Propellant Propulsion

Propulsion using gel-propellant rockets is a new technology that will probably play an increasingly important role in the Army's missile arsenal over the next 30 years for the reasons described above. Oxidizer-and-fuel gel propellants are thixotropic; that is, they convert from a gelled quasi solid state to a liquid flow state under the application of shear stress. A gel-propellant propulsion system therefore operates like a liquid propulsion system and can be controlled by throttling or using a pulsed duty cycle. It has higher performance (especially density impulse) than liquids because the fuel gel contains a high loading of aluminum. It is intrinsically safer than a liquid propulsion system because the gels form a crust when exposed to the air. This crust plugs tank leaks and inhibits the rapid evaporation of volatile components. It is safer when subjected to direct hits than a solid propulsion system because the oxidizer gel is stored separately from the fuel gel.

A schematic diagram for a typical gel-propellant propulsion system is shown in Figure 42-3. The oxidizer and fuel gels are expelled from their respective tanks by the pressure from the solid gas generator. The flow rate of the gels is controlled (throttled and/or pulsed) by a hydraulic control valve and injected into the combustion chamber. A face shutoff injector is recommended for a smart propulsion system because it prevents loss of volatile fluids caused by heat soakback between pulses. The loss of volatile fluids causes solidification of the gels and plugging of the engine's injector. The combustion chamber and nozzle are protected by carbon-carbon or silica-phenolic ablative liners.

The performance of a typical metal-loaded gel-propellant propulsion system for missiles is shown in Table 42-6. The Group believes that a missile system using the gel-oxidizer and gel-fuel propellants developed by the U.S. Army Missile Command could be put into production and fielded by the year 2000.

Two elements of gel-propellant propulsion systems that have considerable potential for technology improvement are the propellant feed system and the propellants themselves. Expulsion of gel propellant can be

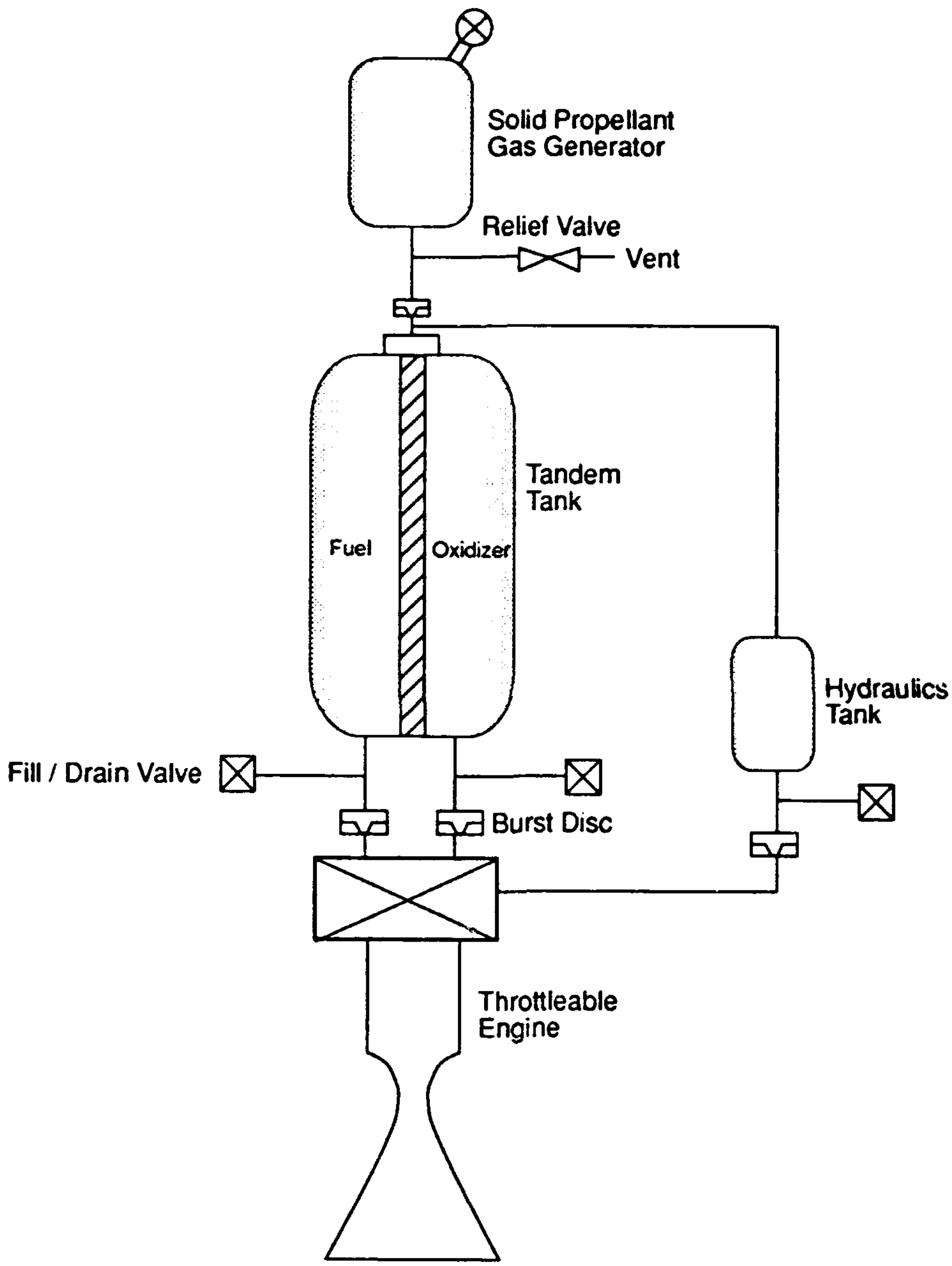


FIGURE 42-3 Schematic diagram of a typical gel-propellant propulsion system.

TABLE 42-6 Performance Characteristics for Storable Gel-Propellant Rockets (Theoretical Equilibrium)

Time Frame	Propellant System	Specific Impulse (s)		Density Impulse ($lb\text{-}s/in^3$)		Propellant Mass Fraction, Propulsion Stage Only
		P_c = 1000 psia		P_c = 1000 psia		
		to 14.7 psia	to Vacuum (ϵ = 54:1)	to 14.7 psia (ϵ = 10:1)	to Vacuum (ϵ = 54:1)	
Current	IRFNA/MMH (aluminum-loaded fuel)	267	313	15.7	18.4	
Current	IRFNA/MMH (50% carbon-loaded, low-smoke)	253	309	12.9	15.8	
Future	ClF_5/MMH (aluminum-loaded fuel, oxidizer/fuel = 3.0)	286	332	16.2	18.8	
		P_c = 3000 psia		P_c = 3000 psia		
Current	IRFNA/MMH (aluminum-loaded fuel, smoky)	289	336	17.0	19.7	
Current	IRFNA/MMH (50% carbon-loaded, low-smoke)	274	334	14.0	17.0	
Future	ClF_5/MMH (aluminum-loaded fuel, smoky)	308	357	17.5	20.2	

NOTE: P_c = chamber pressure (psia); ϵ = nozzle expansion ratio (exit area/throat area); IRFNA = inhibited red fuming nitric acid; MMH = monomethylhydrazine; ClF_5 = chlorine pentafluoride.

controlled by use of pressurized gases and bonded rolling diaphragms or elastomeric diaphragms. This capability will be needed for missions requiring several cycles of shutoff, deceleration, and engine restart. Other higher-performance combinations of liquid propellants might also be gelled if innovations in propellant chemistry and technology are pursued. Much work is needed on developing smokeless, high-density-impulse gel propellants for applications that require very low exhaust signature, but also need high-response, real-time, on-demand thrust management, and multiple periods of ballistic cruise.

If the Army diligently continues its development of gel propulsion technology, the battlefield commander of 2020 could have at his disposal a variety of flexible, programmable missiles with a high kill probability. Such missiles would be highly field-mobile and easily supported logistically. They will have high survivability and low risk levels for personnel safety because they will conform to the DOD insensitive-munitions guidelines. Initially, metal-loaded gel-propellant missiles would be introduced primarily for air defense, strategic and tactical missile defense, and possible ASAT applications where smoke signature is not significant. Evolution of smokeless versions would later be phased into smart tactical missiles for battlefield force projection and for deep attack with guided, evasive end-game capability. The Technology Group anticipates that by 2020 gel-propellant propulsion systems for smart missiles will become very cost-effective as a result of automated manufacturing, personnel experience, and—most important of all—high kill probability in defense of targets of the highest value.

PROPULSION FOR AIR VEHICLES

In general the Army satisfies its needs for manned fixed-wing air mobility by acquiring and modifying various aircraft available commercially or developed by the Air Force. Most of its directly funded aviation resources are focused on rotorcraft development. Propulsion for these rotorcraft are becoming predominantly turboshaft engines for the main power plants and turbojets for auxiliary propulsion. The primary technological evolution of these gas-turbine engines is expected to come from private-industry research and the previously mentioned DOD/NASA IHPTET initiative. The tri-service Joint Turbine Advanced Gas Generator project, which is an activity of particular focus for the Army, complements in the near term the tasks of the IHPTET.

As a resource to the STAR Systems Panels, this section describes the current and forecasted future characteristics of propulsion systems for various types of Army air vehicles, both manned and unmanned. Robotic or tele-operated air vehicles UAVs are an important and rapidly growing element of the Army's battle-zone capabilities for surveillance, target designation, and even force projection. The propulsion system needs that derive from conceptual designs of aircraft able to perform some of these missions are not expected to be satisfied by ongoing DOD or industry advanced engine technology plans. Therefore, this area of propulsion technology will need direct Army support.

In response to a charge to the Technology Group to envision "very far-out, but not science fiction" technologies that could be enabling technologies for future Army systems, the group considered the concept of using laser or coherent millimeter-wave beams to supply energy for electrically driven propellers of very-high-altitude UAVs. A preliminary technology description of such a system was given to the STAR Systems Panels. That preliminary description is included below as a technology forecast for directed-energy-beam-powered propulsion of UAVs.

Battle-Zone Applications

Manned rotorcraft, which are typically powered by gas-turbine engines, provide a wide range of Army battle functions, including scout and attack, assault missions, tactical team support, defensive air-to-air combat, and air mobility for troops and equipment (Bill et al., 1988).

A variety of *fixed-wing, lightweight manned* aircraft powered by conventional reciprocating engines are deployed to monitor enemy operations and perform intelligence-gathering missions. The Guardrail aircraft, which provides an airborne and ground communications intelligence system for the intercept and location of communications emitters, is an example.

UAVs and remotely piloted vehicles (RPVs) are usually powered by small, lightweight reciprocating engines (often with a solid-fuel strap-on rocket as boost engine for rapid deployment). They perform a wide range of surveillance, target location and illumination, and battlefield management missions, generally from low altitude. Desired characteristics for UAV propulsion units are low signatures, low fuel consumption, ease of operation and maintenance, high reliability, and low cost. For some low-altitude missions, propulsion flexibility to provide high maneuverability may also be needed. At very high altitudes, UAVs can perform like small satellites, circling in tight patterns. These UAVs could be stationed high above hostile zones, looking more or less straight down, or stationed high above friendly zones and using very-long-slant line-of-sight surveillance.

Current and Near-Term (About 10 Years) Characteristics

Gas Turbine Engine

Significant improvements in thrust/weight ratio, fuel consumption, and thrust/airflow ratio can be achieved through higher combustion initiation temperatures, higher maximum temperatures, and the use of advanced materials to reduce component and structure weight. Programs such as IHPTET (DOD/NASA), the Small Turbine Engine Research Program (NASA Lewis Research Center), the Advanced Rotorcraft Transmission Program (NASA Lewis Research Center), and the tri-service Joint Turbine Advanced Gas Generator project are developing new technologies for materials, analytical modeling and measurement techniques, components, contingency power concepts, and structures. These programs are expected to produce increases of up to 100 percent in the thrust/weight ratio in engines for Army rotorcraft and manned fixed-wing aircraft.

Ramjets

Ramjet applications for Army air vehicles are essentially directed toward high-speed target drones (Mach 3 to 6) or unmanned high-speed surveillance vehicles. Ramjet propulsion technology for air vehicles is the same as that described above for air-breathing missile propulsion. Some current and near-term developments are liquid-fuel ramjets, gas-generator-fuel ramjets, (fixed-fuel-flow and variable-fuel-flow ducted rockets), and solid-fuel ramjets. The dual-combustion ramjet/scramjet, which has a conventional ramjet combustor stage, could have future application for very high-altitude, very high-speed (Mach 6 and above) drones or single-pass, very-high-altitude reconnaissance UAVs.

Reciprocating Engines

Near-term improvements in the shaft-power/weight ratio and specific fuel consumption of small, conventional-cycle reciprocating engines is expected to occur through the use of lightweight composites and high-temperature ceramics. Specific fuel decreases will result from higher-temperature combustion in ceramic-lined chambers. These chambers will have to be matched to development of correspondingly high-temperature lubricants.

NASA Lewis Research Center is evaluating the compound-cycle engine, which combines the lightweight features of a gas turbine with the heavier but highly efficient diesel reciprocating engine. Preliminary studies have indicated that a high-efficiency compound engine, developed by applying current technologies to the Napier Nomad Compound-Cycle Engine (the most fuel-efficient aircraft engine ever flown), may offer sufficient fuel savings to be competitive with gas turbines.

Electromagnetic-beam-powered propulsion

Small propeller-driven high-flying UAVs that are powered by electric motors using electromagnetic radiation as their primary energy source have been developed over the past 20 years. Use of these small solar-energized vehicles has been limited to daylight hours at high altitude, with glide-down at night. The specific energy of today's best secondary batteries is not sufficient to power such aircraft for more than a few hours after sunset. In recent demonstrations, a very small UAV was flown using a microwave transmitter on the ground to power its engine. This limited accomplishment presents a challenge to determine whether an optimized integration of solar energy, beamed power from the ground or even from an airborne platform, and advanced energy storage devices such as composite flywheels can be combined with advances in extremely lightweight composites and high lift-to-drag wing designs to create a vehicle with indefinite life aloft.

Future Characteristics and Figures of Merit

Table 42-7 presents FOM indices for each of the four systems described above. Both gas-turbine and reciprocating aircraft engines of all sizes should see large increases in thrust or brake horsepower per unit weight over the next 30 years as a result of new computerized analysis and design methods, new composite and ceramic materials, and on-line engine control systems. However, the improvement in specific fuel consumption of engines beyond the goals of the year 2000 is expected to approach an asymptote, as the inherent physical limits for standard fuels are approached. Better diagnostics and easier maintenance will improve reliability and lower total life-cycle costs. The Technology Group anticipates that the fundamental technology improvement goals of programs such as IHPTET will be achieved within a reasonable time frame. The group therefore recommends that the Army bootstrap from this and other DOD-NASA-industry programs, investing additional funds primarily for system engineering and integration technologies applicable to the Army's specialized air vehicles. A similar recommendation is made for ramjet-type thrusters as they might be utilized in Army missions.

TABLE 42-7 Assessed Figures of Merit for Air Vehicle Propulsion for Years 2000 and 2020

	Figures of Merit											
System Concept	Functionality 2000	Functionality 2020	Mobility 2000	Mobility 2020	Supportability 2000	Supportability 2020	Survivability 2000	Survivability 2020	Manpower 2000	Manpower 2020	Cost 2000	Cost 2020
Gas Turbine	4	5	3	5	3	4	2	3	2	3	3	4
Ramjets/ Scramjets	3	4	3	4	3	4	3	3	2	3	3	4
Reciprocating	4	5	4	4	3	5	2	4	2	3	3	4
High-Power Microwave	2	4	3	4	2	4	1	3	3	3	2	3

NOTE: Index Values: 1 (minimal) thru 5 (excellent).

Satellite data have been valuable to the Army for positioning prior to engagements and maneuvering during extended engagements. However, in some areas of the world and for certain types of engagements, low-orbit spacecraft may not be available, or if they are, they can supply surveillance information only periodically. The use of UAVs by the future Army is expected to increase. Such air vehicles could provide surveillance and target discrimination/designation on a continuous basis. Current very high fliers have limited time aloft. Those that are solar-powered slowly work their way up during the day, but must glide down at night because batteries to store solar-supplied energy weigh too much. UAVs using combustion engines for power are altitude-limited by oxygen availability, although they might achieve extreme altitudes for a short time by carrying onboard liquid oxygen. One such UAV under development is named Perseus (Monastersky, 1991). This vehicle, which incorporates liquid-oxygen tanks, is expected to reach an altitude of about 80,000 ft after a 90-minute climb. It would then have only about a one-hour cruise time before a several-hour glide down to earth.

Transferring energy directly to UAVs with a coherent beam of millimeter-wave radiation or a midpower laser of appropriate wavelength could provide a fundamentally different method of maintaining such vehicles aloft at altitudes as high as 20 to 25 km. Because UAVs for surveillance or target-designation could have unique leverage in future battle-zone operations, the Technology Group has chosen to provide a brief and preliminary description of the concept.

Technology Forecast: Propulsion Power for UAVs by Directed-Energy Beam

As mentioned above, it is *technically* possible to maintain a propeller-driven UAV aloft indefinitely by supplying energy to its onboard electric motor via a coherent, narrow beam of high-frequency microwave or laser radiation projected from the ground. A UAV powered by microwaves could incorporate thin-film etched-circuit *rectennas* as an integral part of its wings, which would have a high lift/drag ratio. The rectennas would collect and rectify the microwave energy transmitted to the craft from ground-based antennas. To achieve the high ratio of lift to induced drag required to make the system operable at high altitude with reasonable engine power, the wings must be long and narrow. The designs developed for the man-powered Daedalus aircraft would provide a baseline for continued evolution.

A conceptual layout of such a UAV, which could carry a payload in the 40- to 60-kg range is shown in Figure 42-4. The total system and payload weight of 225 kg could be lifted with wings 30 m long and 3 m wide, providing a lift/drag ratio of 50:1 at sea level at a velocity of about 9 m/s. The thrust of 4.5 kg at sea level would require shaft power of 0.55 hp (0.41 kW). The

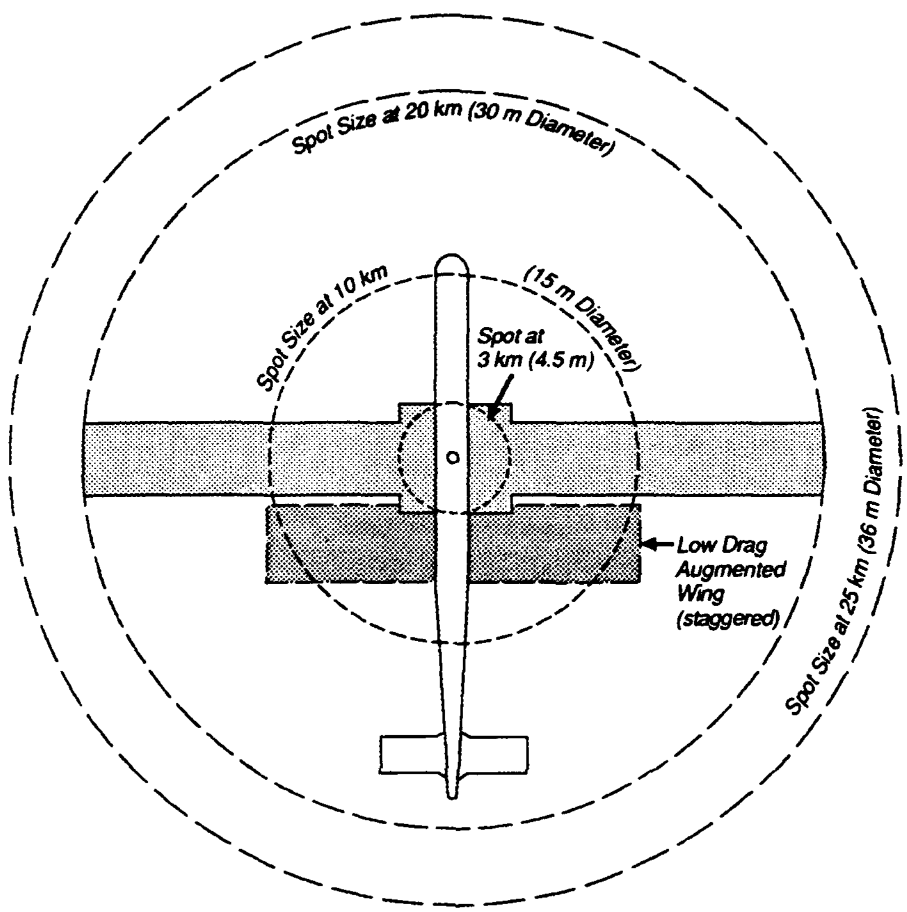


FIGURE 42-4 Plan view of UAV with rectenna wings. Circles represent spot size of the beam at thr^e altitudes from a 5-m antenna transmitting directly overhead at 94 GHz.

lift-to-drag reduction at high altitude, combined with the higher velocity necessary to provide the 225-kg lift, would increase the required shaft power to 5.5 hp (4.1 kW) at 25 km (82,000 ft). These ideal values serve to delineate the power requirements for the ground-based beam projection system. Because the Daedalus wing type does not efficiently intercept the projected beam at high altitude, low-lift, low-induced-drag surfaces can be added to augment the collection cross section. Such devices would be deployed above certain altitudes to optimize the ratio of intercept area to drag (i.e., to power required). A schematic of one possible augmented-surface configuration is included in Figure 42-4.

Figure 42-5 shows the beam power requirements at the projector versus cruise altitude for the idealized device of Figure 42-4. Computed values are

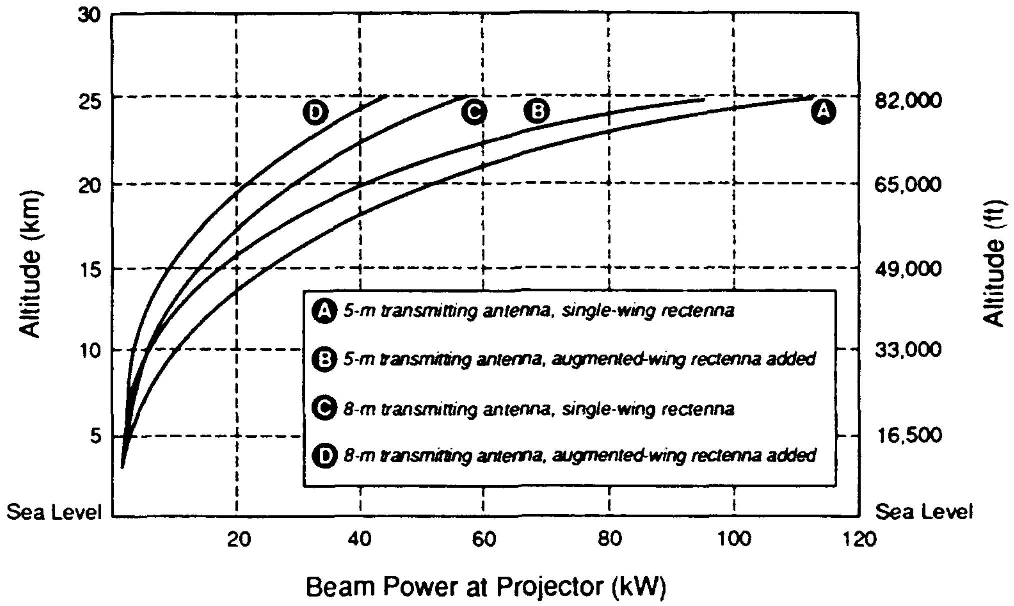


FIGURE 42-5 Transmitter beam power versus UAV station altitude.

plotted for two antenna diameters, 5 m and 8 m, projecting a 94-GHz beam *directly overhead*. The one-way atmospheric absorption of the beam is assumed here to be 1.3 dB. Two rectenna configurations are shown: with the primary wing only (curves A and C) and with the augmented-area configuration (curves B and D). Curves A and B are for the 5-m antenna; curves C and D are for the 8-m antenna. The high leverage of (effective) antenna diameter on reducing the overall projected power makes this a key element of the technology to examine. Such antennas can be made up of phased arrays of smaller dishes or a large phase-compensated single structure. Since the antennas do not require fast sweeping motions and need, in fact, very small angular capability, the larger diameters should not be too formidable a problem.

It should be possible to achieve rectenna conversion efficiencies of 85 percent, electric motor efficiencies of 90 percent, and propeller efficiencies of 90 percent. Propeller tip speeds at higher altitude would be limited by increasing the pitch angle. The efficiencies of millimeter-wave generators at 94 GHz (optimum for beam divergence angle versus atmospheric absorption for a given antenna size) should approach 25 percent in the future. Thus, the primary electric power unit needed to generate a beam with 20 to 50 kW of power at an altitude of 20 km would require wallplug power in the range from 80 to 200 kW and engines with 125 to 320 brake horsepower. Such power generators and transmitting equipment, other than the antennas, could be housed in a standard Army trailer-type vehicle.

Obviously there are many issues and system design trades that need to be examined. Innovative design approaches should evolve configurations that can perform a variety of mission profiles. UAVs stationed at very high altitude over friendly edges of the battle zone could use long-slant-range observations. Stealthy forays over enemy zones during daylight periods could use power from solar cells mounted on top of the wing. The craft would return to its directly overhead "friendly" station in the evening. Such a scenario would minimize hazardous takeoffs and landings, time spent at lower altitudes in gusty wind environments during long climb-outs and glide-backs, and other limitations to high-altitude UAV missions.

Many of the technologies needed to develop this system already exist or are being developed. In fact, a Canadian research group recently demonstrated the flight of a microwave-powered UAV using readily available components. The power level, range, and aircraft size were, however, very limited. Two key technological elements for this system concept are the transmitter and the rectenna. Microwave transmitters at 3–7 GHz with power outputs in the 75-kW class are commonplace and are not considered a technological constraint. However, for the reasons given above, a transmitter operating at 94 GHz (3.2-mm wavelength) is definitely preferred. High-power transmitters at this frequency are less common, but a 50-kW gyrotron microwave generator operating at 140 GHz (2.1-mm wavelength) has been tested in a research program.

Rectenna technology is being explored in programs such as the NASA-Lewis Rectenna Technology project (in conjunction with Raytheon Corporation). This effort is developing rectennas at 2.45 and 20 GHz for use in transmitting power to the ground from space-based solar-power satellites. The program has experimentally demonstrated rectenna conversion efficiencies in excess of 85 percent at 2.45 GHz. Schematics of such a rectenna are shown in Figures 42-6 and 42-7 (Raytheon, 1987). The weight of such devices is approximately 150 g/m^2.

For remote-piloted UAVs powered by millimeter-wave directed energy beams to be in service by 2020, several key technologies need to be pursued:

- .lightweight wing structures with high lift/drag ratio, optimized for very high altitude and incorporating rectennas on the undersurface as an integral part of the wing structure;
- high-efficiency rectennas operating at 94 GHz;
- large diameter, very lightweight low-cost projecting antennas operating at 94 GHz;
- medium-power 94-GHz transmitters, which employ gyrotrons, other tube technology, or free-electron masers;
- lightweight geartrains for use with high-rpm electric motors; and
- propellers designed and constructed for very high altitude.

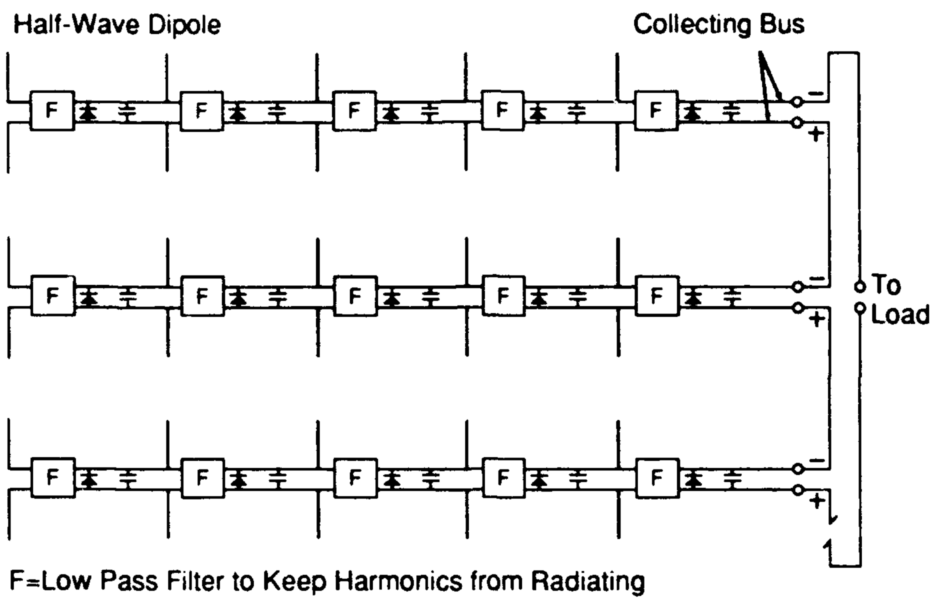


FIGURE 42-6 Schematic diagram of functions performed on the foreplane of the two-plane rectenna construction format. These functions include collection of the microwave energy by the half-wave dipoles; low-pass filtering; rectification and ripple removal; and dc power bussing. Source: Raytheon, 1987.

An alternative concept for beaming energy from the ground to a very-high-flying UAV is to use a mid-infrared laser. The application's continuous long duty cycle demands that this be an electrically powered device or a closed-cycle regenerable carbon dioxide laser, either device operating at 10.6 μm. The use of a 10.6-μm laser beam with a mirror diameter of 1 m provides a spot diameter that is less than 5 percent of the 94-GHz beam with a 5-m antenna. However, these infrared beams are more susceptible to power attenuation by light fog, clouds, and drizzle than are millimeter waves. Both types of energy transmitter beams should be explored.

SURFACE MOBILITY PROPULSION

This section discusses some of the requirements for propulsion systems to be used for Army ground vehicles operating in the battle zone. Technologies are identified whose evolution could provide major improvements in the functional performance, maintainability, and logistic support of future advanced-design ground vehicles. This discussion is based

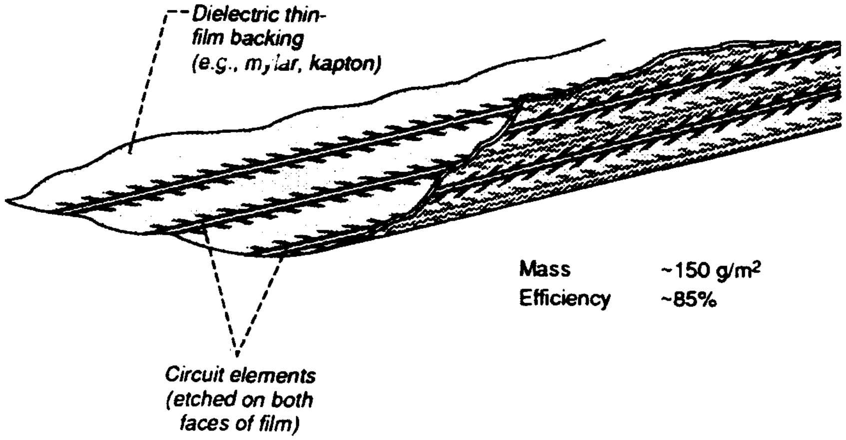


FIGURE 42-7 Configuration of thin-film microwave rectenna. Source: Raytheon, 1987.

on briefings and unpublished communications prepared by various Army personnel, together with Army publications pertinent to land mobility issues.[3]

Battle-Zone Applications

Application areas for surface vehicles may be divided into (1) heavy divisions with combat vehicles exceeding 40 tons, such as main battle tanks (e.g., M1 Abrams), and (2) light divisions with only vehicles below that weight limit, such as armored personnel carriers, infantry fighting vehicles (e.g., M2

[3] References used in preparing this section include three working papers prepared by George E. Checklich of the U.S. Army Tank and Automatic Command (1989a, b, c). Published references drawn upon include AUSA, 1989; DOD, 1987; General Dynamics Corp., 1987; Jane, 1986; JCS, 1984; McClelland, 1987; and Rodler and Shafer, 1987.

Bradley), cavalry fighting vehicles (e.g., M3 Bradley), self-propelled artillery, reconnaissance vehicles, and other tracked support vehicles. Although the character of the threats to our combat vehicles may vary widely, depending on the potential opponent and the circumstances of engagement, two potential threat elements must be considered in developing advanced technology for these vehicles:

- An opponent may have numerical superiority, at least during the initial rapid deployment of U.S. ground forces during a contingency operation.
- An opponent, even a small hostile group, may possess advanced antivehicle or antiarmor guided missiles and other weapons of advanced technology.[4]

One response to these threats is to produce vehicles with lighter weight, smaller silhouette, and greatly increased mobility to enhance survivability through evasive maneuvers. These systems will depend on the existence of technologies to produce future lightweight and low-volume propulsion systems, such as smaller, high-performance diesels; gas-turbine engines; or hybrid electric drives.

Current and Near-Term (About 10 Years) Characteristics

The Technology Group considered four categories of technologies related to surface mobility propulsion that it believes could be applicable to the Army's future battle-zone needs. These are identified in Table 42-8 and briefly described in the following paragraphs.

Engines

Naturally aspirated Diesel reciprocating engines provide power for many current military vehicles. To satisfy the need for more efficient engines, *turbocharging* is also being used. The boosting of engine horsepower by using exhaust gases to drive a turbocompressor has proved to be a reliable means to obtain higher outputs with improved fuel economy. The need for still more horsepower is driving the development of an even more efficient and economical system, called *turbocompounding*. This new system also uses exhaust gases to drive a turbocompressor, but it couples the turbocompressor

[4] Future threat circumstances and potential counters to them are discussed at length in *STAR 21*, volume 1, especially in chapters 1 and 6 (NRC, 1992).

TABLE 42-8 Surface Mobility Propulsion Concepts and Technology Areas

Propulsion Concept	Technologies of Interest
Engines	reciprocating, gas turbine, rotary, nuclear power plant, electric sources
Transmissions and Distribution Systems	mechanical, hydrostatic, hydromechanical, hydrokinetic electric
Mechanical Subsystems and Components	air intake and filtration, cooling system, lubrication system, auxuliary drives
Other Propulsion System Concepts	integrated propulsion systems, fuel-energized electric propulsion systems, ground-effect machines

directly to the flywheel through a gearing arrangement, in addition to pressurization of intake air.

Stratified-charge combustion is a technology that will allow a reciprocating engine to meet the requirements for multifuel operation. This technology employs a precombustion chamber with a spark ignition device. A fuel-rich mixture is injected into this chamber and ignited. In turn, it ignites the lean mixture, at a high compression ratio, in the main combustion chamber.

The fielding of the M1 main battle tank with a gas turbine engine as the primary power unit has increased interest in developing turbines for future combat vehicles, both near and far term. Turbine engines offer the vehicle designer a high-horsepower, lightweight power plant that will meet many of the operating needs on future battlefields. Simple turbines, similar to those used on fixed-wing and rotary-wing aircraft, would seem to be ideal for ground vehicles because of their weight and size. Their current fuel consumption level is unattractive, but recuperated turbine engines can reduce fuel consumption to more acceptable levels as a result of increased overall energy efficiency achieved by preheating the inlet air with the exhaust gases. The addition of recuperators increases the weight, volume, and cost of the engine system, as occurred with the Advanced Gas Turbine engine (AGT 1500) installed in the M1 tank. The increased power/weight ratio and other engine improvement goals of the IHPTET program (described above in the sections on "Missile Propulsion" and "Propulsion for Air Vehicles") should greatly benefit the Army's future use of turbine power plants for ground mobility.

Rotary engines have been in development for many years, using both government and industry funding, but they have not yet received wide acceptance for Army use because of problems with reliability and fuel economy. A staged-combustion version of this engine, using a stratified charge with spark ignition configuration, has managed to overcome some of these problems. The addition of a turbocharger has reduced the fuel consumption to at least that of a typical commercial Diesel engine. The rotary design, using modular components, can be assembled into multiple-rotor configurations, resulting in a family of engines that offer ratings from 375 to 1500 hp, a typical range for combat vehicle requirements.

Nuclear power plant technology offers the advantages of range and simple logistics. However, the safety considerations, large volume, and high initial cost preclude it from being a serious candidate for combat applications.

Electric sources—batteries and fuel cells—offer the advantages of power flexibility, convenient packaging, and low signature. But there are also disadvantages when used as primary energy sources: their weight and size, low range, logistics problems, and high initial cost. Their use as components in hybrid electric drive systems is discussed below.

Transmissions and Power Distribution Systems

Four basic transmission technologies are used in automotive applications: mechanical, combinations of hydraulic and mechanical (hydromechanical), electric, or combinations of hydromechanical and electric.

Mechanical. Mechanical transmissions with brake steering are manually actuated to shift the gears. This type of transmission, which was used from 1920 to 1960, has nearly been phased out of Army battlefield vehicles.

Combinations of Hydraulic and Mechanical. Hydrostatic transmissions use a positive displacement pump to drive a positive displacement rotor; it is commonly used in construction applications, such as forklifts. Hydromechanical transmission is a hydrostatic transmission coupled with mechanical gearing in several ranges; it has been used on the Bradley M2 infantry fighting vehicle and M3 cavalry fighting vehicle. Hydrokinetic transmission (referred to in Society of Automotive Engineers' nomenclature as "*hydrodynamic*") uses a torque converter in combination with mechanical gearing. Hydrokinetic semi-automatic transmission with clutch-differential steering was used in Army vehicles between 1950 and 1980; hydrokinetic automatic transmission with a hydrodifferential has been used since 1970 and is projected to be used until 2000.

Electric. Although the Army has not used electric drives for its combat vehicles, it does recognize their advantages. Electric drives offer improved use of space and flexibility of configuration, continuously variable drive for efficient engine operation and increased mobility, and reliability and maintainability. Later in this report is a discussion of the Technology Group's recommendation to consider seriously the development of electric drives for the far term (2020).

Other Propulsion System Concepts

System-Engineered Integrated Propulsion Systems. Work has been under way since 1982 by the Army Tank and Automotive Command to develop advanced propulsion systems using contemporary (nonelectric-driven) technology for vehicles to be produced about the year 2000. Under this Advanced Integrated Propulsion System (AIPS) program, all components of the propulsion system—engine, transmission, cooling system, air filtration, auxiliary power, inlet and exhaust ducts, as well as diagnostics, signature reduction, and maintainability—would be *designed* as an integrated system rather than as separate items. This system-engineered approach should result in a great reduction in space requirements, fuel consumption, and life-cycle costs, and should also increase the available power.

Fuel-Energized Electric-Drive Propulsion Systems. Electric-drive propulsion systems incorporate (1) a fuel-efficient prime power source, such as an advanced reciprocating, rotary, or gas turbine engine; (2) an alternator coupled to it; (3) a power conditioning and distribution system; and (4) electric motors coupled through a final gear drive at each wheel or track drive sprocket. A microprocessor control unit is used to control operation of the whole system. Electric drives powered by diesel or turbine engines have proven reliable when used on trains and large earth-moving equipment. Such electric-drive systems offer these advantages:

- improved weight distribution, because the system lends itself to flexible modular design;
- wheels or sprockets driven individually, eliminating complex hydrokinetic transmission or differential drive systems; and
- the potential for also delivering high power to weapon systems such as electrically energized guns.

Although this system is still in a preliminary stage of development for heavy and light combat vehicles, it has the potential to provide the greatest improvements in capability and flexibility by 2020.

Ground-Effect Machines. This concept permits vehicle mobility over a variety of relatively flat surfaces that are otherwise very difficult to traverse, such as tundra, soft or muddy land, ice, sand, swamps, and water. In a ground-effect machine, a layer of pressurized air supports the vehicle a small distance above the surface over which it is traveling. This form of support can handle depressions, rocks, and other surface irregularities; the scale of irregularities that can be traversed depends on the specific design of the skirt confining the air cushion. The air cushion minimizes the impacts of these disturbances at the driver's station and the weapon station.

Many ground-effect machines are in commercial operation for use over combined land-water routes, and there have been a number of designs produced for vehicles carrying very heavy loads over fragile arctic tundra.

Propulsion systems for ground-effect vehicles have generally been either separate engine-driven propellers, ducted fans, or laterally ducted air from the support compressor systems. Air vehicle system technologies evolved for aircraft are thus the most applicable. Propulsion system optimizations, however, are driven by the low velocity of surface mobility vehicles and the difficult directional control requirements resulting from zero traction and gravitational forces induced by nonlevel terrain. Therefore, the selection of specific power-plant technologies for providing both the support air cushion and the mobility and control forces are best considered in terms of an entire system concept. Both the STAR Mobility Systems Panel and the Special Technnologies and Systems Panel included such system concepts in their deliberations.

Table 42-9 presents the Technology Group's composite figure-of-merit indices for each of these surface propulsion technologies and system concepts for both the near term (about the year 2000) and far term (about the year 2020). The selection of certain technology areas for inclusion in this summary report, and in some cases for recommended emphasis by the Army, was based in part on their realistic potential to achieve high future values (4 and 5) in several of the figures of merit.

Future Characteristics and Figures of Merit

A review of available source material (see references listed at the beginning of this section) indicates that the main thrust of technology and systems development for surface mobility is and should be directed toward technologies that can provide lower weight, smaller volume, and higher total system fuel efficiency. These characteristics will reduce size and weight and/or permit increases in the payload or range of the combat vehicle. This point is illustrated in Figure 42-8, which shows system volume distribution of a representative armored field vehicle. The secondary thrust is in power transmission systems and other mechanical subsystems or components, and in

TABLE 42-9 Assessed Figures of Merit for Surface Mobility Propulsion for Years 2000 and 2020

System Concept	Figures of Merit: Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Reciprocating Engines	3	4	3	5	3	4	3	4	3	4	3	4
Gas Turbine Engines	3	5	4	5	3	4	3	4	3	4	3	4
Rotary Engines	2	4	3	5	2	3	3	4	3	4	2	3
Integrated Propulsion Systems	3	5	3	5	3	4	3	4	3	4	3	4
Electric-Drive Propulsion Systems	-	5	-	5	-	5	-	5	-	4	-	4
Ground-Effect Machines	-	4	-	5	-	4	-	4	-	4	-	4

NOTE: Index Values: 1 (minimal) thru 5 (excellent).

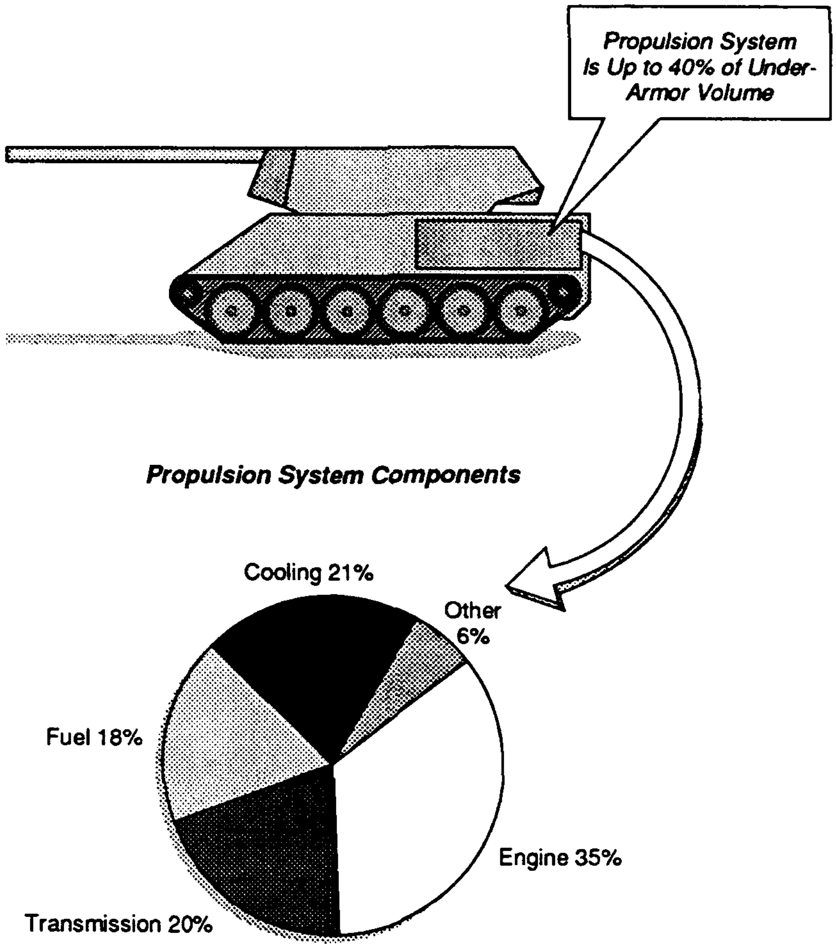


FIGURE 42-8 Propulsion system size in a typical 40-ton Diesel-powered vehicle.

integrated powerpack propulsion systems. Two approaches deserve particular attention:

- the integrated propulsion system concept; and
- fuel-energized electric-drive propulsion systems.

The integrated propulsion system concept being developed by AIPS includes engine transmission, cooling, and filtration systems; power conditioning; auxiliary power; and intake and exhaust ducts. AIPS also incorporates features to reduce the signature and improve maintainability and diagnostic capability. The program promises major improvement in both the near term and the far term in functionality, mobility, supportability, survivability, and cost. The Technology Group anticipates an increase in horsepower per unit weight, a significant decrease in fuel consumption, and an increase in power availability relative to today's best ground-vehicle propulsion systems. Improvement in maintainability and diagnostics will decrease the life-cycle operating costs and perhaps decrease the manpower requirements.

The Army should continue to emphasize the integrated approach to the total propulsion system design, while also providing for replaceable modules of system elements. The extent of the improvements will be enhanced by the design of highly efficient reciprocating and gas-turbine engines that require a minimum of cooling capacity, together with advances in high-temperature composite materials and compatible high-temperature lubrication or antifriction concepts.

Clearly, no matter what technologies are selected for engines and transmissions, an integrated-propulsion-system design approach is the best way to maximize overall system performance and improve all the figures of merit. The Group has therefore included a technology forecast on the concept of integrated propulsion systems, including but not limited to the exisitng AIPS program.

The concept of a fuel-energized electric-drive propulsion system offers the opportunity for major gains in total battle-zone effectiveness. It will make possible improvement of significant parameters that affect surface vehicle mobility (such as ground pressure, center of gravity, weight distribution, suspension, and power density). The Technology Group anticipates that internal combustion engine technology will advance to the point of the production of high-temperature engines that produce little friction and that operate without separate oil and water systems. As a system alternative, ultra-high-temperature gas turbines with high pressure ratios and nonrecuperative simple cycles should be available for use as an outgrowth of the IHPTET technology demonstration programs.

Integrating these advanced engines with advanced electric drives and having a flexible modular power distribution system delivering power to each wheel or track will provide the means to improve power density and weight distribution significantly and decrease signature and fuel consumption. The basic modules of a hybrid electric drive propulsion system could be used to provide other power requirements in the battle zone for the highly "electrified" army of the future. Electric power systems for mobile platforms would also supply all required energy for electric-power weapons.

Technology Forecast: Integrated Propulsion Systems

The concept of formal, total systems engineering to establish the design criteria for elements of major integrated weapon systems evolved rapidly from its start in the late 1950s to meet the complex demands of the nation's intercontinental ballistic missile programs. The extensive use of these techniques will be crucial to the Army's ability to incorporate very rapidly advancing component technologies effectively into equally rapidly changing vehicle concepts demanded by future Army missions.

For the slower evolving vehicle needs of the past, individual Army technology organizations and their contractors worked fairly independently on the technology and engineering development of various major elements of a propulsion system. Such generic development work was not always closely constrained by explicit design criteria derived from system engineering optimization of specific next-generation vehicles. In some cases of fast-changing new vehicle needs, significant mismatches occurred between available engines and transmission drives. Problems were encountered, for example, in trying to match advanced turbine engines with transmission systems developed for Diesel engines. The resulting overall vehicle systems have poorer performance, operational characteristics, maintainability, and cost-effectiveness than the underlying technologies could have produced.

At the Army Tank and Automotive Command, an integrated systems-engineering approach is incorporated in the AIPS program. Two concepts are being evolved; a system based on Diesel engine technology from the Cummins Engine Company and a gas-turbine system from the General Electric Company. The availability of new, advanced computer programs to model interactions among engine, transmission drive units, and control systems as they are designed increases the effectiveness of this approach.

Figure 42-9 shows the past trend in sprocket horsepower per cubic foot for total propulsion systems and the projected improvement over the M1 gas turbine engine, based on the AIPS goals (Checklich, 1989a). This improvement by a factor of 2.2 provides a reasonable basis for forecasting that very advanced integrated systems should by 2020 achieve sprocket horsepower per cubic foot in the range of three times that of the M1 tank.

Table 42-10 presents forecasted improvements based on information from the U.S. Army Tank and Automotive Command (Checklich, 1989a), in the specific fuel consumption of advanced Diesel engines (pounds of fuel per shaft brake horsepower-hour) as various component and engine system elements are incorporated. For a minimum-friction, uncooled, very-high-temperature, high-compression-ratio turbocompound diesel engine, a reduction in specific fuel consumption of 30 percent less than 1980 technology appears possible. Of course, in the field the specific fuel consumption for *traction* horsepower is much greater when engine shaft power is finally delivered through the complex transmission to the drive sprockets or wheels. Assuming an integrated system design approach, advanced engines, new transmission concepts, and computer-driven system controls, the Technology Group envisions reductions in vehicle *sprocket* specific fuel consumption of 40 to 45 percent by 2020.

TABLE 42-10 Predicted Improvement in Diesel Engine Brake Specific Fuel Consumption as New Technologies Are Incorporated

Diesel Engine Evolution 1980 to 2000+	Predicted Brake Specific Fuel Consumption of Engine (lb/hp-hr)
Baseline: Diesel, turbocharged, after-cooled	0.34
Turbocompound Diesel	0.33
Uncooled engine block	0.32
Incorporation of other uncooled components	0.28
Minimum-friction "adiabatic" (no active cooling)	0.25

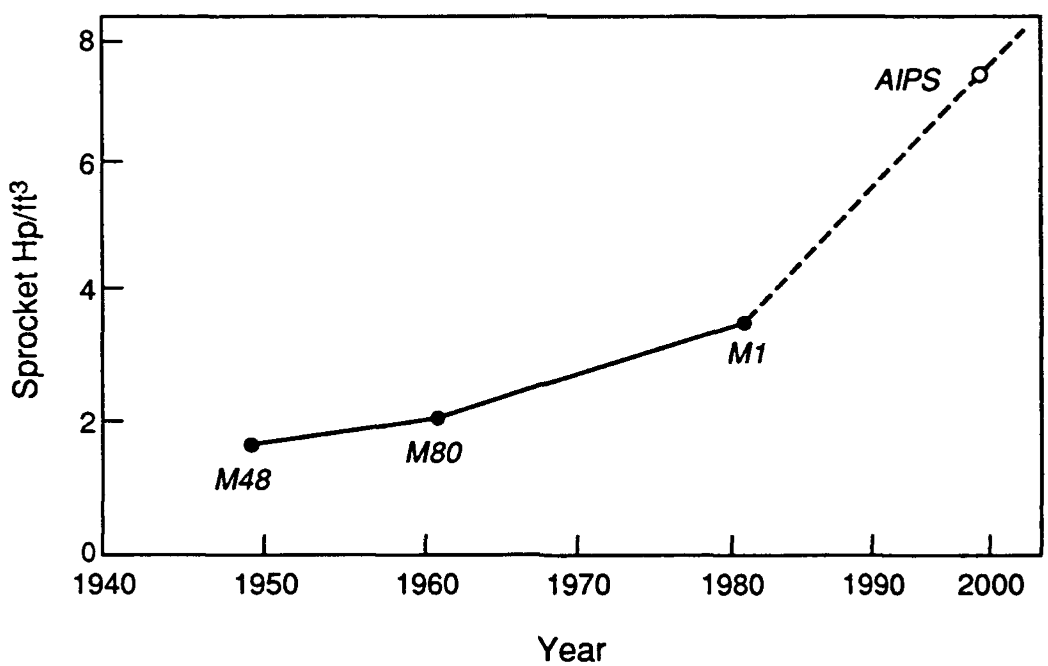


FIGURE 42-9 Projected improvements in power density of delivered propulsion systems resulting from integrated propulsion system engineering designs. Courtesy of U.S. Army Tank and Automotive Command.

Technology Forecast: Electric-Drive Propulsion

Electric-drive propulsion systems have not been employed in Army combat vehicles to date. Electric-drive units powered by diesels and turbines have been extensively used in civilian applications, such as train locomotives and heavy off-road equipment. However, studies carried out by the Army in the 1960s and 1970s indicated unfavorable size, weight, and fuel efficiency, compared with mechanical transmission and drive assemblies. Dramatic developments over the past 10 years in all component areas of electric-drive systems, including turboshaft engines, justify a thorough and creative re-examination of all-electric transmission and drive units and of hybrid mechanical-electric systems.

- New magnetic materials have nearly twice the energy product of the best magnets of the mid-1970s; they permit alternator power densities to be at least twice as great at higher engine speeds (rpms). The Technology Group expects that future high-temperature superconductors will give further substantial increases in power densities.
- New high-voltage power integrated circuits provide order-of-magnitude improvements in power conditioning units (see "Power Conditioning" in Chapter 43). They can be driven by microcomputer signals and directly drive the gates of power-switching devices.
- Variable-speed traction motors with high maximum rpm ratings have demonstrated improvements of almost a factor of two in both power/weight and power/volume ratios as a result of magnets with higher energy product and operation at higher rpm. The decrease in motor weight and volume with higher rpm operating range more than offsets the compensatory change in final reduction gear ratios.
- Energy storage using advanced batteries or flywheels (driven by and generating electrical energy) have shown similar large gains in energy/weight and energy/volume ratios. In particular, flywheels of crossed-fiber composites with a solid geometry can store up to five times the energy of the best available secondary batteries.

A schematic of an electric-drive system for tracked vehicles is presented in Figure 42-10. It shows both an electric-only transmission configuration and an additional mechanical transmission path that would be typical of a hybrid-drive system. A comparison of designs embodying these drive concepts with the DDA-X-300-4A mechanical drive system of the Army's 19.5-ton tracked vehicle is presented in Table 42-11 (FMC Corporation, 1987; General Dynamics, 1987). With existing technologies and components, reductions in propulsion system weight of 35 percent and volume reductions of 50 percent could be achieved by 2000. Beyond the selection of basic components for the near-term demonstration vehicles, there are considerable opportunities for continued technology evolution in many areas. In addition to the anticipated

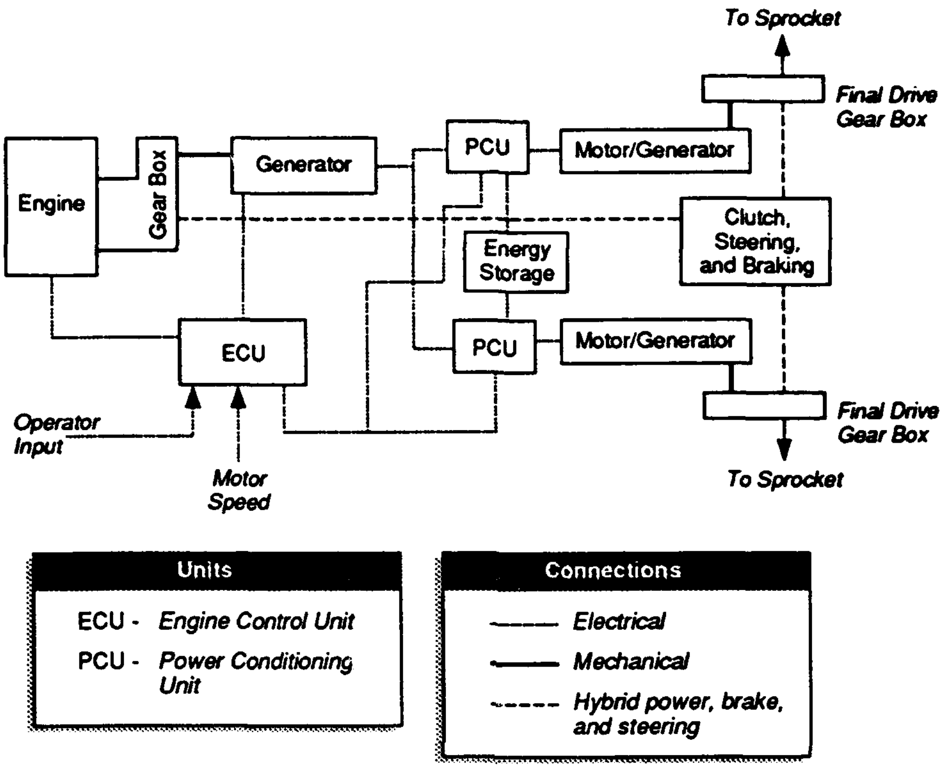


FIGURE 42-10 Electric drive for tracked vehicles.

continuing advances in all of the electric power elements identified above, the Technology Group anticipates further significant gains in primary motive power engines—both turbo-diesels and gas turbines. Similarly, advanced heat exchangers and energy storage devices, such as composite flywheels, should be exploited to provide even greater power-plant densities, efficiencies, and operational flexibility to electric-drive vehicles, whether tracked or wheeled.

The direct coupling of high-rpm turboshaft engines and high-frequency (400 Hz or more) electric-power generation units could provide specific power outputs of over 2 kWe/kg. Power conditioning units can expect to reach more than 20 kWe/kg at power output levels of 500 to 1000 kWe.

TABLE 42-11 Comparison of Mechanical, Electric, and Hybrid Drive Systems for an Army 19.5-Ton Tracked Vehicle

Power Drive (500 hp)	Weight (lbs)	Volume (ft^3)
Mechanical: DDA X 300-4A	2000	20.0
Electric: permanent magnet generator, permanent magnet trac (design)	1440	9.3
Hybrid: permanent magnet self-syntrac (design)	1240	9.5

Source: General Dynamics, 1987.

Electric-drive vehicles provide many opportunities for configuration options, particularly in vehicle profile, weight and traction distribution, and signature reduction in critical situations. Individual traction motors at each wheel or sprocket can be operated differentially for steering, and during braking can run in reverse to regenerate electrical energy. If the system incorporates sufficient energy storage (high power and energy density), over 90 percent of this braking energy can be recovered for later use during acceleration. Also, energy can be transferred directly to storage from the primary alternator, for later use in major "burst speed" requirements, super traction loads, or low-signature operation. This energy storage would permit the use of primary engines with smaller maximum horsepower, so the primary engine can be optimized for a narrow range of cruise-level rpm. For all types of operational mobility profiles, this would result in significant reductions in the actual "traction work delivered" specific fuel consumption. The more stops and starts and the more difficult the terrain, the greater the savings in fuel consumption relative to non-electric-drive vehicles. In addition, the weight, size, and vulnerability of braking-load thermal control systems can be reduced. The modularity of the electric elements will also enhance full standardization, interchangeability, ease of field replacements, and use of components from damaged vehicles to reactivate other damaged or non-operating vehicles.

The Technology Group believes that U.S. (and foreign) auto makers will eventually move to electric-drive automobiles, trucks, and off-road equipment. In current plans (which are driven at present by environmental laws), the auto makers are focused on battery-supplied mobile energy sources. (See, for example, Scientific American, 1992; Smithsonian Magazine, 1992.) However, fundamental physical limits on battery physics and chemistry related to power and energy density, peak power draw, lifetimes under the extreme loads of mobile operation (in contrast to today's "start the car" requirement), and so on, lead the Technology Group to conclude that mechanical energy storage systems will evolve in the commercial world. Such units could be re-energized in 5 to 10 minutes at electric-energy supply stations. Recovery of energy when braking for stops or hill descent would extend the average mileage between re-energization stations. The Technology Group also forecasts that additional yearly average mileage between storage-unit re-energizations will be achieved by using new cost-effective solar-energy panels, since the electric-drive system to use photovoltaic energy would already be in place. Finally an overall systems optimization could result in a hybrid configuration, with a small gas-powered engine operating over only a narrow range of rpm around its design point for maximum fuel efficiency.

The Army should be ready to take full advantage of these various electric-drive technologies as they evolve in the commercial world. However, the special needs of battle-zone vehicles and the probable unavailability of electric-energy supply stations in most battle zones would suggest that hybrid electric-drive systems with primary engines powered by JP-8 fuel should be the focus of Army technology support.

GUN OR TUBE PROJECTILE PROPULSION

This section summarizes and projects potential Army battle-zone requirements for future gun or tube projectile propulsion systems. Included are descriptions of a range of projectile propulsion technologies that could be of importance in the long term (the year 2020 and later).

Battle-Zone Applications

Under future battlefield conditions, the Army will probably face a variety of high-value targets that have increased mobility, improved firepower, and greatly improved armor (both design and materials). These targets will also be equipped with radio-frequency jamming and decoy capabilities. Compared with today's state of the art, future Army battlefield artillery and heavy guns will require higher mobility and firepower rates, lower dispersion patterns and ordnance signatures, smarter ordnance, shorter time to target, and ordnance that can better penetrate or defeat armor. These advanced requirements will be reflected in future gun and tube projectile specifications as lower-weight ordnance loads; low-weight guns and tubes; high rates of projectile loading; high ordnance-firing rates; lower guns or tube-erosion rates; smart warheads—especially for fire-and-forget operations—higher muzzle velocities; and high-velocity armor-penetrators. Also reflected in these requirements will be greater survivability for personnel and for expensive launch platforms.

Current and Near-Term (to 10 Years) Characteristics

Propulsion systems for gun and tube projectiles can be divided into two categories: chemically energized systems and electrically energized systems. The Technology Group considered ten areas of new propulsion system technologies for gun and tube projectiles that are applicable to the Army's future battle-zone needs. Six of these technologies are chemically energized.

Chemically Energized Guns

1. *Modular Charge.* The modular charge concept aims toward simplifying the currently fielded twelve-zone bag to a five-zone charge. This change permits charges to be built up at firing time, rather than discarding bag increments. Modular-charge technology also permits the incorporation into the combustible case of additives that reduce gun wear.
2. *Unicharge.* The unicharge extends the rigid combustible case and stick propellant to a single universal increment. Its main advantages accrue from simplified autoloading, decreased propellant waste, and greatly improved logistics.
3. *Rocket-Assisted Projectile and Rocket-Assisted Kinetic Energy Projectile.* This approach to increasing projectile velocity, which has been evolving for some time, has resulted in rounds with increased velocity and range, such as the M549 and the M650 rounds. Current programs are exploring the use of rocket-assisted kinetic energy (KE) projectiles with depleted uranium rod penetrators. Both concepts would permit the development of hand-held or light machine-mounted, tube-launched rocket motors that reach very high velocities in relatively short ranges, for kinetic energy kills on armor and other hard structures.
4. *Traveling Charge.* With a conventional gun and projectile, combustion occurs in the chamber, and expanding gas follows the projectile down the barrel. There is considerable loss of kinetic energy in accelerating the propulsion gases. In the traveling-charge concept, the high-burn-rate propellant moves with the projectile, generating the propulsive gas as the projectile is accelerated. Thus, the kinetic energy losses (which are a considerable fraction of the projectile kinetic energy) are eliminated and the projectile net muzzle velocity is increased. Additional benefits include a reduction in the heat transmitted to the barrel and decreased barrel wear.
5. *Low-Vulnerability Ammunition and High-Energy Low-Vulnerability ammunition.* Efforts are under way to develop gun propellants that would be less vulnerable to damage-related premature detonation of on-board ammunition. Characteristics of such munitions include a higher thermal ignition threshold, lower burn rates at low pressure, and resistance to fracture by impact. A number of energetic materials, energetic plasticizers, and

improved bonding agents have been coupled with improved elastomeric binders to produce attractive candidate propellants. However, the objectives set forth in the DOD Insensitive Munitions Initiative for less-vulnerable munitions appear likely to be better realized through the Army's program for liquid gun propellants. The latter seem more likely to provide the characteristics listed above while retaining greater overall flexibility in applications.

6. *Liquid-Propellant Guns*. Army work on liquid propellants has focused on the development of the regenerative liquid-propellant gun. This uses a differential-area piston to pump a liquid monopropellant. The program retains current gun barrels and recoil mechanisms but requires a redesigned breech. General Electric Company has successfully demonstrated liquid guns with bores of 25 mm, 30 mm, and 105 mm. The propellant currently under consideration for the 155-mm gun is LPG-1846, a water-based hydroxyl ammonium nitrate system. With respect to spill, the Navy has used a similar system safely. This kind of propellant also appears to be less sensitive to shock and has demonstrated long-term storage stability. Some of the potential benefits include higher loading densities (which also may result in higher muzzle velocities), lower flame temperature, lower barrel erosion, improved logistics, automatic loading capabilities, higher rates of fire, improved stoichiometry, and reduced gun flash. Of course, projectile muzzle velocities are limited by the maximum gas velocities of the reaction products for optimized maximum barrel pressures.

In addition to these chemically energized systems, there are presently three candidate approaches to electric guns: EM (electromagnetic) railguns; EM coilguns, and electrothermal-chemical (ETC) guns. All employ electrical energy to provide all or a significant fraction of the energy needed to fire projectiles at higher performance levels than conventional systems. Schematics of these three propulsion concepts are shown in Figure 42-11. EM guns use intense magnetic fields and very high electric energy, and have recently attained projectile velocities not otherwise achievable by any gas-driven gun at containable pressures. ETC guns use more modest electrical energies to initiate and control chemical reactions in energetic propellant formulations (generally referred to as the "working fluids"); these reactions produce the propulsion gas pressures that accelerate the projectile (Oberle and Jamison, 1988). EM coilguns employ ringlike coils in both the projectile and the gun tube. A current is established in the projectile coils, and successive coils in the gun tube are sequentially energized, accelerating the projectile down the tube (IEEE, 1989; Juhasz et al., 1988; NASA JPL, 1986; and Oberle, 1988;). Because of size and weight constraints, the Technology Group doubted the ultimate battlefield advantage of an EM, single-pulse coilgun system. However, new concepts for polyphase asynchronous generators, which could provide a more constant force along the gun rails or coil, are attractive

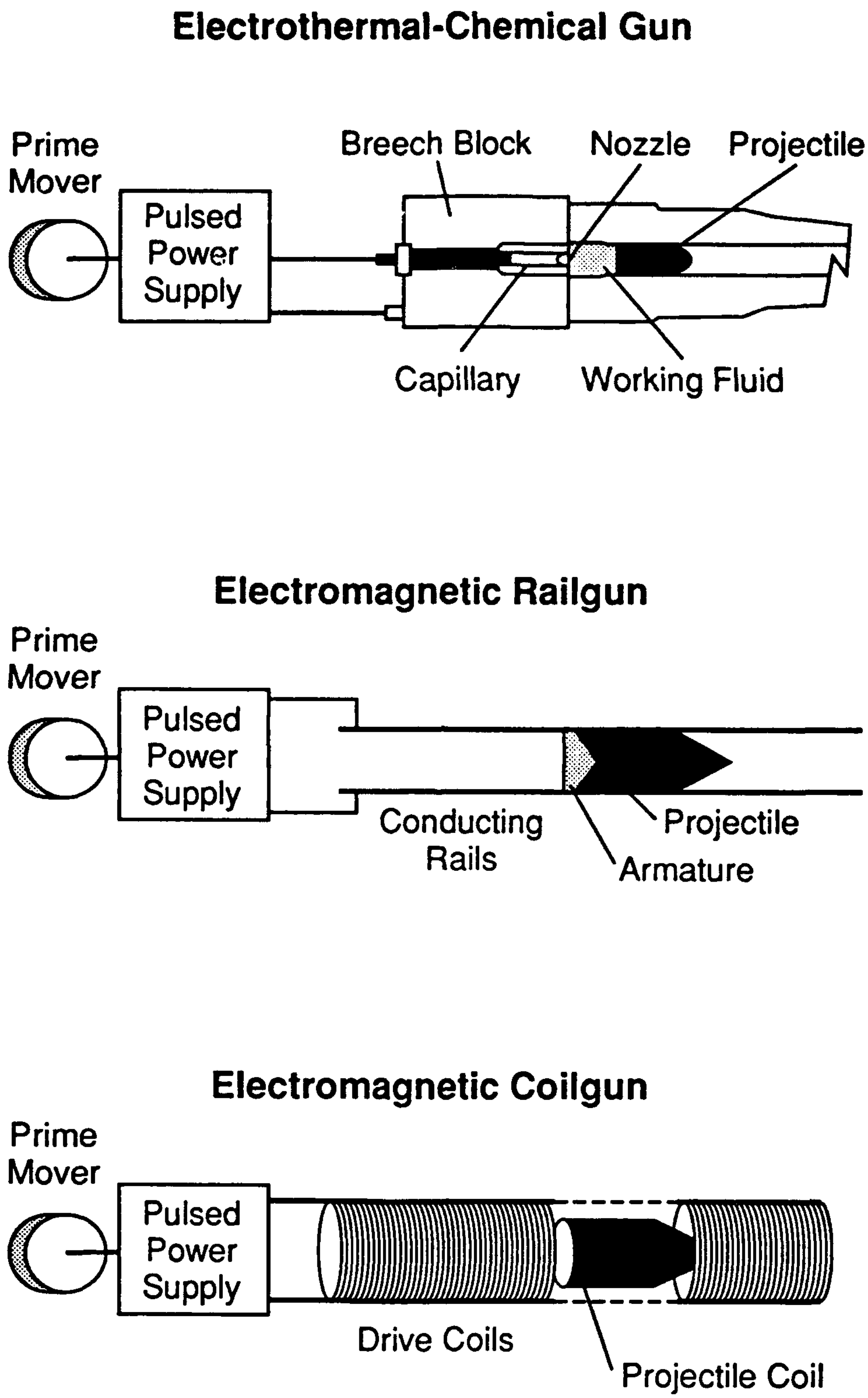


FIGURE 42-11 Technologies for electrically energized gun propulsion. Courtesy of Armament Research, Development and Engineering Center.

enough to support a re-examination of coilgun concepts, as well as EM railguns (Institute for Advanced Technology, 1992). Also, the application of this technology to performance enhancement, through barrel extension velocity boost, is worthy of careful study and, if study results are positive, test and evaluation.

EM Guns

The EM gun offers the potential for accelerating projectiles to much higher muzzle velocities because it is not limited by the kinetics and gas dynamics of conventional chemical charges. Other potential advantages include improved velocity control and no muzzle flash. EM guns employ a gun tube consisting of parallel conducting rails in an electrically insulating structure. Currents in the million-ampere range are sent through the rails when the circuit is closed by means of a conducting armature. Magnetic interactions establish forces that accelerate the projectile, which is placed in front of the armature, down the gun tube.

In electric-gun technology, power conditioning includes prime power from homopolar generators, compulsators, and alternators combined with capacitors, batteries, and pulse-forming network elements. In one example, a generator is used to build up current in an inductor that stores magnetic-field energy; the generator slows down as the inductor current builds up. To launch a projectile in this type of gun, the inductor current is switched into the launcher.

High muzzle velocity is useful for KE rounds directed against short-range to medium-range armored targets. For advanced armor, it may even be essential. But its utility for artillery rounds in general-purpose area fire is uncertain; the answer depends on systems issues, such as projectile cost and the effects of extreme acceleration, aerodynamic drag, and frictional heat on the sensors and electronics carried in guided projectiles. Among the pacing elements for EM field artillery are the requirements to reduce size and weight of the power conditioning systems and ancillary components (DARPA, 1987; Systems Planning Corp., 1990). As remarked above, the emerging technology for polyphase asynchronous generators may prove highly beneficial to the performance of such EM guns.

ETC Guns

Developments in electrically energized ETC guns have resulted in new power supplies, inductors, conductors, and switches to the point that practical guns driven by electrically generated plasma have been demonstrated. While the propulsion principle is much the same as in conventional chemical propulsion, the hot gases are produced by electrical generation of a plasma from the propellant (Oberle and Jamison, 1988). The use of low-molecular-weight gases permits high muzzle velocities to be achieved. A 10-mm gun has generated a velocity of over 4 km/s for small projectiles. Recent advances with a reactive fluid (combustion-augmented plasma), using markedly reduced electric power levels, have resulted in more than 70 successful firings of a 10-mm device, 100 firings of a 30-mm device, and 14 firings of a 90-mm device (Army Science Board, 1989). The Defense Nuclear Agency announced in March 1992 that a 5-inch naval gun, modified for ETC propulsion, had successfully fired a 25-kg projectile at velocities above 1 km/s. The muzzle energy of the projectile was 14 MJ (Defense Nuclear Agency, 1992).

Velocity dispersion has recently been reduced to less than 1 percent (not a proven natural limit), so ETC technology is now within the bounds of present practical chemical propulsion. There are joint programs, in which the Army, Navy, Marines, Defense Nuclear Agency, and Department of Energy are participating, to define the ultimate limits for EM and ETC guns, as well as other advanced gun-projectile systems. Continuation of such efforts is recommended for informed decisions on the applicability of these new technologies to specific system requirements.

A final category of gun propulsion technologies considered by the Technology Group is light-gas guns, including hydrogen cannon and ram guns.

Hydrogen Cannon

This concept from the Brookhaven National Laboratory involves the electrical or combustion preheating of hydrogen in a porous particle bed to a high (~1500 K) temperature, followed by compression that adiabatically heats the hydrogen to temperatures in excess of 2500 K. The gas discharges through a burst disk and propels the projectile. To achieve maximum velocity (as in other gas guns), gases with low molecular weight are required. Ammonia or hydrogen is recommended for field applications. Ammonia, which decomposes to hydrogen and nitrogen at temperatures in excess of 1000 °F, provides a convenient, available source of hydrogen with far less leakage and risk of explosion than high-pressure hydrogen gas. A Lucite projectile has been driven to 2.5 km/s with a gas compressed to 16,000 psi; 3.0 km/s was predicted for a gas compression of 30,000 psi. While this work is very preliminary, further modest investment with some assessment of total system configuration is warranted, such as overall comparisons of field operability with other advanced gun-propulsion systems, including the EM and ETC guns described above.

Ram Guns

This concept from Washington State University, which has been demonstrated in principle, employs established ramjet technology. A high-velocity projectile travels down a tube (gun barrel) loaded with a mixture of hydrogen and oxygen gas. The projectile's passage down the tube generates a shock wave that compresses the gas ahead of the projectile and induces combustion behind it. There is interest at the Ballistics Research Laboratory in further exploration of the ram concept for guns to be used on existing tanks. The Ballistics Research Laboratory has computed an increase in velocity of the existing armor-piercing round by 500 m/s (D. Kryzinsky, U.S. Army Ballistics Research Laboratory, personal communication, 1989). To fully determine its real potential, further Army support of this concept is recommended. The key question to be addressed is the overall efficiency of this chemically driven system. This must be validated both experimentally and theoretically, and must be consistent with practical projectile barrel-entry velocities of about 10 percent of the ultimate velocity.

Future Characteristics and Figures of Merit

Table 42-12 presents the Technology Group's composite assessment of these ten gun- or tube-projectile propulsion systems against the six figures of merit described above. As was true in other sections, the selection of one representative technology for a detailed technology forecast and assessment, and in some cases for recommended emphasis by the Army, was based in part on its potential to achieve high future values (4 and 5) in several of the figures of merit. On the basis of this assessment, the Group believes that both liquid-propellant and electrically energized gun technologies have good potential for significantly augmenting the future conventional gun capability of the Army.

Liquid-Propellant Guns

The evolution of liquid-propellant guns essentially embodies incremental improvements and is not dependent on high-risk new technologies to enable it. Therefore, one can forecast that a set of carefully system-engineered operational goals for these guns would have a high probability of being achieved. Relative to solid charges, the two most important potential advantages of liquid guns are lower peak acceleration on projectiles and lower barrel erosion rates. However, for future "smart-round" applications, the liquid-propellant guns, despite these advantages over solid charges, must also be shown to have decisive total system advantages over rockets in delivering

TABLE 42-12 Assessed Figures of Merit for Gun and Tube Projectile Propulsion for Years 2000 and 2020

System Concept	Figures of Merit: Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Modular Charge	3	4	4	4	4	4	3	3	4	4	3	4
Unicharge	3	3	4	4	4	4	3	3	4	4	3	4
Rocket-Assisted Projectile	2	3	2	3	2	3	3	3	3	3	2	4
Traveling Charge	2	3	2	3	2	3	2	2	3	3	1	2
LOVA/HELOVA	3	3	4	3	2	2	4	4	3	3	1	2
Liquid-Propellant Gun	3	4	3	4	3	4	3	4	3	4	4	5
EM Gun	2	4	2	4	2	4	2	4	2	3	1	3
ETC Gun	2	4	2	3	2	3	2	3	2	4	1	3
Hydrogen Cannon	2	4	2	3	2	3	3	3	2	4	2	3
Ram Gun	2	4	1	2	1	2	2	3	2	4	2	3

NOTE: Index Values: 1 (minimal) thru 5 (excellent).
LOVA = low-vulnerability ammunition; HELOVA = high-energy low-vulnerability ammunition.

smart rounds that produce the same effects at the targets. The heavy gun system and its mobile platform and propellant supply module must be mobilized into positions as large units before any number of rounds can be projected. Rocket-launched rounds would be lighter as a result of much lower peak acceleration. These lightweight smart rounds and their unitized boosters can be mobilized individually or in groups of any size. Furthermore, if the projectile velocity required for antiarmor missions is greater than 2.5 km/s, neither the liquid-propellant nor powder-charged guns can achieve that requirement. These issues, particularly the tradeoffs with rocket propellant systems, need to be clearly evaluated in order to establish a set of technology goals for liquid-propellant guns that would provide unique and cost-effective operational capabilities in the future.

In the case of close-in (less than 1000 m) antiarmor missions that demand impact velocities around 3 km/s, it is not clear that rocket-driven projectiles are practical. Their effective acceleration would have to be in excess of 460 G at 1000 m. Their flyout times, which are a factor of two longer than those of gun-driven projectiles, could mean the difference between kill (and survive) or be killed in return. For these fairly close-in antiarmor missions, the electrically energized guns could provide an alternative system solution. They can achieve projectile velocities in excess of 3 km/s at all close-in target ranges. Because of their unique potential value to the Army of the future, the Technology Group prepared a technology forecast on electrically energized guns.

Electrically Energized Guns

If the Army moves to introduce electrically driven ground mobile platforms, as recommended in the previous section on "Surface Mobility Propulsion," projectile launchers that are wholly or partially electrically energized would bring about major improvements in the overall performance of weapon systems. Of the several basic concepts for such launchers, the EM accelerator concepts (rail or coil) embody physics that can produce the highest projectile velocities. However, available information on stand-alone EM systems indicates that at muzzle velocities up to about 2.5 km/s, they are considerably heavier than combustion-augmented (exothermic working fluid) ETC systems. Higher projectile velocities (greater than 2.5 km/s) using ETC systems are limited by gas velocities at acceptable operating temperatures, practical barrel pressures, and decreasing ratios of projectile KEto electric input energy. Although very-high-velocity gun-launched projectiles (greater than 3.0 km/s) may have applications in missile and air defense (because of shorter fly-out times), it is not clear that they are optimal or even attractive for general battlefield use. They provide a unique capability for shorter-range antiarmor engagements. However, if developed and fielded for this exacting mission, they would also be effective at longer range against stationary emplacements and armored vehicles.

Advances in power supplies and material technologies in the far term (2020) are expected to reduce electrical equipment weights by a factor of two or more for ETC and EM projectile launchers. Unless the Army develops the technology base for high-energy-density power systems (e.g., batteries, capacitors, switching, transformers, and inverters), electrically energized guns will not be feasible for compact platforms such as tanks. In the case of EM systems, a plasma-armature railgun with a combustion-augmented plasma preaccelerator may provide further reduction in system weight and electric power requirements. Novel cooling concepts to replace the current liquid nitrogen cooling system, which is very heavy, also could make EM systems more attractive. As already mentioned, the development of polyphase asynchronous generators, which would permit the force to be distributed along the length of the rails, may provide significant system improvements for EM guns.

The Technology Group's current assessment is that, at projectile velocities of up to about 2.5 km/s, the combustion-augmented ETC concept probably has less development risk. Present ETC guns can and do use conventional barrel designs and permit rotational projectile launch. They can be configured for very long rod penetrators to minimize the velocity required for antiarmor missions. The EM systems have much greater growth potential in projectile muzzle velocity, but they also have greater system weight and at present appear to face more severe development and field operational problems. The design innovations in power conditioning, and materials improvements necessary to overcome these difficulties and apply this technology in a competitive, fully operational system for future heavy penetrator rods (3 to 5 kg) at velocities of 3 to 5 km/s, are speculative at present.

Further experimental validation of theoretical performance models is required to resolve the many apparent inconsistencies and differences of views the Group found within and between the various study reports on electrically augmented guns. Moreover, there remains a need to adequately address the effect of combining the advances in electric power systems described in another section of this technology report with the total system gains that could result from integrating electric-energized armament with electric-drive vehicles. This has not been done in any of the studies to which the Group had access. For these reasons, it has not been possible to generate a specific technology forecast with selected performance and design data. Most of what is available could be misleading, both in projecting the evolution of key technologies and in comparing the several system concepts.

The Technology Group recommends, therefore, that technology development and systems analysis of design parameters be continued at appropriate funding levels for the several types of electric-energy-augmented launchers, to establish more consistent and validated criteria for functionality, hardware design, and field support. This work is needed so that defensible technology evolution forecasts can be made. Using such information, consistent weapon system studies could be performed to clarify the performance and life-cycle cost-effectiveness of each concept for a variety of future battlefield missions. These concepts for electrically energized propulsion could then be compared objectively with various rocket propulsion concepts for propelling different types of rod-projectiles and both "dumb" and "smart" to meet broad requirement envelopes of range, time of flight, and kill mechanism.

43

Electric Power Technology for Battle Zones

This discussion of electric power technology for battle zones is divided into three topics:

1. continuous electric power generators;
2. pulsed and short-duration power generators; and
3. energy storage and recovery for ultimate electric power output.

Within each of these topics, various technology elements, listed in Table 43-1, were selected for initial consideration. The Technology Group assessed the potential improvements that could be expected for each technology element, relative to six general figures of merit of importance to the Army. Table 43-2 shows a representative set of factors used in determining these relative values.

The Group believes three technologies will require special attention and support if their potential is to be realized:

- turbogenerator power units for continuous power and pulsed or short-duration power;
- key components (capacitors, inverters, transformers) for power conditioning in pulsed or short-duration high-power applications; and
- flywheel (energy storage) systems.

Technology forecasts on these subjects are provided below.

CONTINUOUS POWER GENERATORS

The Group reviewed a number of electric power generating systems that could be important to the Army in 2020 and identified high-leverage technologies that the Army may find advantageous for investment. Systems to generate continuous electric power ranging from less than one kilowatt to several megawatts were considered. Even the best engines for a primary energy source consume their own weight in fuel in about ten hours. Therefore, fuel storage determines overall operational system weight to provide total electric power, and fuel supply will dominate supportability and logistics. However, mobility is also critical; each power unit's size and weight must be made optimally small. Substantial weight reduction of mobile electrical generators and power conditioners can be achieved by increasing generating and distribution frequency from the current 60-Hz standard up to the 400-Hz range and even beyond.

TABLE 43-1 Electric Power Technology Areas

Continuous Electric-Power Generators	**Pulsed and Short-Duration Power Generators**	**Energy Storage and Recovery as Electric Power**
Turboshaft engine generators	Prime power	Primary batteries
Piston-engine generators	Gas turbine generators	Rechargeable batteries
Hydrocarbon-fueled Engines	Controlled combustion MHD generators	Fuel cells
Organic rankine	Explosive driven MHD generators	H_2O
Brayton	Flywheel generators	Other
Stirling	Battery	Flywheels
Fuel cells	Power Conditioning	Pumped liquids
Solar dynamic	Bus power	Compressed gases
Solar photovoltaic	Slow power	Thermal storage
Wind- or water-powered	Fast power	
Radioisotope		

NOTE: MHD = magneto-hydrodynamic.

TABLE 43-2 Specific Factors Selected for Assessing Each Figure-of-Merit Index Value

Figures of Merit	Representative Factors
Functionality	Range of power that can be delivered by this class of device Turndown range Compatibility with lightweight electric generator/conditioner
Mobility	Specific conditioned power (W/kg) Specific conditioned energy (W-h/kg) Modularity Volumetric power and energy (e.g., W/liter)
Supportability	Low parts count Reliability Maintainability Critical or special resource requirements
Survivability	Hardness to threats Low signature Autonomy
Manpower	Operating level Support levels Man-force multiplier
Cost	Nonrecurring Recurring per unit of power and energy Life-cycle operating per unit of power and energy

Battle-Zone Applications

In its concept for warfare in the early twenty-first century, the Army envisions the use of advanced technologies and combat systems with ranges, lethality, and detection capabilities surpassing anything known in contemporary warfare. In the battle zone surrounding and including the battlefield, there will be requirements for electrical power at every level from tens of watts (for surveillance and communication) to kilowatts (for radar and for a variety of electric motors) and hundreds of kilowatts (for field base power demand). Mobility of all system elements will be essential for survival and success. Therefore, although fuel supply may dominate the total system operational weight, mobile electric power units should have high specific power, be compact and quiet, and have minimal signatures in the electromagnetic spectrum from visible frequencies to the radio frequencies (NRC, 1988a).

Current and Near-Term (to 10 Years) Characteristics

Of the continuous power generator concepts listed in Table 43-1, several are already in use by Army systems. Turboshaft engines are currently used in military helicopters and in some tanks. They are now being incorporated in mobile electric power units. They burn jet fuel and have rotational speeds in excess of 20,000 rpm. The high rotational speed could be used to advantage in a high-frequency, lightweight direct-coupled electric generator operating at 24,000 rpm (400 Hz) or higher. Typically, however, they are geared down to 60-Hz alternators. The gears increase weight and noise. The gain in using commercially available equipment designed for 60-Hz operation will have to be weighed against the competing need for lower specific weight and volume to meet Army needs for high mobility.

Of the two types of piston engine generators, Diesel is preferred to gasoline because it uses the same fuel as aircraft and heavy ground transportation. This commonality reduces supply problems. Compared with turboshaft engines, Diesels are heavy, slow, and noisy, but they also have a wider useful turndown range and are easier to service in the field. Their low rotational speed is a good match for 60-Hz power generation, which is satisfactory for the present but will prevent them from efficiently using lightweight, high-speed electric power generators in the future.

The Group also considered three closed-cycle engine technologies with external combustion chambers: the organic Rankine cycle, the Brayton engine, and the Stirling engine.

The *organic Rankine cycle* operates at good efficiency without needing a high turbine inlet temperature. It requires a condenser (which condenses the hot working fluid to a liquid and removes waste heat), heat exchanger, and a liquid pump to recirculate the condensed vapor from the condenser to the heat exchanger. An organic working fluid such as toluene is used instead of steam because steam forms erosive water droplets as it expands and cools in the turbine.

The *Brayton engine* is also a closed-cycle external combustion engine requiring a waste heat remover and recompression of the working fluid (an inert gas). The engine is capable of high rotational speed, but it has a less efficient cycle than a Rankine engine operating in the same temperature range. However, because it generally operates at higher temperatures than the organic Rankine, it can have a higher achieved operating efficiency.

The *Stirling technology*, like the closed-cycle Brayton engine, requires a waste heat remover, an internal heat exchanger, and recompression of the gas. Although it is also inefficient compared with a Rankine engine operating over the same temperature range, this engine is generally designed for higher maximum operating temperatures. Significant interest has been shown in free-piston Stirling devices for small power supplies. Although hydrogen as a working fluid provides the highest performance in a Stirling cycle, problems with long-term leakage of this gas could limit field operations and complicate support logistics. Nitrogen can be used in a Stirling cycle to deal with the leakage problem, but at the cost of lower performance for a given maximum operating temperature.

Existing low-temperature fuel cells generate power from the chemical combination of hydrogen and oxygen. They are poisoned by carbon monoxide and almost any other trace gas. High-temperature fuel cells have shown efficiencies as high as 50 percent and can use carbon monoxide, hydrogen, or ammonia as fuel. However, at the current state of the art, more complex fuels like JP-8 need to be broken down catalytically before they can be used. Because of this slower catalytic process, such fuel cells would not respond well to rapid load fluctuations. For continuous power supplies, this constraint could be overcome by using energy storage to meet peak-load demands. A breakthrough in this area could have enormous implications for the Army.

It is the Technology Group's opinion that the other power generation concepts listed in Table 43-1—solar, wind, water, and radioisotope—were not attractive candidates for continuous power generators in the battle zone.

Future Characteristics and Figures of Merits

Table 43-3 presents the Technology Group's composite figure-of-merit indices for each of these technology concepts in the near term (year 2000) and the far term (year 2020). The Technology Group's selection of certain technology areas for inclusion in this summary report, and in some cases for recommended emphasis by the Army, was based in part on the potential to achieve high future values (4 and 5) for several of the figures of merit.

TABLE 43-3 Assessed Figures of Merit for Continuous Electric Power Generators for Years 2000 and 2020.

System Concept	Figures of Merit											
	Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Internal Combustion Turboshaft Engines	3	5	4	5	3	4	3	3	2	4	2	3
Internal Combustion Piston Engines	3	3	2	2	4	3	4	4	3	3	3	3
External Combustion Piston Engines	2	4	3	4	3	4	3	3	4	4	1	2
Fuel Cells (no major breakthroughs)	2	4	3	4	2	3	3	3	1	3	2	2
Other Concepts	<--------LOW INDICES-------->											

NOTE: Index Values: 1 (minimal) thru 5 (excellent).

The Group believes that, of the various concepts evaluated, turboshaft-engine-driven alternator systems have the best potential for practical, continuous improvement in all areas. To realize this potential, the Army needs to support the DOD/NASA IHPTET program and carry out an aggressive technology effort in advanced lightweight alternators, power conditioning control systems, and unit integration/modularization. A detailed technology forecast for turbogenerator power units is provided below.

Unlike turbogenerator technology, fuel cells that run on liquid hydrocarbons are not an existing technology. They are certainly a possibility, however, particularly in light of the advances made in the previous decade in understanding the catalytic reforming of hydrocarbons (Kerr, 1989). Research in this area with the specific goal of developing a fuel cell that would run on liquid hydrocarbons and air would be worth supporting. If a breakthrough were to occur, the implications for the Army of the future could be enormous.

Technology Forecast: Turbogenerator Power Units

In the opinion of the Technology Group, mobile electric-power systems driven by turboshaft engines have the best potential for evolving into compact, lightweight units with reasonable noise control. Systems with these characteristics will be required in the future, particularly for the intermediate power ranges from perhaps 50 kW up to the megawatt level. The most significant factors controlling the specific power of an integrated unit are engine rotating speeds, generator frequency, and generated voltages. To a first approximation, the physical size of an engine is proportional to torque. Increasing the speed increases the shaft power proportionately with a modest change in weight. Thus, high-speed turbines have the best potential for achieving both lightweight and low-volume power systems. The weight advantage gained by high-speed operation of advanced engines can be lost, however, by coupling through a gear box to heavy low-frequency generators and power conditioners. The present Army standard of 60 Hz requires that either engines with speeds greater than 3600 rpm must be geared down to 3600 rpm or the high-frequency alternating current that is directly generated must be rectified to direct current (dc) and then converted back to 60 Hz alternating current (ac) with an inverter (NRC, 1988a). Both approaches introduce weight, inefficiency, and unreliability into the system.

Optimization design studies performed for the space station suggest a different overall approach: let the alternator rotate at the turbine speed and produce power at that frequency (Nored and Bernatowicz, 1986). Turbine speeds of 24,000 rpm or higher are achievable and efficient. When directly coupled, 24,000 rpm gives ac power at 400 Hz (which is standard for aviation). Using these higher frequencies for power generation can reduce the weight of the active components in the system by a factor of about six, compared with a system at 60 Hz. Solid-state converters could then be used to shift the frequency to 60 Hz for distribution. In some cases, one may even wish to consider 20 kHz for distribution in compact systems (Hansen, 1986).

The voltages used for power generation and distribution also have high specific-power leverage. The required conductor cross-section, hence its weight, decreases as the square of the voltage, so this is an important parameter.[1] The present practical voltage limit (about 1 kV) for mobile systems is set primarily by the reliability limits at high voltage of semiconductor devices. Improvements in high-voltage semiconductor devices could permit more system-optimized voltages to be used.

As the technologies contained in the IHPTET program (discussed in earlier sections of this chapter) evolve over the next 20 years, the shaft specific powers of high-rpm engines should approach 10 kW/kg. Similar progress is anticipated for high-rpm alternators with stationary armatures and separately excited rotating-magnetic-flux generating units. The weights of these generators are almost inversely proportional to their rotating speed (rpm). Thus they should be designed for 400 Hz and directly coupled to the gearbox output shaft at 24,000 rpm. Although some special generator units have been operated at specific powers as high as 20 kWe/kg, the Technology Group believes that generators built to military standards will more generally achieve 10 kWe/kg.

In systems at high frequency, power conditioning components are small, lightweight, and highly efficient, particularly when using series resonant conversion in ac/dc converters. Advanced technology should yield systems with power densities in the range of 15 to 30 kWe/kg. Power densities as high as 100 kWe/kg are conceivable for power conditioners by growing the complete inverters in a fashion similar to present complex integrated circuits.

Table 43-4 provides forecasts of how the technology of mobile integrated electric power units could evolve over the next 30 years. The existing field generators of category A are nearly all Diesel 60-cycle units based on the technology of the 1970s. The units in category B use turbine engines but are nonoptimally coupled through gear boxes to 1980s-technology 60-cycle generators and power conditioning elements.

Thus the Technology Group emphasizes that attention to technology development always should be balanced across all of the system elements during each evolutionary period. Because the weights of all elements are summed in the denominator of the specific-power calculation, it does little good to make one element's weight vanishingly small at great expense, while

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[1] Power (P) = V^2/R, where V is the voltage and R is the resistance. In a cylindrical cable of cross section area A, R is inversely proportional to A. Therefore P is proportional to V^2A. For a given power, the required area A is inversely proportional to V^2.

TABLE 43-4 Estimated Progression of Mobile Electric Power Units

Category	Technology Circa	Power System Technology	Specific Power (kWe/kg)
A	1970s	Diesel, 60 Hz, integrated unit; power range 10–750 kWe; military standard	0.02–0.05
B	1985	Turbine 24,000 rpm, gearbox, 60 Hz, 100–800 kWe, integrated unit	0.4–0.6
C	2000	Turbine 24,000–72,000 rpm, 400-Hz power, various alternator and power control technologies, integrated unit	1.0–1.3
D	2020	Turbine, 24,000–72,000 rpm, 400 Hz Engine: 8–12 kWe/kg, Alternator: 10–20 kWe/kg, Power control unit: 15–30 kWe/kg, Integrated unit factor: 1.5×	2.6–3.6

the integrated unit is dominated by some other older technology subsystem. In forecasting the specific-power range for category C in Table 43-4, the group assumed that turbine engines, which had a specific power of about 5 kWe/kg in the early 1990s (category B), would evolve to about 6–8 kWe/kg by the year 2000. High-rpm generators were assumed to achieve a specific power of between 5 and 8 kWe/kg by 2000.

Figure 43-1 shows how the duration over which power is delivered affects the total chargeable system's power/weight ratio for the existing and estimated future mobile electric-power units of Table 43-4. The diagonal limiting line in the figure represents the maximum specific energy available from combustion of the JP-8 fuel that will be used in the Army's diesel engines or turbine engines. An overall efficiency of 39 percent is assumed from maximum fuel heating value to conditioned electric power. The *y*-axis gives the specific power based on the total system weight: kilowatt-hours divided by the weight of the total integrated system, including engine, generator, power conditioner, integration factor, and fuel consumed. For many engagements in the future, actual operating times may be relatively short (hours to hundreds of hours). Therefore specific power of the hardware units will be critical to mobility and initial operational capability.

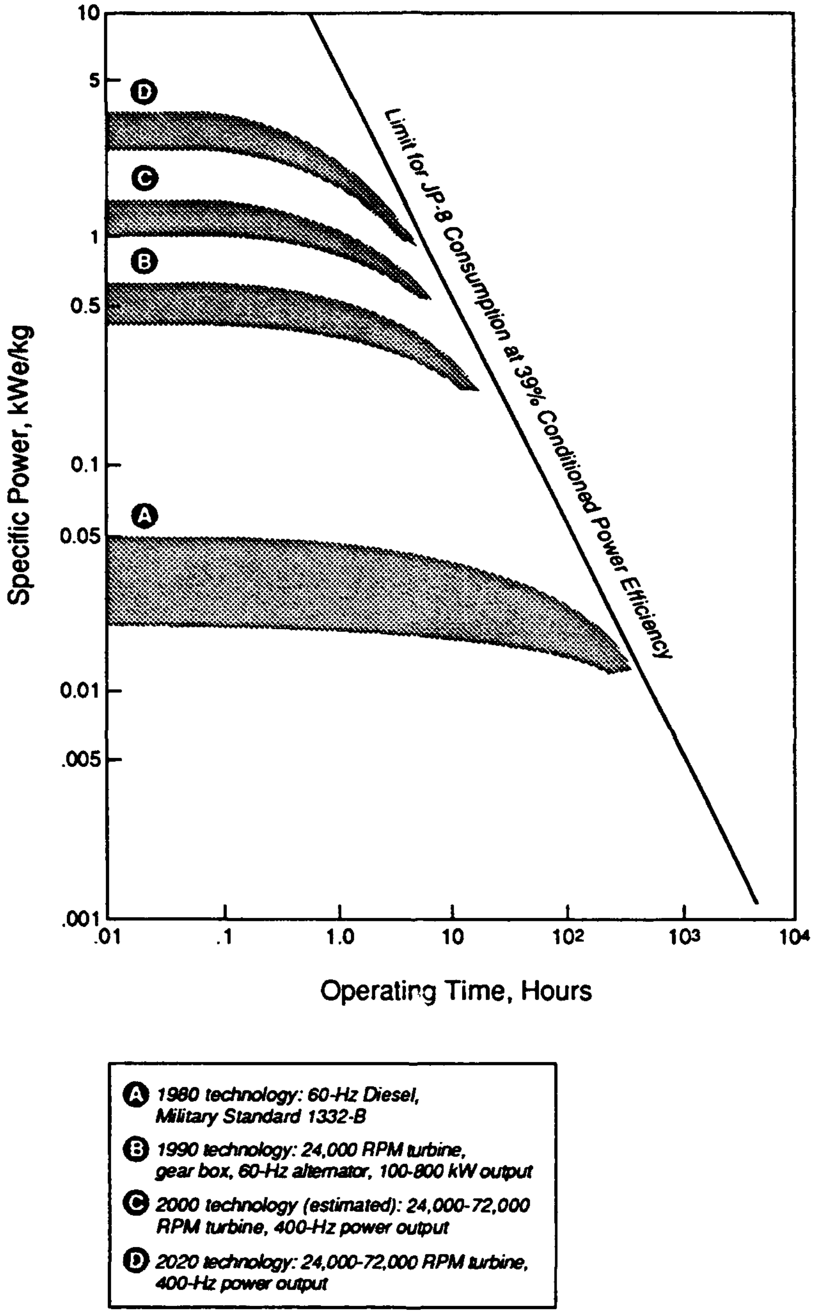

FIGURE 43-1 Specific power versus operating time for advanced turbogenerators. The diagonal line represents maximum specific electrical energy from hydrocarbon fuels (JP-8).

PULSED AND SHORT-DURATION POWER GENERATORS

This section assesses and projects future Army battle-zone requirements for lightweight, compact, pulsed or short-duration electric power generators with outputs of up to tens of megawatts of average power. Earlier studies have shown that this class of generator is approximately 50 percent prime power and 50 percent power conditioning, with respect to either mass or volume. The Technology Group believes that direct-pulsed high-power generator subsystems will evolve to provide specific power in the range of 10 to 100 kWe/kg. Such progress could make a variety of electromagnetic beam weapon systems attractive for the Army's use in the battle zone. Table 43-5 presents the range of operating parameters of interest for military pulsed power systems.

Battle-Zone Applications

In the future, mobility and supportability of various types of electric power systems will be essential for survival and success. Pulsed or short-duration power generation at average power levels up to tens of megawatts, with precise power conditioning, could be required to drive future Army directed energy weapon systems (see Table 43-6).

TABLE 43-5 Projected Operating Parameter Ranges for Electrically Energized Systems

Parameter	Projected Range
Average Power	0.1 to > 10 MWe
Peak Power	kWe to GWe
Pulse Durations	0.05 to 1000 microseconds
Repetition Rate	1 to 1000 Hz
Voltages:	
Bus-continuous (recommended to always remain below the Paschen minimum breakdown—180 V)	24 to 180 V ac+dc
Pulsed Power	1 to 1000 kV
Duty Cycle:	
Bus power	on for 30 minutes to days
High power	on for 1 to 30 minutes

TABLE 43-6 Pulsed-Power Requirements for Future Army Applications

Average Power (kWe)	Peak Voltage (kV)	Run Time (s)	Application[a]
<1	<50	>1000	ECM, LADAR, communications
1–10 (or even 100)	<100	>10	LADAR, RADAR
10–1000	<500	>100	HPM, RADAR, DEW
>1000	>100	>100	DEW, Antimine, Antiarmor

[a]ECM = electronic countermeasures; LADAR = laser radar; HPM = high-power microwave; DEW = directed energy weapons.

Sources: Furgal, 1988; NRA, 1988a; and Sarjeant, 1989.

Current and Near-Term (to 10 Years) Characteristics

A general schematic for the types of power systems the Technology Group believes are needed in high-efficiency systems is presented in Figure 43-2. A prime electric-power source feeds into a bus-conditioning stage to alter the voltage level for optimum, reliable power distribution to a "slow-power" conditioning stage (of millisecond pulse duration). If necessary, it feeds this set of repetitive pulses into a "fast power" conditioning stage to create pulses of a microsecond or less in duration.

Pulsed-power generation systems can be divided into two major subsystems as illustrated in Figure 43-3: (1) energy storage or prime power generation, followed by (2) power conditioning. The Technology Group considered five classes of energy storage and prime power generation:

1. *Open-Cycle Combustion-Driven Gas Turbine Generators*. These systems burn fuel in excess air to produce hot combustion gases, which are then expanded through a turbine to drive a generator, producing the prime power. These systems have very attractive power densities, particularly for high power levels. They are good candidates for future pulsed-power generation (see the discussion of turbogenerator power units, above).
2. *Magneto-Hydrodynamic Generator Driven by Solid or Liquid Propellants*. In these systems, solid propellant grains or a bipropellant liquid combination burns at elevated pressure and extremely high temperature. The propellant is seeded with an ionizable material such as potassium, and then passed through a magneto-hydrodynamic channel, where part of the energy in the ionized gas is directly converted to electric power. (This technology and the following technology were considered in combination with dc generators.)
3. *Explosive-Driven Magneto-Hydrodynamic Generator*. In this system, an explosive charge is used to drive a "single-shot" magneto-hydrodynamic power generator. The advantage of this system is that a pulse with a very high power level is produced, thus avoiding much of the power conditioning requirement of other systems.
4. *Flywheel Energy Storage and Power Generation*. Large amounts of power can be stored in a flywheel as it is "spun up." By coupling the flywheel to a generator, that power can be tapped rapidly. New materials have greatly increased the efficiency of flywheel systems (see below).
5. *Battery Energy Storage and Power Generation*. The Technology Group believes that the use of rechargeable batteries for very high power pulse applications will not be extensive because of limitations in power density in comparison with either gas turbines or flywheels.

The Group also examined the three main elements of all power conditioning systems: bus power conditioning, slow power conditioning, and fast power conditioning.

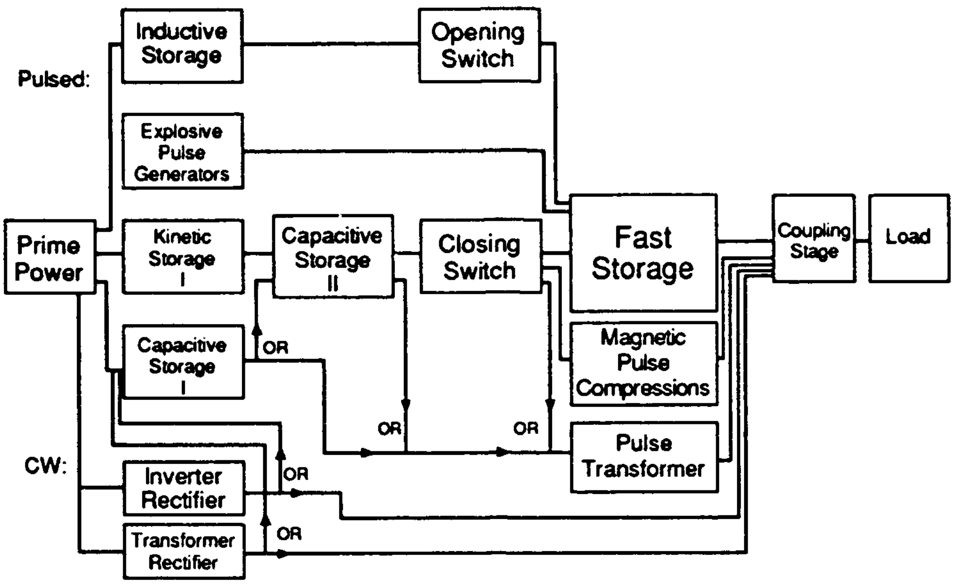

FIGURE 43-2 Alternatives for multimegawatt prime power and power conditioning. Choice among "OR" branches depends on the load to be served.

1. *Bus Power Conditioning.* This technology takes the electrical feed from one of the prime power sources listed above into a conditioning stage, where the voltage level is altered for optimum, reliable power distribution to a "slow power" conditioning stage. The major components of this first stage of power conditioning are inverters and transformer/rectifiers.

2. *Slow Power Conditioning.* The slow power conditioning stage produces repetitive electrical pulses in the millisecond time frame. Switches, capacitors, and transformers are the major components used in this stage of power conditioning.

3. *Fast Power Conditioning.* If required for the particular application, a final stage of power conditioning can be used to convert the pulses with a millisecond duration from the slow power conditioning stage to pulses of a microsecond or less. This stage uses transmission lines, capacitors, switches, and magnetic devices as the primary components.

Future Characteristics and Figures of Merit

Table 43-7 presents the composite figure-of-merit indices for these generator and power conditioning technologies in the near and far terms. The Technology Group's selection of certain technology areas for inclusion in this summary report, and in some cases for recommended emphasis by the Army,

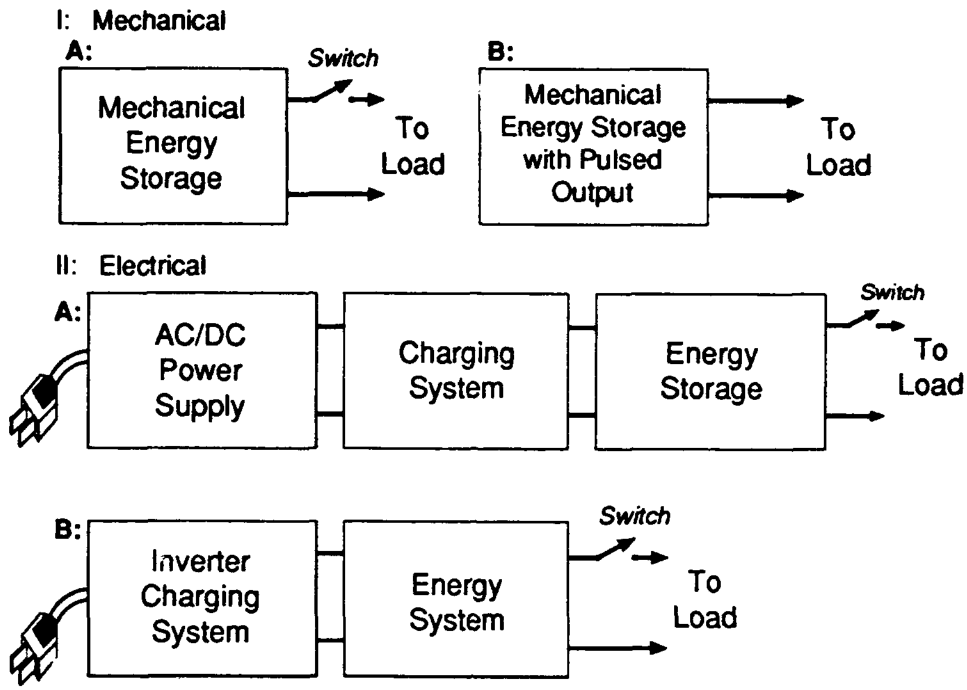

FIGURE 43-3 Alternative techniques to provide multimegawatt prime power and power conditioning. Choice depends on the load to be served.

was based in part on the potential to achieve high future values (4 and 5) in several of the figure of merit.

On the basis of this assessment, the Group believes that only two of the five categories of energy storage or prime power generation that were discussed in the previous section have broad-based applicability to the Army's needs for high-energy pulsed power by the year 2020. These are (1) open cycle, combustion-driven gas turbine systems and (2) flywheel energy storage and power generation. For power conditioning, this Technology Group believes that the areas of bus and slow power conditioning are broadly based in their applicability to Army systems of the future. As indicated in Table 43-7, the Group anticipates major improvements in these systems over the next 30 years, if properly nurtured by Army R&D programs that focus technology advances on requirements specific to the Army.

The Group expects the development of open-cycle combustion-driven gas turbine systems that can use a broader range of fuel types, thus easing the logistics problem of fueling these generators with a single type of scarce fuel. These new systems will be much more rugged than today's turbogenerators because of the introduction of advanced materials and processing methods. Also anticipated are approaches to reducing the effluent signature to enhance the survivability of future systems.

TABLE 43-7 Assessed Figures of Merit for Pulsed and Short-Duration Power Generations

System Concept	Functionality 2000	Functionality 2020	Mobility 2000	Mobility 2020	Supportability 2000	Supportability 2020	Survivability 2000	Survivability 2020	Manpower 2000	Manpower 2020	Cost 2000	Cost 2020
Energy Storage and/or Prime Power Generation												
Open-cycle combustion-driven gas turbine	3	5	3	4	3	4	2	3	2	4	2	3
Solid- or liquid-propellant driven MHD	2	4	2	3	2	3	2	3	2	3	2	3
Explosive driven MHD	1	4	3	4	2	4	2	4	2	3	1	3
Flywheel energy storage and power generation	2	5	2	4	2	4	3	4	4	5	3	5
Battery energy storage and power generation	2	3	2	3	4	5	3	5	3	4	2	2
Power Conditioning												
Bus power conditioning	1	5	2	5	2	5	4	5	3	5	3	5
Slow power conditioning	3	5	2	5	1	5	4	5	2	4	3	5
Fast power conditioning	1	4	2	5	1	4	2	4	2	3	2	3

NOTES: Index Values: 1 (minimal) thru 5 (excellent). MHD = magneto-hydrodynamic.

Flywheels

Flywheels have potential for improvement in the FOM categories of functionality, mobility, supportability, manpower, and cost. Most of the anticipated improvements in flywheels will come from major advances in composite materials with ultrahigh strength/weight ratios. These materials will enable energy density to increase by an order of magnitude over high-strength steels because they can sustain higher angular velocities. The Group believes that the cost of fabricating composite flywheels with optimally tailored structural properties will decline dramatically over the next 30 years, as more military and industrial applications are found for composites. (A later section contains a detailed discussion of flywheel systems.)

Power Conditioning

Power conditioning currently represents between 50 and 80 percent of the total mass of high-power pulsed generator systems. For the battle zones and mobile applications of the future Army, it will be essential to greatly increase the power density of these stages. Studies reviewed by this Group indicate that a reduction of at least an order of magnitude in specific weight is possible before intrinsic physical, chemical, and mechanical limits are reached (Furgal, 1988; NRC, 1989; Sarjeant, 1989; Vitkovitsky, 1988). These advances will come about primarily through new, molecularly tailored materials and through greatly improved techniques for thermal management, including advanced heat pipes and thermal cold plates. The Group also believes that the power conditioning systems that evolve over the next 30 years will degrade gracefully (Furgal, 1988; NRC 1989). In other words, single-point failures will result in only a small decrement to performance, because the systems are designed in a way that enables the automatic bypass of a degraded element. The anticipated progress in key parameters for power conditioning subsystems is given in Table 43-8.

TABLE 43-8 Forecast of Power Conditioning Module Power and Power Density

Parameter	Today (per system)	Tomorrow (10 years) (per module)	Future (3 years) (per module)
Average power			
kWe/kg	0.05	10	>100
kWe	100	100	1000
Pulsed power (as pulsed energy)			
kJ/kg	0.3	1	>10
kJ	50	500	5000

Of the categories of electrical pulsed or short-duration power generators presented above, the areas of bus and slow power conditioning are broadly based in their applicability to Army systems of the future. The Technology Group strongly recommends high-temperature, high-power electronics development as a mainline thrust, along with techniques for improved heat rejection into the adverse operating environment of the battlefield. Therefore, four technology forecasts have been provided for this technology area, all of them relating to components of power conditioning systems: capacitors, inverters, switches, and transformers.

Technology Forecasts

Capacitors

As the Army's requirements for compact electrical power systems grow substantially over the next 30 years, the development of capacitor technology is a major enabling technology element. For microsecond to fractional-second energy storage and discharge, this passive capacitor technology is unequaled in flexibility and adaptability to meet a broad range of future requirements (Burkes, 1978; Furgal, 1988; NRC, 1988a,b, 1989; Sarjeant, 1989; Sarjeant and Burkes, 1987; Stephens, 1989; Vitkovitsky, 1988).

At present, energy conditioning at pulse repetition rates of less than 1 Hz and 10 to 30 MJ per pulse has been achieved for pulse durations from 0.05 to more than 1000 μs. The maximum voltages decrease from megavolt levels at shorter pulse durations to tens of kilovolts at the longer pulse durations (Burkes, 1978; Sarjeant, 1989; Sarjeant and Burkes, 1987; Vitkovitsky, 1988). Voltage levels are determined by the nature of the load. Innovative capacitor and related insulation systems, operating at near their ultimate voltage breakdown limits (10 to 15 times today's operational levels), would enable the development of lightweight systems. The best current commercial capacitors achieve specific power densities of 1 to 10 kWe/kg and specific energy densities of 1 to 300 J/kg. Repetition rates will be up to several kilohertz, necessitating the development of capacitor technology integrated with that of negligible-loss switching topologies and voltage-multiplication pulse transformers. Most systems are projected to be classifiable by voltage according to their average power and run-time characteristics (see Chapter 44, "High-Power Directed Energy Technology").

For future Army needs (30 years out), compact systems would be enabled with capacitor energy and power densities 10 to 100 times those available today. The Technology Group believes that the development of new solid and liquid materials, in conjunction with advancing methods of manufacturing technology, will be feasible with tools emerging from present technology programs (Furgal, 1988; NRC, 1988a, 1989; Sarjeant and Burkes, 1987). What will be required is a tightly integrated development program for materials and components, tailored to areas of need for the three main classes of capacitor technology (polymer film, ceramic, electrolytic).

Figure 43-4 shows recent and projected progress in capacitor energy density. Capacitor developers in industry have taken a preeminent role in this integration of materials development with the practical realization of advanced capacitors. The Technology Group believes that the Army will need to support a system-responsive, technology-based development program in each of these capacitor areas. The program goals should be demonstration hardware that will operate at the power and energy densities needed, at not less than one-tenth in unit capacitance (Furgal, 1988; Sarjeant, 1989; Vitkovitsky, 1988).

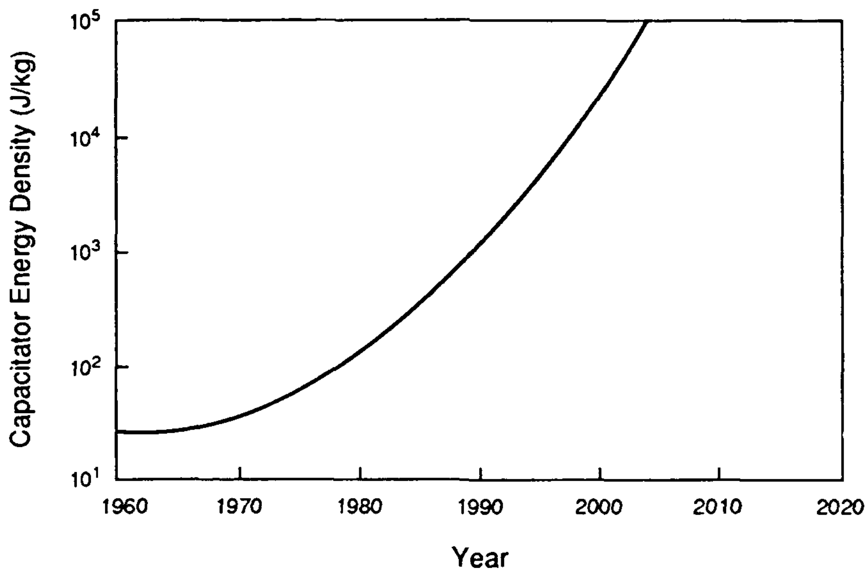

FIGURE 43-4 Projection of specific energy density for new capacitor technology (Staffiere, 1989).

Capacitors with specific power densities of 200 to 1000 kWe/kg and specific energy densities of up to 20 kJ/kg may be feasible in the future (NRC, 1989; Staffiere, 1989). Recent discoveries have resulted in capacitors whose performance degrades gracefully and does not result in single-point failure for the system. Now, for the first time, the potential exists for novel capacitor technologies that offer radically different availability over the system life. Indeed, throughout the system's normal life, even in adverse environments, the failure modes of this new technology will provide graceful and predictable reduction in performance, so that total system operation can be retained, although at a reduced performance level.

Table 43-9 projects performance for capacitor technology that will be the state of the art. It lists selected examples of several classes of advanced capacitors that further research could develop as practical, highly compact units. For large production volumes, the unit cost of these advanced units is projected to be comparable with the cost of current technology (NRC, 1988).

TABLE 43-9 Performance of State-of-the-Art and Projected Advanced Capacitor Systems

Capacitor System	Energy Density (kJ/kg)		Power Density (kW/kg)		Repetition Rate (Hz)	Critical Research Areas[a]
	Now	Future (2020)	Now	Future (2020)		
Polymer Film	0.6	20	60	2,000	100	Film Impregnants, Foils, >150°C, 1 MJ/unit
Ceramic	0.01	5	100	50,000	10,000	Ceramics, Electrodes, >500°C, 1 kJ/unit
Electrolytic	0.2	2	20	200	100	Electrolytes, Separators, >200°C, 10 kJ/unit

[a]Technology factors that must be addressed to achieve the projected future performance.

Inverters

The Army's requirement for efficiently conditioned electrical power will continue to grow dramatically over the next 30 years. Part of this requirement will come from the conditioning needed to provide the electrical bus (i.e., the extension cords interconnecting the system elements) with the power quality, reliability, and maintainability that will keep electric-powered systems operational during warfare. Eliminating the present single-point failure topologies that result in catastrophic failure of electrically powered assets can be accomplished by developing advanced inverters (Furgal, 1988; Sarjeant, 1989; Staffiere, 1989; Vitkovitsky, 1988).

The objective is to provide the soldier with a power source that degrades gracefully when damaged during war, continuing to operate, albeit at reduced performance, so that electric-powered assets remain available for their missions. In point-failure situations, bus conditioning via bidirectional inverters would continue to supply power from generator-to-generator feed lines redundantly, isolating damaged generator members of the system and permitting load sharing under inverter control (Burkes, 1978; EEB, 1988, 1989; Furgal, 1988; NSB, 1988; Sarjeant, 1989; Staffiere, 1989; Stephens, 1989; Vitkovitsky, 1988).

Because no other power-conditioning technology can provide this control, inverter bus power conditioning is vital to the electrically powered Army of the future (Burkes, 1978; Furgal, 1988; NRC, 1988a, 1989; Sarjeant and Burkes, 1987; Staffiere, 1989). However, the Army will need to support development of this technology. As illustrated in Figure 43-5, little substantive progress in cost-performance ratio has been made in the last 5 to 10 years in the power-density scaling of bus power elements for main computer systems. Indeed, little progress is forecast for the future (Staffiere, 1989). Figure 43-6 shows that, during this same period, the power system rose from 35 to 47 percent of the computer volume per million instructions per second. This lack of progress in power supply performance has been attributed to the lack of investment in power miniaturization (Staffiere, 1989). Advanced electronics demands advanced bus-power conditioning, including power supplies, to support the fast, survivable, high-technology Army systems of the future (Furgal, 1988; NRC, 1988b; Sarjeant, 1989; Stephens, 1989; Vitkovitsky, 1988).

The requirements of future weapon systems could be met through a focused development program that increases the inverter subsystem power densities by 10 to 100 times over the 0.01 to 0.2 kWe/kg of current military systems. Needed improvements include:

1. Modular, molecularly grown block power conditioners that are fault-tolerant and whose performance degrades gracefully and

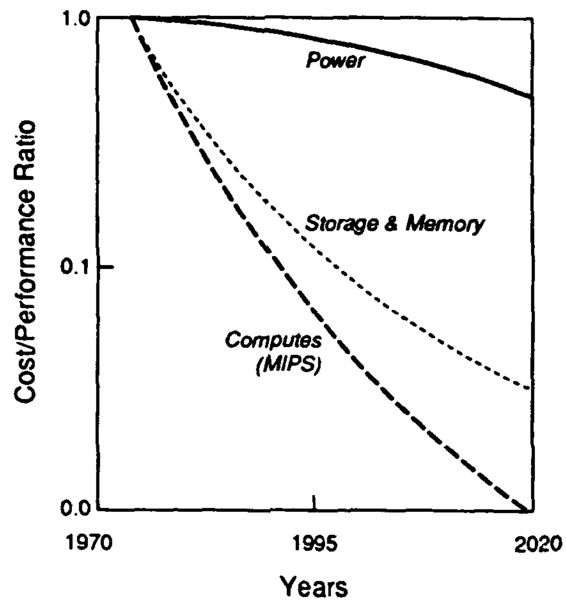

FIGURE 43-5 Technology advancement with time of major computer systems elements as a function of cost versus performance ratio (Staffiere, 1989).

2. Voltage management modules that are interchangeable, stackable, and can be connected in parallel—essentially indefin.ely—to create the quality of ac/dc voltages needed in the field.

For further discussion, see National Research Council (NRC, 1988a, 1989), Furgal (1988) and Sargeant and Burkes (1987).

The second improvement would provide a universal, intelligent, bus power conditioning module, with per-module, power break sizes that are cost-effective for the Army. Modules would probably come in sizes of 1, 10, 100, and 1000 kW. The component development for the capacitors, switches, and transformer technologies needed in such "hybrid integrated circuit" inverter modules is described in other technology forecasts in this chapter.

In sum, bus power conditioning of the future will move in the same direction as the universal field battery concept (NRC, 1988b; Stephens, 1989). Total interchangeability will be maintained within power module classes, whether the modules are used in an ac power bus conditioner at 60 Hz, as a dc power supply for power electronics, or for power distribution interconnections to permit generator redundancy in parallel architecture systems. A result of this concept is that power regulation is preserved, so that the need for individual power quality or power regulation specifications would then become unnecessary. This would dramatically reduce the dozens of different generators needed for mobile power in the battlefield today. The effect of this reduction upon depot and field support is expected to be

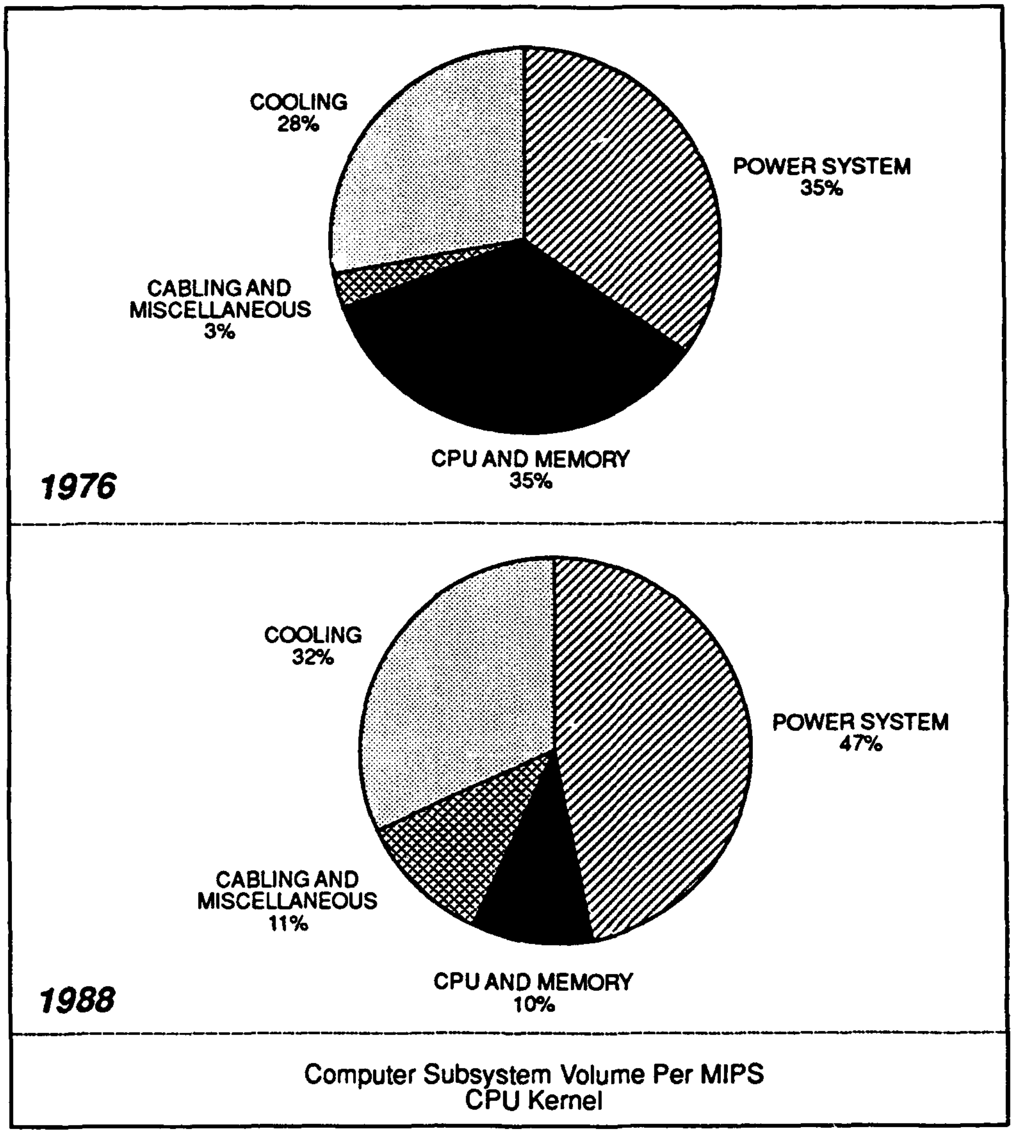

FIGURE 43-6 Actual volume distribution of computer central processing unit (CPU) kernel from 1976 to 1988, for typical commercial systems (Staffiere, 1989).

significant (Furgal, 1988; NRC, 1988a,b, 1989; Sarjeant, 1989; Stevens, 1989; Vitkovitsky, 1988).

Technology Forecast: Transformers

Future Army systems will use compact transformer magnetics for both pulsed and high-frequency applications. For each of the projected requirements in Table 43-6 (above), conventional power system technology is between one and two orders of magnitude too large, in both weight and volume (Burkes, 1978; Estrov and Scott, 1989; Furgal, 1988; Haynes, 1989; NRC, 1988a,b, 1989; Sarjeant, 1989; Sarjeant and Burkes, 1987; Sarjeant and Dollinger, 1989; Stephens, 1989; Vitkovitsky, 1988). Transformers are a major technology element in providing either pulses of energy of submilliseconds duration or (with other topologies) for high-frequency ac voltage transformation. The latter is needed for conventional inverter dc-dc step-up or step-down applications and for single or multiphase ac power to charge the advanced capacitors and feed the bus distribution architecture in multiple, redundant, reliable power sources for the battlefield (Burkes, 1978; EEB, 1988, 1989; Furgal, 1988; NRC, 1988a,b, 1989; Sarjeant, 1989; Sarjeant and Burkes, 1987; Stephens, 1989; Vitkovitsky, 1988).

Magnetics account for between 10 and 20 percent of power system mass and volume at 60 Hz ac. However, moving to inverters that operate at much higher frequency and synthesizing the necessary 60 Hz ac with the increased inverter frequency reduces the magnetics mass until it becomes negligible except at high voltages. With the advent of planar magnetics, hybrid integrated techniques can now be considered for high-power electronics systems, eliminating the bulk of conventional transformer interconnections. Advances in planar capacitor insulation techniques will also enhance reliability in the adverse environment of the battlefield by inhibiting aging processes, particularly at high temperature (Estrov and Scott, 1989; Furgal, 1988; Haynes, 1989; NRC, 1988a, 1898; Sarjeant, 1989; Staffiere, 1989; Vitkovitsky, 1988).

Reducing the weight of transformers by at least a factor of 10 is feasible, paced somewhat by voltage scaling, for both burst and continuous modes of operation (Vitkovitsky, 1988). For very compact systems at higher voltages, vacuum operation (as demonstrated in the Strategic Defense Initiative/Defense Nuclear Agency Space Experiment Aboard Rocket) may well eliminate the massive insulating fluids needed in current practice (NRC, 1989). The Technology Group anticipates that the move to higher frequencies will require the development of new, more stable magnetics and insulating materials that use molecular engineering approaches, like those demonstrated in recently successful capacitor programs (NRC, 1989).

The use of transformers for pulsed charging of large power conditioning systems that contain capacitors or transmission lines is an application that now becomes far more practical with the invention of a new type of megavolt transformer, the Rohwein transformer, at Sandia National Laboratories (Figure 43-7). This new technology is capable of directly powering high-energy systems into the megajoule class, providing the systems designer with opportunities for new types of compact power conditioning in the future (Furgal, 1988; NRC, 1989; Sarjeant, 1989; Vitkovitsky, 1988).

Transformer technology has, in general, demonstrated scalability in power and energy per pulse or cycle, with the major limitations being voltage effects (e.g., corona damage to materials) and a lack of high-efficiency thin magnetic materials for the cores. Hence, manufacturing technology advances are needed in magnetics, types of cores, windings, and close-tolerance fabrication. The combined improvements from development of magnetics with

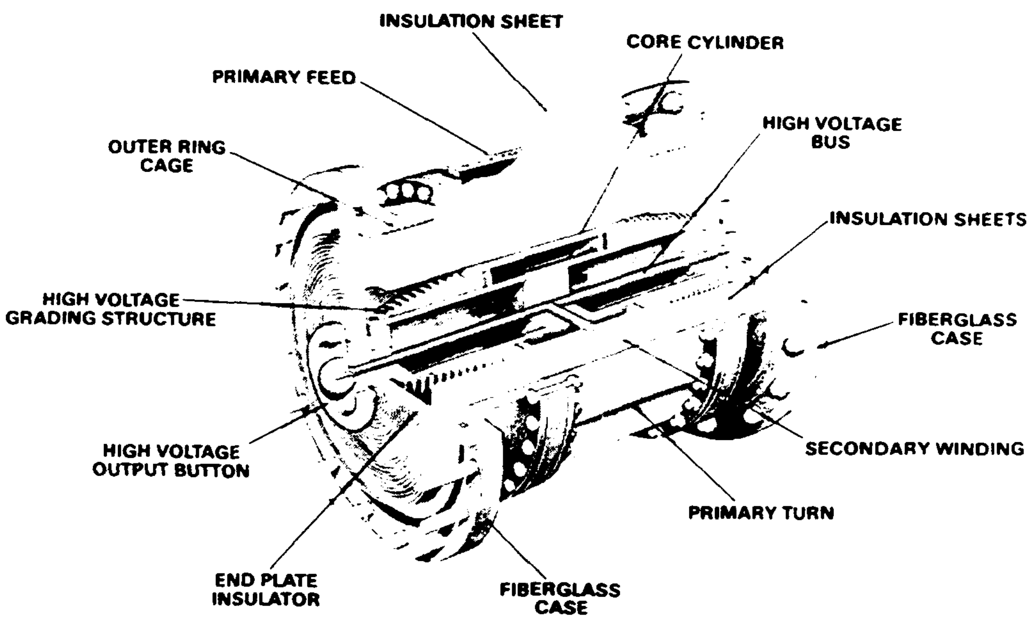

FIGURE 43-7 Prototype of a 1-megavolt transformer. Original photograph courtesy Sandia National Laboratory.

far lower loss (such as the amorphous types), high-stress grading insulation (both bulk and interlaminar) and either vacuum or insulating gases—are expected to reduce transformer masses to a much smaller fraction of the total weight of future advanced systems. Power flow will be enhanced substantially by replacing Litz wire with composites or new winding topologies. This change will reduce power losses substantially and increase efficiencies to well over 95 percent, even in multikilojoule megavolt systems (Furgal, 1988; Haynes, 1989; NRC, 1989; Sarjeant, 1989; Vitkovitsky, 1988). Pulse transformers of the Rohwein type require only a small percentage of their mass in actual magnetic materials, substantially enhancing their power density.

The scaling of all these new technology elements to the range of powers and energies needed in future Army systems, as noted in Table 43-6, is feasible if the process is integrated with a focused materials development program. Because of scalability of transformer technology, the Technology Group believes the most effective program for the Army to undertake is one in which materials development for transformers is integrated with capacitor and inverter programs, while retaining a separate magnetics program in transformers. Voltage scaling is a critical issue that should be addressed on a fundamental basis in such a transformer program (Burkes, 1978; Furgal, 1988; NRC, 1989; Sarjeant, 1989; Vitkovitsky, 1988).

Switches

All systems that control electrical power require the presence of electrical switches and the capability to open or close them. Future advanced Army systems will need power switches with an excess of 100 kWe/kg power flow capability, if the switch volume and mass are to be a negligible portion (less than 1 percent) of the total system mass. The second rationale for developing Army-specific advanced high-power electronics switching is the need for highly reliable switches whose life, prefire, and fault-withstand (nonfusion) energies are well known and scalable, particularly as the average power level of advanced Army systems continues to escalate (Burkes, 1978; Furgal, 1988; NRC, 1988a,b, 1989; Sarjeant, 1989; Sarjeant and Burkes, 1987; Stephens, 1989; Vitkovitsky, 1988).

Switches for continuous duty need to be scalable in repetition rate operability from today's 1–100 Hz up to frequencies greater than 100 kHz for future inverters and for bus power conditioning systems that have power conversion efficiencies near unity. Although diverse types of closing and opening switches demand development, the essential properties of high efficiency (>98 percent), negligible inductances (<1 nH/A), and wide temperature ranges of operation (-55°C through +500°C desirable) drive the overall requirements. These are independent of solid state, gas, magnetic, or liquid. (Burkes, 1978; Furgal, 1988; NRC, 1988a,b, 1989; Sarjeant, 1989; Sarjeant and Burkes, 1987; Stephens, 1989; Vitkovitsky, 1988).

Feasible advances in switch technology are illustrated in Figure 43-8. Current work being funded under the Strategic Defense Initiative will give the systems designer a closing switch capability, for mobile systems, rated for multikilocoulombs, a repetition rate from 1 to 100 Hz, and a range from 0.5 to 20 kV. This unique switching capability may well make possible the first reliable, high-energy mobile systems.

The development of switches, unlike that of other components, has traditionally demanded specific point designs. Future programs will have to address the generalized scaling modeling needed to ensure that switching algorithms for all classes of applications are available to the design engineer. Analysis of the state of the art shows that improvements by factors of 10 to 50 are feasible in the areas of power flow and fault tolerance. Nonetheless, megavolt-class switches will present an extraordinary challenge: achieving specific inductances of under 10 nH/MV at energy densities of greater than 1 kJ/kg at the prefire rates needed in large systems (under 1 part in 10 million). For low-voltage systems in which the switch is used only in an average power mode, such as an inverter switch, the root-mean-square current limits will apply. Modeling the limits of solid-state switches for all power classes is vital to success in this area (NRC, 1988a, 1989; Furgal, 1988; Sarjeant, 1989; Sarjeant and Burkes, 1987; Vitkovitsky, 1988).

Although switching technology has received substantial investment support since World War II, modest progress has been made in the fundamental understanding of the processes limiting high-power switch performance, particularly for ionized media switches and high-charge-flow solid-state switches. The statistics of failure are not substantiated by fundamental scaling models. A tightly focused investment strategy is needed to ensure that intrinsic switch limitations do not become a limiting element on the efficiency or reliability of advanced power conditioning systems. Because the technology base is weak, the development of switch technology has been rather application-specific. Switch development must now be integrated with system scalability demonstrations, to emphasize the fundamental scalability of each of the specific point designs. To date, scalability has been demonstrated only for solid-state switches and the orientation-independent ignitron switches (Burkes, 1978; NRC, 1988a,b, 1989; Furgal, 1988; Sarjeant, 1989; Sarjeant and Burkes, 1987; Stephens, 1989; Vitkovitsky, 1988).

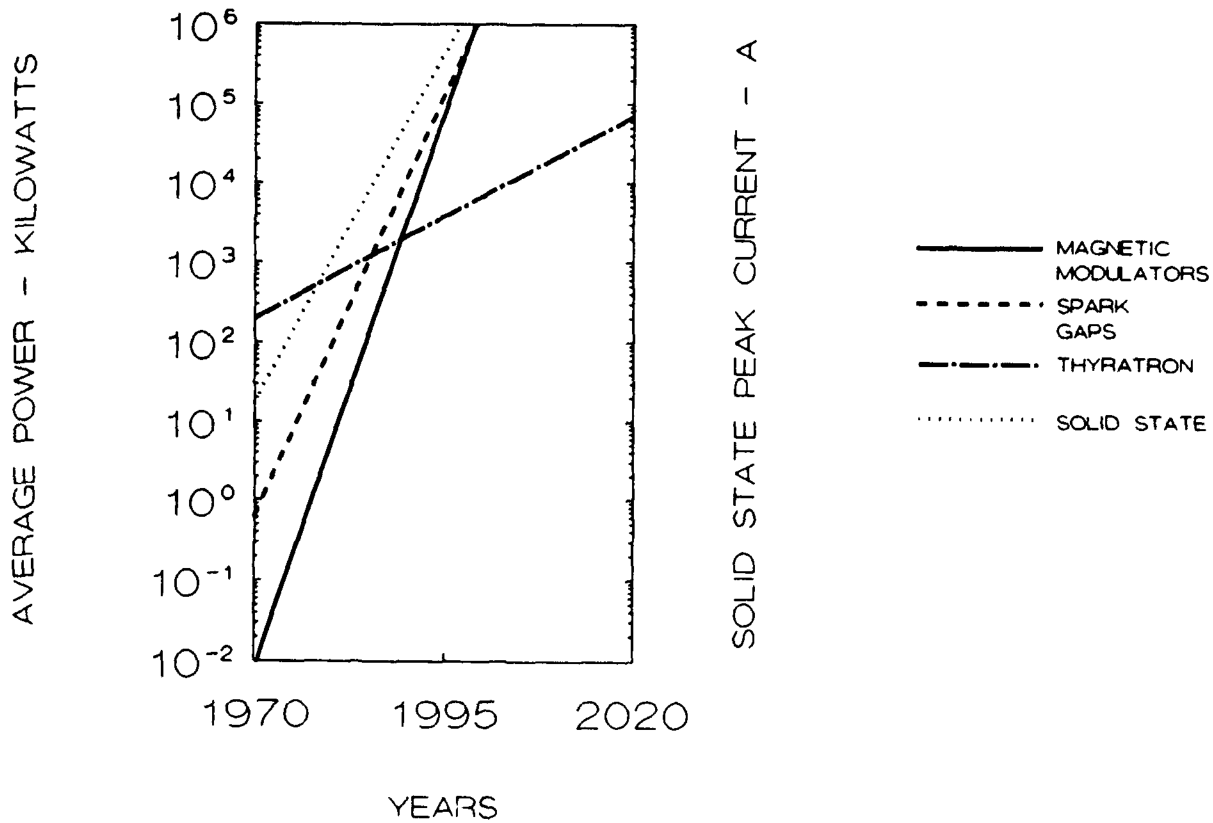

FIGURE 43-8 Technology advances in active and passive switches.

ENERGY STORAGE AND RECOVERY

This section projects future Army battle-zone requirements for energy storage and recovery systems that provide electric power outputs. It describes certain key technologies and forecasts their future progress. This assessment draws substantially from the Energy Engineering Board report, *Mobile Electric Power Technologies for the Army of the Future* (NRC, 1988a).

Battle-Zone Applications

By the year 2020, there will probably be a greater dependence on electric power for vehicle drives as well as for a wide array of battlefield electronics and for new electrically driven weapon systems. The reduction of the signature of power generation units also will become increasingly important in the battle zone of the future. This will increase dependence on compact energy storage systems (chemical or mechanical) in which the stored energy can be rapidly recovered as an electric work output.

The Technology Group believes that technology improvements in low-signature devices such as secondary batteries or flywheels will be necessary to provide useful electric systems for the intense, short-term conflicts expected on the future battlefield. Mobile, hybrid systems, consisting of combinations of internal combustion engines and energy storage devices such as batteries, could be used for both vehicle propulsion and field electric power. Moving into the battle zones, the devices could operate on their internal combustion engines; under battle conditions, they could switch to the low-signature energy storage devices.

Current and Future Characteristics and Assessed Figures of Merit

This section considers nine classes of current or evolving energy storage and electric-power recovery technology that could apply to the Army's future battle-zone needs:

- primary batteries;
- rechargeable batteries;
- hydrogen-based fuel cells;
- fuel cells based on nonhydrogen fuels
- stationary flywheels;
- vehicle flywheels;
- pumped liquids;
- compressed gases; and
- thermal energy storage.

The Technology Group believes that five of these options are particularly attractive for the Army's future needs:

Primary Batteries. Primary, or nonrechargeable, batteries are currently used in a wide range of applications in the Army where very low levels of electric energy (i.e., watt-hours) are required. The older alkaline dry cells are giving way in many applications to lithium cells, such as the lithium–sulfur dioxide cell and the lithium–thionyl chloride cell. Lithium cells with lives of 5 to 10 years are available and will undoubtedly be improved over the next 30 years.

Rechargeable Batteries. The Technology Group forecasts that rechargeable battery systems capable of a large number of charging and discharging cycles will play a much greater role in the Army of the future. A significant part of the future battle-zone electric power requirements during engagements can come from advanced battery systems. Today's lead-acid battery technology needs to be replaced with much more innovative battery systems. A new lithium–organic rechargeable cell appears to have some promise. (A discussion of an advanced rechargeable battery system follows.)

Hydrogen-Based Fuel Cells. These devices electrochemically oxidize or "combust" hydrogen with oxygen (or air) and directly convert chemical energy to electric work. Because they are essentially isothermal devices, not limited by heat engine thermodynamics, they can in principle have very high energy densities (watt-hours per kilogram), limited only by the specific free energy change in converting hydrogen and oxygen to water. The great obstacle to hydrogen-based fuel cells for mobile, battle-zone applications is the volumetric problem of storing hydrogen. Although hydrogen produces a great deal of energy on a weight basis, it produces very little energy on a volume basis, even when stored at high pressure.

Fuel Cells Based on Nonhydrogen Fuels. Today hydrogen is the only fuel that can be electrochemically oxidized in a fuel-cell system at practical rates. The ideal system would directly convert the free energy of combustion of other fuels, such as hydrocarbons, into electric work. Other fuels are used today in prototype fuel-cell systems by either externally or internally reforming them to a mixture of hydrogen and carbon dioxide, then using the hydrogen electrochemically in the fuel cell. A major breakthrough in electrocatalysis in the next 30 years would allow other fuels to be electrochemically oxidized at useful rates.

Stationary and Vehicle Flywheels. Flywheels coupled directly to a variable-speed motor-generator have the potential of compactly storing large amounts of energy and rapidly delivering electric work. The motor-generator would function as a generator when the system was drawing on the energy stored in the flywheel and as a motor when energy was being stored in a flywheel by spinning it up. Of course, for many configurations flywheels could also be spun up mechanically using reciprocating or turboshaft engines. By using advanced composite materials, flywheels that could store as much as an order of magnitude more energy per unit of flywheel mass than can be obtained with flywheels of the best alloy steel.

The remaining four energy storage and recovery concepts do not appear attractive for Army needs in the extended battle zones of the future.

Table 43-10 presents the Technology Group's composite figure-of-merit indices for each of the potentially useful concepts. The selection of certain technology areas for inclusion in this summary report, and in some cases for recommended emphasis by the Army, was based in part on the potential to achieve high future values (4 and 5) in several of the figure-of-merit categories.

The Technology Group believes that two of the energy storage and recovery technologies have broad-based applicability to the needs of a more mobile Army in the future: (1) rechargeable batteries and (2) flywheels. The Group anticipates major improvement in the performance of both technologies over the next 30 years, if properly nurtured by Army R&D programs that focus on the specific requirements of the future Army.

For advanced rechargeable battery systems, the Group forecasts that significant improvements in mobility and supportability will derive from improvements in energy density of the newer batteries by as much as fivefold over state-of-the-art lead–acid systems. A factor of two to three improvement over lead–acid batteries is predicted for power density. To be applicable to the Army's needs, devices in research today must evolve into rugged, fully reliable batteries. It is important that the Army focus its R&D on a few systems, with the objective of developing, at most, a few battery systems that will cover the broad range of future Army needs. Table 43-11 presents some parameters of interest for several rechargeable battery concepts.

Flywheels have the potential for improvement in the figure-of-merit categories for functionality, mobility, supportability, manpower, and cost. Most of the improvement will come from major advances in composite materials with ultrahigh strength/weight ratios. The Technology Group forecasts an increase in energy density by an order of magnitude over high-strength steels. It also believes that the cost of fabricating composite flywheels with optimally tailored structural properties will decline dramatically over the next 30 years, as more and more military and industrial applications are found for composites. Because of its potential to achieve very high specific-energy storage as well as very high specific power, flywheel technology is discussed in more detail below.

TABLE 43-10 Assessed Figures of Merit for Energy Storage/Electric-Power Recovery Systems for Years 2000 and 2020

System Concept	Functionality 2000	Functionality 2020	Mobility 2000	Mobility 2020	Supportability 2000	Supportability 2020	Survivability 2000	Survivability 2020	Manpower 2000	Manpower 2020	Cost 2000	Cost 2020
Primary Batteries	3	3	3	4	4	5	4	5	4	5	2	3
Rechargeable Batteries	3	4	3	5	4	5	3	5	3	5	4	5
Hydrogen-Based Fuel Cells	3	4	2	3	2	3	2	3	3	4	2	3
Fuel Cells Based on non-hydrogen Fuels	1	?	3	4	2	4	2	5	2	5	2	4
Stationary Flywheels	2	5	2	5	2	5	3	4	4	5	3	4
Vehicle Flywheels	2	4	2	5	2	5	2	4	3	5	2	4

NOTE: Index Values: 1 (minimal) thru 5 (excellent).

TABLE 43-11 Performance of State-of-the-Art and Advanced Battery Systems

Battery System	W-h/kg Now (to 2000)	W-h/kg Future (2020)	W/kg Now (to 2000)	W/kg Future (2020)	W-h/liter Now (to 2000)	W-h/liter Future (2020)	$/kWh Now (to 2000)	$/kWh Future (2020)	Problems
State-of-art lead–acid	35	40	110	150	80	100	150	100	Low energy density Fairly high self-discharge
Bipolar lead–acid	38	50	—	79	—	85	-	100	Costs more than conventional lead-acid, low specific power
Na/S	90	120	110	140	140	180	1000	100	Operates at 350°C
Ni/Cd	35	40–50	50-60	80–90	80	90-100	250–300	200	Sensitivity to overcharge
Zn/Air	90	140	100	150	—	—	—	35–45	System weight dominated by electrolyte weight Low energy efficiency
AL–Li/FeS	80	150–200	95	180–220	—	—	High	100	Operates at 400°C

Technology Forecast: Flywheel Systems

Flywheels coupled to variable-speed motor-generators are a class of energy storage technology for electric-power recovery systems that embodies significant advantages in specific power and specific energy for fulfilling Army battle-zone needs by 2020. Figure 43-9 shows one possible configuration taken from an article in *Scientific American* (Post and Post, 1973).

Flywheel systems for high power and energy density would probably be configured as sets of counter-rotating wheels. For a given weight, a solid wheel can store about twice the energy of a rim-wheel design. The wheels would be sealed within a low-pressure compartment (perhaps containing helium at low pressure) to reduce air friction. Damped gimbal mounting would minimize the gyroscopic torques that would otherwise be transmitted to the vehicle.

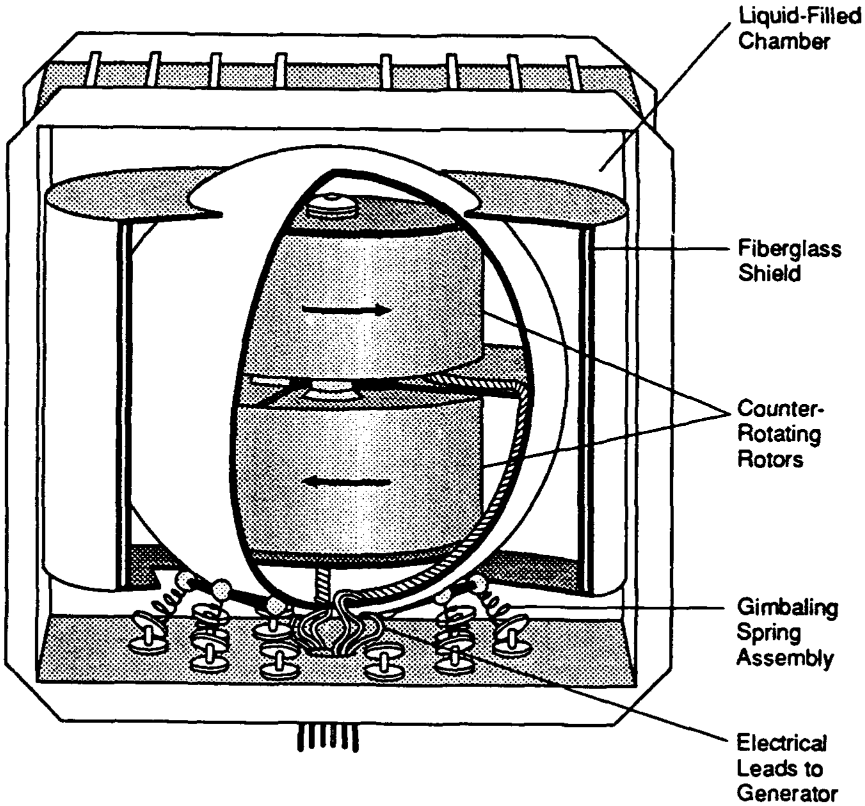

FIGURE 43-9 Conceptual high power density flywheel system. From *Flywheels* by Richard F. Post and Stephen F. Post. Copyright © 1973 by Scientific American, Inc. All rights reserved.

In quantitative terms, the limiting amount of energy that can be theoretically stored in a flywheel of a given weight is proportional to the ultimate tensile strength of the flywheel material divided by its density. Practically realizable values of advanced systems are expected to range from 40 to 60 percent of the theoretical values. Until now, most flywheel systems have been made of steel. However, the higher the specific strength (tensile strength divided by density) of the flywheel material, the greater the energy storage capacity of the flywheel. Composite materials containing ultra-high-strength fibers have specific strengths more than an order of magnitude greater than steels, so they are outstanding candidates for advanced flywheels.

Figure 43-10 compares the theoretical energy storage capabilities of a number of different materials with the energy densities of a lead-acid battery and an advanced battery that is near the limits one might achieve by 2020. The energy storage potential of flywheels made from advanced composite materials could potentially exceed that of the best advanced batteries.

An additional consideration from a systems point of view is that batteries drop off significantly in effective specific energy as the power level is increased. For example the specific energy of lead-acid batteries drops from

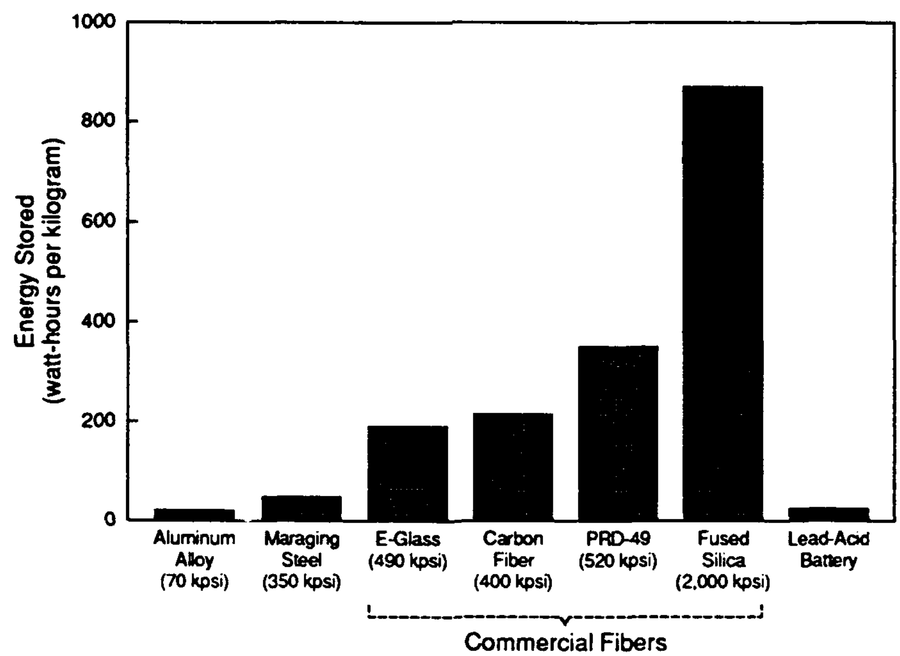

FIGURE 43-10 Storage capacity of flywheels and lead–acid battery.

about 35 W-h/kg at a power drain of 20 W/kg to about 23 W-h/kg at a power output of 80 W/kg. Similarly, the general characteristics of a Li-Al/FeS battery are expected to result in about 75 percent of the specific energy available at 70 W/kg as is available at 20 W/kg: 110 and 150 W-h/kg, respectively. In contrast, energy can be extracted from a flywheel system at very high power levels with no change in total available specific energy. Since the flywheel can also be respun quickly (limited primarily by the maximum power ratings of the coupled generator/motor and the primary engine), these differences in characteristics can significantly expand the operating envelopes of hybrid electric-drive systems that use flywheel storage rather than battery storage.

The key to developing an advanced flywheel system lies in being able to design and engineer composite wheels with the fibers properly oriented in the directions of maximum stresses. The cost of fabricating composite materials with optimally tailored structural properties probably will decrease dramatically over the next several decades; as composites are used in more military and industrial applications. The Technology Group suggests that the Army focus significant development activity on engineering prototypes of flywheel devices that use advanced fibers and resin matrices. For example, one goal might be to design and demonstrate a flywheel system for vehicular use that can store 50 kW-h of energy in a system whose total weight is less than 400 kg (125 W-h/kg). Comparable lead-acid batteries would weigh about 1600 kg.

If composite flywheel technology is nurtured by the Army, the Technology Group forecasts that flywheels could be competitive with advanced batteries for mobile, battle-zone electric power applications. Of particular value might be various types of electric drives for a range of surface vehicles. They would also offer size and weight advantages for a variety of forward-station stationary power-supply applications.

44

High-Power Directed Energy Weapons Technology

The Technology Group divided this topic into two subtopics: (1) high-power lasers and (2) high-power radio frequency (RF), millimeter-wave, and microwave controlled-burst and coherent directed beams. A number of technology elements in each subtopic were surveyed for potential value to the Army in the future. Those elements selected are shown in Table 44-1.

TABLE 44-1 High-Power Directed Energy Technology Elements

High-Energy Lasers	High-Power RF, Microwave, and Millimeter-Wave Beams
Gas dynamic lasers	Very high frequency - warhead
Chemical (direct) lasers	Ultrahigh frequency - warhead
Excimer lasers	High-power microwave - warhead
Free-electron lasers	Millimeter-wave - warhead
Ionic solid-state laser arrays	Phased beams (klystron), 3–15 GHz
Coherent diode-laser arrays	Phased beams (gyrotron), 15–50 GHz
Explosively driven lasers	Phased electron amplifier, 50–300 GHz
Nuclear-driven lasers	Electro-optical burst generators

The Army's Strategic Defense Command presently has implementing responsibilities for ground-based strategic defense against ICBMs (intercontinental ballistic missiles), SLBMs (submarine-launched ballistic missiles), and other long-range missiles directed at ground-based targets. The technology development of high-power directed energy weapons (DEW) for these strategic-defense missions is currently coordinated and funded through the SDIO (Strategic Defense Initiative Organization). There also are a number of DEW concepts that could provide significant force projection capabilities in various future battle-zone scenarios. If the Army is to become and stay pre-eminent in the world in the exploitation of these fundamentally new methods of projecting force in the battle zone, it will need to provide significant resources and direct management attention to the innovative evolution of these weapon concepts and their underlying or enabling technologies. This Army attention is important both to the timely development of fieldable directed-energy offensive weapons and to the assessment of design criteria for protection of Army assets against hostile DEW threats of all types.

In support of the STAR systems panels, the Technology Group chose to provide detailed technology forecast assessment for five DEW technologies believed to have applicability to future battle-zone operations:

- coherent solid-state ionic laser arrays;
- coherent solid-state diode-laser arrays;
- phase conjugation for high-power and medium-power laser optical systems;
- high-power millimeter-wave beam generator-projectors; and
- high-power microwave beam generator-projectors.

This selection does not mean that all other concepts such as chemical lasers were assessed negatively for Army applications. Several types of chemical lasers are applicable in either a primary or an underlay mode to defense against strategic and tactical ballistic missiles and cruise-type missiles. These lasers are expected to evolve under SDIO sponsorship with the close participation of the Army's Strategic Defense Command. Some of the other DEW technologies in Table 44-1 do not appear reasonable for battle-zone use. Certain other directed-beam technologies and concepts have not been included for reasons of security classification.

HIGH-POWER LASERS

Potential Battle-Zone Applications

The function of DEWs on the battlefield has been defined by the Joint Chiefs of Staff as the "disruption, deception, upset, and/or destruction" of enemy systems (JCS, 1984). This section summarizes high-power laser technologies applicable to the Army's strategic defense mission and to the disruption or destruction of portions of enemy assets in the future battle zone. One objective of the Group's technology support to the STAR systems panels was to forecast technology progress that could support weapons introduction by 2020. A primary attribute of high-power lasers is their ability to deliver threat-negation energies propagated at the speed of light, with the capability for rapid retargeting against multiple threats. They also can be supplied with a large equivalent magazine capacity (i.e., 50 to 100 energy bursts of 1- to 3-second duration) at a quite low cost per round (i.e., propellant costs).

Laser weapon systems typically consist of three key functional subsystems: (1) the high-power laser, which generates a coherent beam of light; (2) the pointer-tracker, which stabilizes and controls the beam for placement on the target; and (3) fire control, which initially acquires the target, performs battle management, and provides executive control of the overall weapon system. Typically there is also a platform subsystem, depending upon system basing and appropriate support equipment subsystems. Several potential Army applications for high-energy lasers are summarized below.

Antisensor or Antipersonnel Missions

Battles in 2020 will be fought with a broad range of sophisticated sensors. The Army is already addressing this prospect by using low-power lasers to develop countermeasure techniques in the optical domain similar to those employed in electronic warfare. As the threat becomes more sophisticated and hardened against spoofing and jamming countermeasures, the power requirement must be increased. Hence, there may be a need to develop moderate-power laser systems with sources capable of crazing and destroying the optics, detectors, and other elements of the sensor function. Such systems require moderate power sources that may be either in or out of the operating wavelength band of the threat sensor, depending on the type of damage physics involved. They also must be capable of being packaged with the appropriate beam and fire-control functions on small mobile platforms operating at or near the forward line of troops.

Battle-Zone Air Defense

High-power lasers (0.3 to 1.0 MW) can have unique capabilities for defending high-value assets from current air threats and those expected to exist in 2020. As the ability of an enemy to stand off and launch a coordinated, multiple-missile attack becomes more plausible, it will become essential for the Army to have a cost-effective air defense weapon that will not be saturated easily by such a threat. In such a close-in, ground-based defense application, the laser weapon only needs to be effective at ranges out to 10 km, with most engagements occurring at 1 to 5 km. The average laser power requirement is about an order of magnitude less than for the ASAT (antisatellite) mission. For high-power lasers to be practical in this role, the systems should be engineered to a weight and volume that will permit transportability and, in some cases, even high mobility. Such a system, ideally, also would have a magazine capacity (propellant supply) large enough to allow it to be logistically maintained without radical change to Army operational procedures.

Ground-Based Ballistic Missile Defense

The most effective time for high-power lasers to perform strategic ballistic missile defense is during the boost phase, before re-entry vehicles and decoys are dispersed, and when the threat missile is reasonably vulnerable to optothermal or optomechanical kill effects. The Army's Strategic Defense Command plans to have a *ground-based* high-power laser that will direct its kill energy on the ballistic missile via space-based relay mirrors, after appropriate compensation has been made for beam distortion caused by the earth's atmosphere. For this application, lasers with *very* high power are necessary to deliver sufficient kill energy in a short time over a long range. Wavelength selection is important for minimizing beam dispersion.

Antisatellite

In many potential war scenarios, the Army may wish to engage hostile satellites directly from the ground in the battle zone. Because of softer targets and shorter propagation for low and medium earth-orbit satellites, the power requirement can be an order of magnitude less than for ballistic missile defense. Geosynchronous satellites may require power levels as high as for ballistic missile defense. Adaptive optics will be required to maximize brightness and atmospheric propagation.

Current and Near-Term (to 10 Years) Characteristics

Of the eight types of laser-generating elements listed in Table 44-1, only four appear to be of potential interest for Army applications. These four technologies are listed in Table 44-2, along with four beam control subsystems that also have high-leverage potential for Army applications.

Chemical Lasers

Chemical, or direct reaction, lasers create a population inversion and lasing of an excited-state species directly from the chemical reaction of two or more reactant species. The most highly developed chemical laser technology involves hydrogen fluoride (HF) or deuterium fluoride (DF) lasers. These lasers have operated efficiently over the range from several watts to several megawatts of continuous power. HF lasers operate at multiple spectral lines located nominally at 2.7 μm. DF lasers operate at multiple spectral lines located nominally at 3.8 μm. Oxygen-iodine chemical lasers are atomic lasers that operate on the transfer of energy from excited oxygen, produced by a

TABLE 44-2 High-Energy Laser Technologies with High-Leverage Potential

Laser Beam Generators	Beam Control
Direct-Reaction Chemical wavelengths, from 0.5 to 3.8 μm	Beam Transfer Adaptive optics
Free-Electron Superconducting RF MOPA 0.5 to 1.5 μm, 0.5 to 10 MW Induction linear accelerator 0.5 to 1.5 μm, 2 to 200 MW	Beam Combining Adaptive Phase conjugated Beam Projection Segmented mirrors Phase conjugated
Solid-State Ionic Coherent phased array	Coherent Arrays
Solid-State Diode Coherent phased array	Pointer-Trackers Active Phase conjugated

chemical reaction, to atomic iodine, which lases at 1.3 μm. This shorter wavelength has advantages for long-range beam projection by reducing the projecting optic diameter.

One advantage of chemical laser systems over high-power electric-power lasers such as a free-electron laser (FEL) is their mobility, which is due to the absence of requirements for large electrical power and beam generation hardware. Their major disadvantage in battle-zone operation is the need to operate the laser cavity at low pressure (20–50 torr), which necessitates an active pressure recovery system. In ongoing technology development projects, pressure recovery is usually done with steam ejectors. For weapon systems in the field, the ejection system would be an array of short-length diffuser-ejectors driven by water-diluted gas turbine engines. The Army has successfully demonstrated the use of solid-matrix cartridge-type exhaust canisters to absorb the laser exhaust gases completely. For pulsed mode, the chemical laser cavity can be operated at about 1 atm, so pumping may not be necessary.

Free-Electron Lasers

The FEL is an electrically powered laser that extracts light energy from a beam of free electrons as they pass at relativistic velocity through a spatially periodic magnetic field. The interaction of the electronic beam with the magnetic field produces synchrotron radiation, which can then be developed into a laser beam of coherent light by the introduction of an appropriate optical system. The wavelength can be varied by changing the energy of the electron beam and the period of the magnetic field; this wavelength tunability is an enormous asset for the FEL. Two types of FEL are being developed today. One uses electron-beam accelerators driven by RF radiation. The other uses magnetic induction for electron-beam acceleration. FELs are primarily of interest for defense against strategic ballistic missiles; they do not appear practical for any battle-zone mobile tactical applications (i.e., mobile hard-kill weapons).

Ionic Solid-State Lasers

The operation of an ionic solid-state laser is based on the excitation of ions that are doped into either a crystalline or a glass host material. The source of excitation is either a flashlamp or incoherent diode-laser arrays. The output of this type of laser is in the form of high-peak-power pulses. With a glass host, these lasers can operate at low repetition and high power; with a crystalline host at high repetition and low power. At their current state of development, these lasers can reach efficiencies of 2 to 5 percent with flashlamp pumping and 10 to 15 percent with incoherent diode-laser pumping. Major issues being addressed include current laser weights (1 to 2 lbs/W of average power) and flashlamp operating lifetimes (10^8 to 10^{10} pulses). Of course, the use of diode pumping eliminates the issue of flashlamp operating life. Ionic lasers that operate at 1.06 μm and 1.3 μm are being developed by several government agencies for various applications requiring low to moderate average power.

Solid State Coherent Diode-Laser Arrays

The lasing wavelength of these devices is determined by a current-induced bandgap transition in a semiconductor. They are essentially continuous-wave devices with no energy storage capability. Power levels of the output beam of 10 to 1000 W, at intensities of up to 1 kW/cm^2 at the generator face, should be achievable in the next 5 to 10 years at efficiencies of 30 to 50 percent. The laser wavelength is tunable over a limited range by adjusting the composition and temperature of the semiconductor. Three technology issues with this laser are (1) phase locking large numbers of diodes (hundreds or even thousands) into a coherent module array, (2) removing the waste heat from the high-power-density operation of such modules, and (3) the coherent combining of modules into high-power arrays. This type of laser technology is being developed in a number of separate projects by both the Army and the Air Force.

Future Characteristics and Figures of Merit

The Technology Group is convinced that the four types of lasers described above could each be developed until they achieve the performance levels needed for various types of potential Army applications. Table 44-3 presents the indices assigned to each of these four laser systems with regard to the six figures of merit the group used as a guide for technology focus. However, the selection of certain technology areas for inclusion in this report—and in some cases for recommendation to the Army for special attention—was not done by arithmetically adding up the six indices nor by any specific "weighted" summation. Rather, the Group used a realistic assessment of the potential to achieve high future values (4 and 5) in several of the figures of merit as one important factor in arriving at an overall judgment.

Advanced Chemical Lasers

Significant effort is under way on the technology of short-wavelength chemical lasers operating in the visible or ultraviolet region. Several technology approaches to achieving this goal are being investigated. One near-term short-wavelength chemical laser being investigated by the U.S. Army Missile Command operates on the HF overtone lines. Another research approach, by the Air Force, uses oxygen and iodine. For continuous-wave DF lasers, work is in progress on solid fuels and solid fluorinated compounds as cartridge-fed reactants. These might be combined with exhaust-absorber cartridges or advanced diffuser/ejectors.

It is noteworthy that the nation's chemical laser technology over the past 10 to 15 years has been guided mainly by mission visions that demanded long-range engagements. In the case of the HF laser for space-based systems, the engagement range was on the order of a thousand kilometers. For ground-based tactical use, keep-out kill ranges of 10 to 20 km were needed to defend against nuclear warheads. Therefore atmospheric propagation, beam wavelength, mirror diameters, adaptive optics, and so on, were all considered crucial. If one instead considers defense of high-value targets against nonnuclear air or missile threats, the kill range can be as close as 500 m, as long as penetration of the incoming threat to its intended target is prevented.

This alternative thinking may change perceptions about the potential functional capabilities and cost-effectiveness of chemical lasers in the battle zone. For an "assured-kill" underlay to a system architecture for tactical ballistic missile defense and for terminal defense against all types of airborne

TABLE 44-3 Assessed Figures of Merit for High-Power Lasers for Years 2000 and 2020

System Concept	Figures of Merit											
	Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Chemical	3	4	3	4	2	3	2	4	1	3	2	3
Free Electron	3	4	1	2	2	3	2	2	2	2	1	2
Ionic Solid State Coherent Arrays	4	5	4	5	3	4	3	4	3	4	2	4
Solid State Coherent Diode Arrays	2	4	4	5	2	5	3	5	3	4	2	4

NOTE: Index Values: 1 (minimal) thru 5 (excellent).

threats, the technology requirements look quite different. The problems of blooming, turbulence, intensity on target for reasonably small beam directors, and so on, are no longer controlling. One does not need to demand very short wavelengths, perfect optics, and multimegawatt power levels. The technology that has evolved for DF lasers over the past 20 years could be quite adequate for underlay and terminal-defense tasks in a total defense architecture. Such lasers can produce output powers of 200–800 kW with 1.6X diffraction-limited beams. Used with 1-meter, or smaller mirrors, these DF lasers are fully capable of fast kills on all types of aircraft. They would be especially effective against fast, highly maneuverable end-game missile targets.

Advanced Free-Electron Lasers

Because of its work in the Ground-Based FEL Program of the SDI/U.S. Army Strategic Defense Command, the Army is the government agency most involved in the development of FEL technology. Continued advances in nonlinear optics could greatly reduce the size, cost, and complexity of beam director systems for RF superconducting FELs. Advanced resonator concepts may permit size reduction and improved performance. New approaches for coating copper cavities with superconducting compounds could permit cost reductions for superconducting RF FELs, as well as improved reliability. The forecast use of FELs will be for ground-based defense against ballistic missiles or for ASAT missions.

Technology forecasts are provided below for two of the above laser technologies, which could have unique roles on the tactical battlefield: coherent diode-laser arrays and ionic solid-state lasers. Another area of technology related to beam control and projection—that of phase conjugation—could also have a major influence on the ability to field cost-effective high-power lasers as battlefield weapon systems. Therefore, a brief technology forecast is also provided for this technology.

Technology Forecast Assessments

Coherent Diode-Laser Arrays

A successful approach to producing coherent coupling of small diode lasers into 10-W to perhaps 100-W modules and the coherent combining of these modules into arrays has a realistic potential to achieve output powers in the multikilowatt class over the next 20 years. Coherent diode arrays having useful beam powers from 1 watt to the kilowatt region can enable small LADAR transmitters, imagers, pointer-tracker illuminators, rangefinders, secure communication transmitters, and IFFN devices (identification of friend, foe, or neutral). Advanced thermal management concepts now being explored could permit coherent laser source intensities approaching 1 kW/cm^2. With the development of new materials using the various rapidly improving solid-state technologies, output wavelengths could span the spectral range from mid-infrared (2–3 μm) to the blue visible. The potential usable beam efficiencies of advanced diode-laser systems can be forecast to improve for multiple-array modules from the 20 percent value already demonstrated to values close to 50 percent. Large phase-locked arrays of these continuous-mode diode modules are projected to reach useful beam efficiencies ranging from 20 percent to 30 percent for output at the multikilowatt level.

The Air Force's Phillips Laboratory is funding a set of programs at several contractors to pursue diode laser design, fabrication, phase locking, and heat removal technologies. Several methods of coherent coupling are being pursued, including injection locking, oscillator/amplifier external optical cavities, and the Talbot effect. Some of these coupling approaches are cumbersome because they require wavefront sensing and an exceptional number of electonic controls. A simple, robust, all-passive optical coupling method, perhaps using binary or diffractive optics, needs to be developed. Coherent array modules with an average power of tens of watts, at source intensities of hundreds of watts per square centimeter, are expected in the next few years.

The current emphasis in diode-laser research is on devices that employ the GaAs/GaA1As multiple quantum well. These devices produce beam radiation in the region from 750 to 850 nm. Research is being carried out on other semiconductor materials that operate in the near-infrared to mid-infrared range and the visible spectral range. While a major effort is needed to achieve scalable output in these spectral regions, the technology regarding coherent coupling and packaging is expected to be directly applicable to other wavelengths. Figure 44-1 illustrates recent progress and projected evolution of diode-array power and waste heat removal. The wallplug efficiency for different types of incoherent arrays for ionic laser pumping are shown in Figure 44-2. ("Wall plug efficiency" is the ratio of energy in the output laser beam to the "total system" energy needed to run the laser, as opposed to the conversion efficiency, which is the ratio of output beam energy to laser excitation energy.)

Both the absolute beam power level and the source output intensity of diode laser arrays will be limited by the technology for removal of waste heat. To scale arrays to power levels in the kilowatt class with source intensities of hundreds of watts per square centimeter, it will be necessary to remove a heat load that, assuming a laser output efficiency of 50 percent, equals the laser output. For larger coherent arrays, this heat rejection load could be two times the gross power level. Analysis indicates that microchannel cooling can

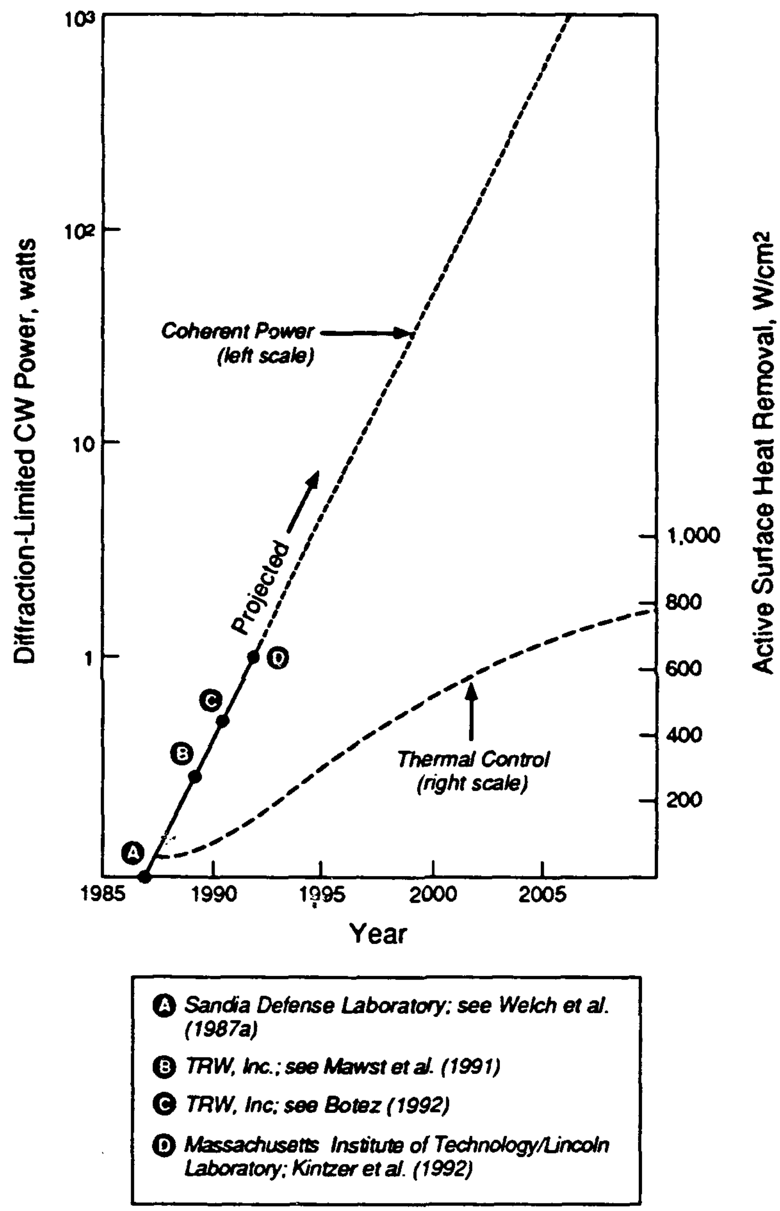

FIGURE 44-1 Recent progress and predicted advances in coherent power and thermal control of monolithic diode lasers.

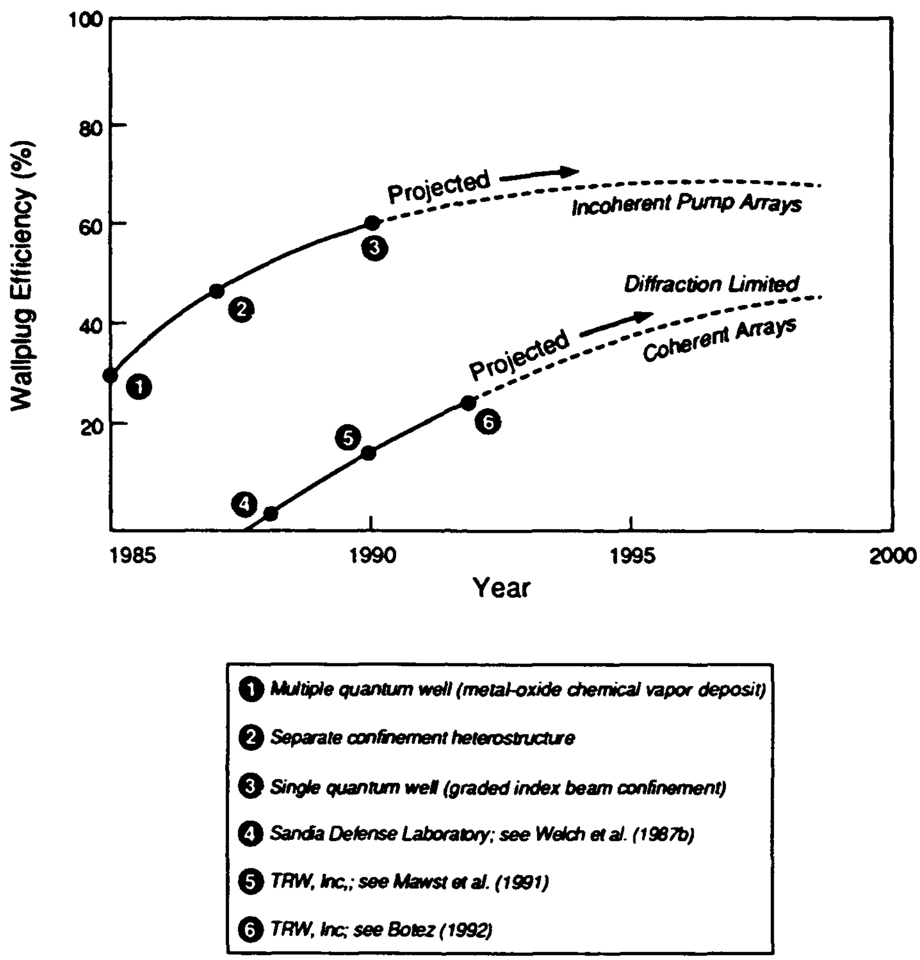

FIGURE 44-2 Wallplug efficiency has exceeded 60 percent for incoherent diode arrays at room temperature; coherent arrays have reached 25 percent.

provide the required capability. The Technology Group believes that this cooling technology has promise as a solution for midpower diode lasers and should be supported by the Army.

The continuous output power (P) of monolithic diode-laser wafer arrays scales as:

$$P = q \cdot Au/(1 - u),$$

where q is the rate at which heat is removed from the array in watts per cm^2, A is the area of the wafer, and u is the device efficiency. Projected advances in each of these quantities for the next several years are shown in Figure 44-1.

Ionic Solid-State Lasers

Solid-state pulsed lasers of low average power (1–50 W) are currently flashlamp pumped and are used for rangefinders, target designators, remote sensing, and communication applications. Solid-state lasers of midpower level could be used for long-range optical countermeasures, mine detection, and IFFN. Even high-power coherent coupled arrays appear possible; perhaps with average powers as high as 1 MW. These lasers could perform hard kills of many kinds of targets at ranges up to 10 km. Because solid-state lasers enable a growing range of battle-zone functions, the Army would benefit by supporting an effort that integrated the resources of multiple government agencies toward this technology.

The use of incoherent diode arrays to pump ionic solid-state lasers is projected to provide large cost reductions over flashlamp pumping and may attain wallplug efficiencies of up to perhaps 30 percent. Tunability from the mid-infrared to the violet region may be achievable with development of new materials and diode pumps. Such lasers may be capable of reaching several kilowatts of average power from a single amplifier. The Air Force is currently investing in midpower technology with near-term goals of 10 J per pulse at 100 Hz (1 kW average power). In the very long term, one can envision coherently coupled large arrays of diode-pumped ionic laser modules approaching a megawatt of output power. In the future, the specific power of solid-state lasers can be improved from poor values of less than 2 W/kg to 10–20 W/kg, as a result of projected improvements in amplifier efficiency, advanced power supply, and new thermal management techniques for the diode arrays.

Crystal Lasers. Currently, crystal ionic solid-state lasers that are hardened for military applications can provide an average power of approximately 20 watts (0.5 to 1.0 J at laser pulse repetition rates of 20 to 30 Hz). Breadboard devices have been scaled up to the 50–70-W range. Present devices are flashlamp pumped. They usually employ neodymium yttrium as the gain medium and provide output at 1.064 μm. Some wavelength agility can be achieved through the use of a high-pressure Raman cell containing hydrogen, deuterium, methane, or other gases that provide output at discretely shifted wavelengths.

The replacement of flashlamps with diode-laser arrays can greatly enhance performance and life. Several agencies are working to develop this technology (Department of Energy, Lawrence Livermore National Laboratory; U.S. Navy, Naval Research Laboratory; U.S. Air Force, Wright Laboratory and Phillips Laboratory; and U.S. Army, Night Vision Laboratory). Efficiencies at the fundamental wavelength of greater than 10 percent have been achieved. Diode pumping reduces the thermal load, thus making it possible to scale average powers (by means of higher repetition rates) by a factor of approximately four for a given gain medium size. Diode arrays improve reliability because they degrade gradually rather than catastrophically. In addition, pumping with a diode-laser array increases the lifetime of the ionic solid-state laser to about 10^{10} shots from the 10^7 to 10^8 shots typical of flashlamp-pumped lasers. The cost of diode arrays is a critical issue for Army applications; a diode array for a 20-watt laser now costs more than $1 million. However, advances in solid-state technology are rapid; production costs for diode arrays are likely to decline dramatically in the future.

The efficiency of a flashlamp-pumped crystal laser can be improved to about 5 percent through the use of Nd,Cr:GSGG (gadolinium scandium gallium garnet crystal, doped with neodymium and chromium), a material that absorbs flashlamp light more efficiently than yttrium aluminum garnet crystal (YAG). However, the benefits of this approach will be short term if one assumes rapid development of diode-laser arrays as a pumping alternative.

New solid-state laser materials are being developed to provide enhanced wavelength agility. Titanium-doped sapphire (Ti:sapphire) and chromium-doped alexandrite (Cr:alexandrite) provide continuously tunable output in the ranges of 700–1000 and 650–800 nm, respectively. Frequency doubling then provides continuous operation in the regions of 350–500 nm and 325–400 nm. Reasonable scaling has been achieved: 2 J for Ti:sapphire and about 4 J for Cr:alexandrite. However, because of its short radiative lifetime, Ti:sapphire is best pumped by a doubled Nd:YAG laser rather than by flashlamps or diodes. The result is a complex, low-efficiency device. Cr:alexandrite is difficult to extract efficiently because of a low damage threshold, which leads to low efficiency. Also, this material must be pumped at 600 nm, so a major effort in diode-laser development would be needed before flashlamps could be replaced as pumps for Cr:alexandrite.

Novel materials based on various rare-earth dopants are being developed for operation in the mid-infrared spectrum. Output pulse levels of 1 J at 2 to 4 percent overall efficiency have been achieved at micrometer wavelengths; tunable output from 1.8 to 2.1 μm has been demonstrated, and the materials are compatible with diode pumping. Much more work is needed to achieve tunability within the 2–5 μm window for atmospheric transmission. Development of nonlinear crystals with output in these regions will need to continue.

Glass Lasers. Pulse energy scaling can be achieved by using glass as the host of neodymium (Nd:glass). In a single device, it is possible to achieve 100 J of output energy per pulse at a repetition rate of 1 Hz or 10 J per pulse at 20 Hz. Glass lasers are attractive as a robust countermeasure source, but their efficiency (2 to 4 percent) and bulk may limit their applicability for tactical situations. Because the quantity of diode arrays needed for pumping is proportional to the energy, it is not currently practical to pump scaled Nd:glass lasers with diode-laser arrays. However, if the cost of incoherent diode arrays can be reduced by a factor of 50 to 100 over the next decade, as expected, the applicability of diode-pumped Nd:glass lasers would be greatly enhanced.

Technology Areas for High-Leverage Improvement of Ionic Solid-State Lasers. Affordable diode-laser arrays for pumping are a critical technology need. As noted above, a cost reduction for diode lasers by a factor of 10 to 100 would make ionic solid-state lasers acceptable for tactical applications. This reduction could be achieved if demand is high and an intense, highly automated fabrication effort is undertaken. Current "rack-and-stack" diode laser technology is constrained by costly labor-intensive steps. Monolithic diode-array technology is at present less mature, but it will eventually reduce costs to one-half or one-fourth the cost of the rack-and-stack approach. Therefore, monolithic array development should be given high priority. The development of host materials that are more compatible with diode pumping than Nd:YAG can also lead to reduced costs. Research should be directed toward developing materials with broad absorption lines and good thermo-optical and mechanical properties. Compact power conditioning, at high efficiencies, will need development.

Several optical extraction techniques also hold promise. Nonlinear optical phase conjugation has been applied to solid-state lasers to achieve excellent quality with relaxed tolerances. It also has been used to achieve higher output power by coherently combining multiple apertures. This technology is essential to further relax optical and mechanical tolerances and to reduce device size. This is particularly critical for scaled Nd:glass lasers. Target coupling at reduced powers may also be possible through the use of phase conjugation. Continued research in this area will have a high payoff.

The Technology Group also strongly recommends the development of tunable solid-state laser materials, including rare-earth-doped crystals for the mid-infrared region and laser materials that provide broad coverage of the visible region. Co-doped crystals, in which one ion absorbs energy and transfers it to another ion that lases, appear to be a fruitful approach. Materials that are particularly suitable for diode pumping should be emphasized. The scaling of crystal sizes and reduction of absorption losses at lasing wavelengths should be addressed. Work should continue on the development of nonlinear optical crystals that provide wavelength agility and that are used as q-switches.

Future Status Projection. Crystalline lasers are likely to scale up to an average power of more than 500 W per aperture (1 to 4 J at repetition rates of 200 to 500 Hz). Glass lasers are expected to achieve output of more than 1 kJ at low repetition rates (1 to 3 Hz). Coherent coupling of amplifiers should permit scaling to outputs that are 10 to 30 times these preamplified levels. Diode-laser-array pumps and improved materials can give efficiencies of 10 to 20 percent. If a major development effort for diode-laser arrays is undertaken and demand is high, it is reasonable to expect diode-laser-array costs to decline by more than a factor of 100, making ionic solid-state lasers ideally suited for tactical directed-energy applications.

Phase Conjugation for High-Power Lasers. Phase conjugation is an important new nonlinear optical process in which the two-dimensional phase contour of an incident optical wave can be accurately reversed (and possibly also retroreflected). Phase conjugation permits the correction in real time of optical aberrations and angular jitter for dynamic systems. It generally has a much faster time response and is simpler to integrate into existing systems than conventional adaptive optical systems. Phase conjugation can be used in a high-power laser system for beam cleanup, beam combination, and array phasing. A schematic diagram of the phase conjugation process is shown in Figure 44-3.

Phase conjugation has remarkable capabilities for correcting dynamic optical aberrations, angular jitter, and atmospheric effects. It can also be used for beam combination and array phasing. These capabilities have been demonstrated for pulsed excimer lasers, continuous-wave hydrogen fluoride/deuterium fluoride chemical lasers, pulsed solid-state lasers, pulsed and continuous-wave carbon dioxide lasers, and continuous-wave visible-light lasers. The successful achievement of phase conjugation has powerful leverage on optical systems engineering. Phase conjugation requires matching the characteristics of a laser device with the capabilities of the two major phase conjugation processes—*four-wave mixing* (FWM) and *stimulated Brillouin scattering* (SBS)—as follows:

1. For low-power, continuous-wave lasers, FWM is the method of choice. FWM does not require that the uncorrected laser beam be highly focused into the nonlinear medium.
2. For high-power lasers, the simplicity of the phase conjugation geometry of SBS makes it the preferred approach. In SBS the uncorrected laser beam is focused down into an appropriate nonlinear medium having adequate SBS optical gain. Phase conjugation is then exhibited in the resulting retrodirected beam. Very high laser power levels are necessary to achieve effective SBS phase conjugation. Thresholds, multifoci SBS cells, backseeding,

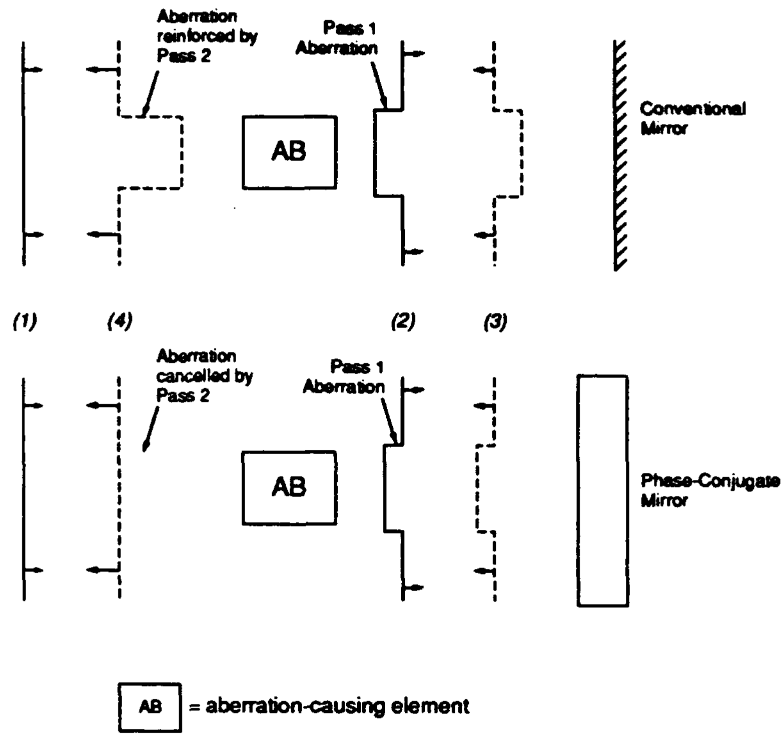

FIGURE 44-3 Schematic diagram of the phase conjugation process.

bandwidth effects, and so on, have been investigated successfully, both experimentally and theoretically.

3. For moderate-power pulsed and continuous-wave lasers, both FWM and SBS phase conjugation have been demonstrated.

The integration of phase conjugation systems into new and existing laser systems offers great promise for drastically reducing the cost and complexity of moderate-power and high-power laser systems. The cost will be lower because of the reduced optical accuracies required. The system will be less complex because adaptive-optics elements or other conventional aberration-correction systems can be eliminated. In many cases, the phase conjugation cell can be directly installed in a laser system by replacing an existing optical element (such as a high-reflectivity cavity mirror). In other cases, some modification may be necessary to realize the full advantages of the phase conjugation technology.

The successful application of phase conjugation to ground-based lasers will permit the correction of atmospheric aberrations, resulting in major increases in laser radiance. In some cases, the factorable characteristics of phase conjugation can be enhanced significantly if applied in concert with other nonlinear optical processes, such as stimulated Raman scattering or harmonic conversion. In applications that require a large increase in laser output power, the remarkable beam-combining capabilities of phase conjugation technology can be applied. The implementation of the beam-combining/array-phasing capabilities of phase conjugation in an N × N semiconductor diode array will permit an N^2 increase in the laser power delivered to a distant target. This advance will permit semiconductor diode lasers to be considered for some high-power laser applications.

Future weapon requirements may greatly exceed the power capabilities of individual laser modules. Increasing the size and weight of current laser modules may become impractical. Advanced phase conjugation techniques may therefore permit the construction of directed energy devices that would be impossible with conventional optical technologies. For example, ultralightweight optical elements with large dimensions (tens of meters) can be erected in space; their relatively large static optical errors can be corrected by phase conjugation to yield nearly diffraction-limited performance.

Novel advanced concepts in phase conjugation include optical countermeasure systems that are able to induce a phase conjugation process in a hostile target optical system, leading to its destruction. Phase conjugation cells capable of automatically tracking targets and pointing directed energy beams for both optical countermeasure and laser force projection could be well developed by 2020. New nonlinear materials will permit large-aperture phase conjugation systems and will make possible order-of-magnitude increases in projected beam intensities on target. The combination of modules into coherent beams by phase conjugation optics may permit hitherto unattainable power and beam quality to be achieved at reasonable cost. The result will be simpler, multiple-laser configurations that are redundant and modular without being complex.

RADIO-FREQUENCY, HIGH-POWER MICROWAVE, AND MILLIMETER-WAVE WEAPONS

This section describes potential Army battle-zone applications for RF, high-power microwave (HPM), and millimeter-wave directed energy technologies. Force projection systems that employ these technologies could enhance the Army's force structure and provide opportunities for new operational modes. Key technologies that would enable these future Army capabilities are identified.

Battle-Zone Applications

The battle zone of the future will be changed significantly by the rapid emergence of advanced sensors, smart weapons, and autonomous systems based on advanced electronics technology. Coupled with this change, however, will be a significant development in countermeasures to these advanced systems. Protection may come from the use of high-power directed-energy combat systems whose purpose is to permanently deny the use of sensors, electronic communication, and other electronically controlled assets by a hostile force. These asset controls will operate over a broad range of approximately 100 MHz to 300 GHz. Although conventional electronic warfare systems operate over a similar range, these high-power electromagnetic-pulse weapon systems can be distinguished from conventional systems by the extent and mode of their action. By severe upset or permanent physical damage to the electronic elements in hostile systems, the electromagnetic-pulse weapons can cause long-term or permanent denial of use of those systems.

Weapon systems whose beamed radiation is in the range from 5 to 300 GHz offer a variety of potential applications for U.S. Army missions, including the following:

- tactical ballistic and cruise missile defense;
- ASAT;
- air defense;
- defense against ground-mobile weapons;
- antisensor;
- antiequipment; and
- antipersonnel.

The application of high-power electromagnetic-pulse and continuous-wave (CW) systems to these missions will require a number of system configurations and operating modes, depending upon the operating frequency of the electromagnetic radiation. The Technology Group considered four frequency regimes:

1. millimeter-wave frequencies (30–300 GHz);
2. microwave frequencies (3–30 GHz);
3. high-power ultrahigh frequency (UHF) RF (0.3–3 GHz); and
4. very high frequency (VHF) RF (0.03–0.3 GHz).

It is conceivable to design missile or air-dropped warheads that would generate a massive short-duration power pulse of radiation in each of the frequency ranges identified above. Radar and electronic suppression missiles are in use today. Such warheads, detonated over distant enemy-occupied battle zones, can produce upsetting or lethal effects in electronic equipment, sensor suites, and even personnel. Radiation warhead systems have reasonably good mobility, supportability, and survivability, and they require low manpower for operations. However, their beams would be very broad and difficult to direct. Functionality for many applications would be questionable except for certain antiradar weapons. Their use for defense against incoming missile and aircraft threats would be doubtful because their target flux is low and the resultant short effective range presents fratricide risks.

RF(UHF) and RF(VHF) directed-beam systems operate at relatively long wavelengths (0.1 to 10 m). Therefore, antennas of reasonable diameter would project beams with very wide divergence angles and large side lobes. As a result, such weapons also would most likely be restricted to very short ranges. Their use on the tactical battlefield would severely restrict the deployment patterns of friendly forces, to minimize the risks of fratricide. In the microwave region (approximately 3–30 GHz), beams with adequately narrow divergence angles and very small side lobes can be projected from multibeam phased-array antennas of reasonable overall array diameters (10–15 m). Such high-gain antennas could accurately direct high-power pulsed beams, with potentially lethal fluxes, at targets up to 50 km away. HPM beams would be employed most effectively as part of a defensive weapon suite protecting high-value installations (cities, airfields, large radars, etc.). Their electromagnetic pulses can produce destructive pulses of skin current in electronic components within the target by "back-door" coupling through unshielded cracks and other openings. These current pulses could be lethal to the electronic systems of high-technology platforms, including fixed-winged aircraft, helicopters, and guided cruise missiles. Because the beam is projected with the speed of light, such weapons could be the first line after target acquisition of a layered ground-based defense. HPM beams could also couple in-band through high-gain operating antennas. Like lasers, the beam pulse intensities on target would continue to increase rapidly (inversely proportional to the square of the distance) as a threat flies in.

Millimeter-wave beams are normally only really effective when coupled to the target in-band through the target's operating antennas. The damage is caused by the amplification of the beam by the receiver's high-gain system, overpowering the focal plane or receiving microcircuits. This in-band coupling (or in some cases coupling on an overtone frequency) usually requires lower peak-power intensities on the target than those required for the back-door coupling of an HPM beam. However, the average power intensity at the target may need to be high because receiver antennas in the millimeter-wave region have quite small areas. At ranges not dominated by atmospheric absorption, millimeter-wave transmitting antennas can be smaller, and total systems more transportable, than for the longer microwave wavelengths.

Figure-of-Merit Indices

The use of figure-of-merit indices to provide additional technology judgment information to the STAR Systems Panels was discussed above in the introduction (Chapter 41). As shown in Table 44-4, the values judged

TABLE 44-4 Assessed Figures of Merit for High-Power Electromagnetic Wave Projectors for Years 2000 and 2020

System Concept	Figures of Merit											
	Functionality		Mobility		Supportability		Survivability		Manpower		Cost	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Video Warhead	2	3	2	4	2	3	4	4	3	4	2	3
UHF Warhead	2	3	2	3	2	3	4	4	3	4	2	3
HPM Warhead	2	3	2	3	2	3	4	4	3	4	2	3
mmW Warhead	2	3	2	4	2	3	4	4	3	4	2	3
Multi-beam Klystron (3–15 Hz)	2	4	1	2	2	3	1	2	1	3	1	2
Optoelectronic Generator (3–15 Hz)	2	4	1	3	2	3	1	3	1	3	1	2
Gyrotron Oscillator (15–50 GHz)	2	3	2	4	2	3	1	3	1	3	1	2
Free-Electron Laser Amplifier (50–300 GHz)	2	4	1	3	2	3	1	3	1	3	1	2

NOTES: Index Values: 1 (minimal) thru 5 (excellent). HPM = high-power microwave; MMW = millimeter-wave; UHF = ultrahigh frequency.

appropriate for various currently available nonlaser directed-energy-beam projectors are generally low. The ratings reflect the many technical and systems issues that have to be resolved before greater optimism is justified regarding both the effectiveness of such systems and the ability to incorporate a controllable beam into a practical battle-zone weapon.

However, the fundamentally different methods of both force projection and kill mechanisms provided by HPM beam weapons presents an attractive potential for inclusion in various *future* weapon suites. The Technology Group predicts, with fair confidence, success in engineering relatively immobile, but very high peak-power repetitive-pulse coherent-beam microwave projectors in the 3- to 15-GHz region and continuous-wave variable-frequency millimeter-wave projectors in the 30- to 300-GHz range. Therefore, their future "functionality" potential has been rated quite high (figure of merit of 4 in Table 44-4). Because they would not survive major warhead hits, their survivability is rated low. However, the high-value assets they would serve to protect are also nonsurvivable unless the threats are effectively eliminated. Therefore, the beam weapons should be considered part of the overall high-value asset being protected. Their unique functional capability was the decisive figure of merit for the Group's recommendation to pursue the technology. The four "warhead" embodiments of electromagnetic generation would have more specialized application in future fluid battle-zone scenarios. Although they have higher figures of merit for mobility, survivability (through numbers), and manpower, their functionality would be more limited.

Before one can evolve practical warhead or ground-based weapon systems using HPM and millimeter-wave generators, the fundamental weapon design criteria for beam generation, divergence control, and lethality, relative to a broad range of potential targets (both attacking threats and supporting enemy assets), must be established at the full target scale (not just at the box level). For microwave beams, the tools required to develop these criteria can be provided by coherent combining of energetic pulses generated by a set of advanced klystrons (or other advanced tubes in the future). For millimeter-wave beams, the pulses can be generated by high-power sweeping-frequency free-electron amplifiers. Therefore, the Technology Group elected to provide TFAs for these two enabling technologies for beam projectors.

Technology Forecasts

Millimeter-Wave Sweeping-Frequency Generators

Introduction. Tunable variable-frequency pulses in the range of 15 to 300 GHz can be used to engage target apertures and sensors, which by necessity are open to radiation, and cause electronic damage. This type of engagement may require much less peak energy fluence to be effective than HPM does, because of the larger coupling cross sections, the gain of the receivers, and the damage mechanisms. However, it also may require substantial knowledge of target components and reliable target recognition at the start of the target acquisition chain, as is the case with the more conventional electronic warfare systems. The ability to sweep frequencies over many pulses reduces dependence on target intelligence and recognition. Gyrotron oscillator sources can be effective to cover the frequency range of 15 to 50 GHz, while free-electron millimeter-wave amplifiers would serve best in the range of 30 to 300 GHz. The important advantage of using high-power narrow beams is increased range.

A millimeter-wave directed energy system should have tunable frequency and must be capable of continuous-wave or high-duty-cycle operation. High average power capability is also necessary to damage incoming smart millimeter-wave or infrared guided weapons at reasonably long ranges.

Table 44-5 shows the central spot diameter and intensity (watts per square centimeter) at 3 and 10 km of millimeter-wave beams projected at 35 and 94 GHz from an antenna 5 m in diameter and using a 1-MW average power source. At 3 km, the fluence on a receiving high-gain antenna of diameter equal to 50 λ would result in catastrophic unit damage. At 10 km, the same receiver could experience first signal-stage powers of 63 and 25 watts for 35 and 94 GHz, respectively. These fluences would probably saturate many systems, force great reduction in sensitivities, or cause long-time upsets. These preliminary calculations of course require more complete study; the total systems maps for these weapon system concepts, played against various targets, need to be examined.

Table 44-5 Estimates of Beam Intensities and Transmitted Total Beam Power for Millimeter-Wave Projectors at 35 and 94 GHz

Target Range (km)	Central Spot Diameter (m)		Total Beam Power at Range[a] (MW)		Central Spot Intensity at Range (W/cm^2)		Potential Power into Receivers[b] (W)	
	35 GHz	94 GHz	35 GHz	94 GHz	35 GHz	94 GHz	35 GHz	94 GHz
3	13	4.8	0.93	0.71	0.62	3.4	780	620
10	40	15	0.79	0.32	0.05	0.14	63	25

[a] The following coefficients for atmospheric absorption at sea level were assumed: for 35 GHz, 0.1 dB/km; for 94 GHz, 0.5 dB/km.
[b] Diameter = $\sim 50\lambda$.

The discussion that follows describes potential millimeter-wave generator technologies that have eventual output powers in the megawatt class, with high-duty-cycle, frequency-sweeping capability over various ranges.

State of the Art. The subsystem that requires the most development is the high-power, tunable millimeter-wave source. Tunable solid-state sources are available over the millimeter-wave frequency range at power levels on the order of a milliwatt. Under development for millimeter waves are traveling-wave tubes with tunability of more than 10 degrees at continuous-wave power levels of hundreds of watts. Their maximum frequency is about 100 GHz. These devices do not cover the higher millimeter-wave frequencies, however, and many units would be required to cover the frequencies from 30 to 100 GHz. Single-frequency extended-interaction oscillators are available with powers of 1 kW at 30 GHz and up to 1 W at 300 GHz.

The only available device capable of an average power approaching a megawatt over the entire millimeter-wave range is the gyrotron. Many are in use at frequencies from 28 to 140 GHz at power levels on the order of 200 kW. A Department of Energy program is under way to achieve 1-MW continuous-wave power at 140 GHz early in the 1990s and at 240 GHz a few years later. The devices are fixed-frequency oscillators. The only way to approximate a frequency-tunable system with gyrotrons is to employ an array of tubes. The closest competitor to the gyrotron in power is the tunable millitron. This device is limited to power levels on the order of hundreds of watts at the low-frequency end of the millimeter regime. Thousands of these devices must be combined to approach 1 MW at even a single frequency.

A device that is potentially capable of very-high-power millimeter-wave radiation and tuning over several octaves in frequency is the free-electron millimeter-wave generator. As noted earlier, a free-electron amplifier is a linear electron-beam device that produces a traveling wave whose frequency is determined by the electron-beam energy and is therefore continuously tunable. Very high peak powers, on the order of a gigawatt, have been demonstrated at 140 GHz; octave tunability has been shown experimentally. Free-electron millimeter-wave generators will require electron-beam energies ranging from 0.5 to 10 MeV.

Free-electron amplifiers (whether producing a laser beam, millimeter-wave, or microwave beam) are distinguished primarily by the type of electron accelerator they employ. Three types have been used: electrostatic accelerators, induction linear accelerators (LINACs), and RF-LINACS. The highest peak-power FEL operation to date has been demonstrated with an induction LINAC. The best devices under development can achieve pulse widths of 10^{-4} seconds with a pulse repetition rate of 5000 per second. FELs driven by an RF-LINAC to produce optical frequency radiation are under development. A full systems engineering study is needed to compare the merits of the two most attractive accelerators for reasonably mobile, battle-zone weapon systems: RF-LINACs and induction LINACs.

Technology Projections and Recommendations. The most important element in a program to evolve this technology will be development of a tunable source for high-power millimeter waves. The Technology Group's projection for progress on various types of millimeter-wave generators assumes technology-driven progress and the availability of reasonable levels of technical manpower and funding to achieve it. Figure 44-4 presents the Group's forecast for the gyrotron and for induction-LINAC-driven and RF-LINAC-driven, multimegawatt millimeter-wave generators. By 1995, continuous-wave power in the megawatt range can be produced either by gyrotrons at fixed narrowband frequencies (so that a number of gyrotrons will be required to achieve frequency sweeps) or by FELs based on induction-LINAC technology. By 2005, megawatt-level continuous-wave power can be forecast for free-electron RF oscillators having tunable frequencies of between 30 and 140 GHz; three output wigglers will be used to maintain high efficiency over the tuning range. The free-electron RF oscillator appears to be the only candidate capable of also evolving to acceptable size and weight for a battle-zone-fieldable weapon. A 1-MW, continuous-wave 30- to 140-GHz sweeping-frequency millimeter-wave weapon prototype of less than 10 tons system weight could be demonstrated in 10 years, given appropriate funding.

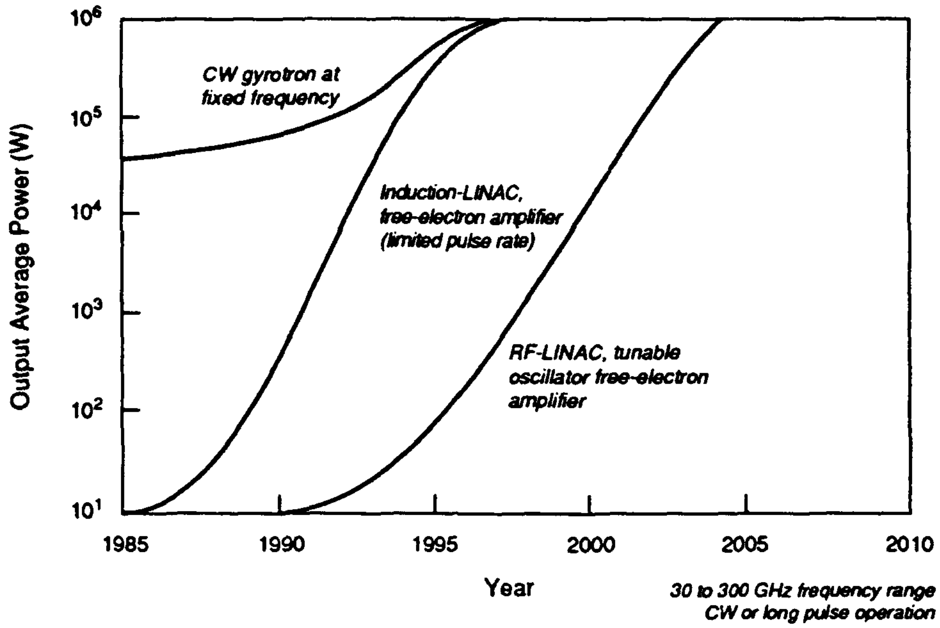

FIGURE 44-4 Technology projection for millimeter-wave sweeping-frequency generators covering the frequency range of 30–300 GHz with either continuous-wave or long-pulse operation.

Multibeam HPM Energetic-Pulse Generators

Introduction. Fixed-frequency single and multiple microwave pulses in the range of 1 to 15 GHz may couple effectively through cracks (back-door coupling) and through functional openings on targets to induce electronic damage by the thermal burnout of junctions. This is a militarily useful approach because it does not rely on prior target intelligence. However, the use of this non-frequency-specific kill mechanism requires higher power density on the target, which, when coupled with a desire for long range of operation, results in a high peak power requirement for the source. The high peak power for the weapon projector leads to a requirement for multiple unit phased aperture sharing. In the upper end of the frequency (i.e., 6 to 15 GHz), high-gain antennas can be used and long-range, narrow-beam propagation in all weather conditions can be achieved.

Today considerable R&D is in progress worldwide for a variety of modulated electron-beam-driven HPM generators, which can be categorized as either (1) intense relativistic-beam cold-cathode electron sources or

(2) conventional thermionic-cathode electron sources. In addition, the tube type can be either an amplifier or oscillator type of generator (the klystron, described below, is a conventional amplifier). Thermionic-cathode sources operating at 100 to 500 kv produce a cold temperature and very well controlled beam, allowing 1- to 10-μs pulses and system efficiency of 30 to 60 percent. However, they are limited by the current density of the electron beams, and hence a single-beam unit is limited to generating peak power on the order of 100 MW.

The klystron tube technology is based on the use and modulation of thermionic-cathode-produced electron beams, where a high brightness (high current and small emittance) dc electron beam is modulated by an input microwave power. This modulation is performed in an initial resonant cavity and causes the electrons to become sharply bunched by time-of-flight micropulse formation at the resonant frequency. In going through an output cavity, up to 45 percent of the electron-beam energy is converted to microwave power. Typical gain of a klystron amplifier is 50 dB. Until recently a single electron beam has been used, typically at up to 500 kV and up to 300 A, to produce up to 60 MW peak microwave power. This technology is exemplified by the Stanford Linear Accelerator Center (SLAC), where 300 of the SLAC-developed 60-MW tubes are used routinely at more than 100-Hz pulse rate and more than 10 hours per day.

State of the Art. The earliest multibeam klystron, constructed in 1960, was sponsored by the U.S. Army Signal Engineering Laboratory; it demonstrated an order-of-magnitude increase in microwave power, but this effort was not continued. In 1986, CSF Thomson Company initiated an effort to demonstrate a compact 1-MW continuous-wave multiple-beam klystron unit for driving space-based neutral particle-beam (NPB) generating accelerators at 425, 850, and 1700 MHz. This effort is now sponsored by the U.S. Army Space Defense Command on behalf of the DOD SDIO.

Recently SLAC has specified the need to drive such accelerators at a power level of 1 GW per linear meter of acceleration cavities, toward a goal of tera-electron-volt colliding linear accelerators. After trying several approaches over the past four years, SLAC has converged on the multibeam klystron concept. A single-beam advanced klystron at 12 GHz has been demonstrated near 200 MW for less than 1-μs pulses.

Today the design of several alternative approaches in klystron and other tube technologies can be verified quite reliably by the use of simulation codes that correctly represent the behavior of beams and their mutual interaction with electromagnetic fields in specific resonant-cavity geometries. These particle-in-cell multidimensional design tools are a major advance in the state of the art. However, a major advance in pulse modulators will be required to drive 1- to 10-GW multibeam klystrons in a compact and lightweight fashion.

Technology Projections and Recommendations. The Technology Group's projection is based on technology-limited forecasting, assuming that the requisite technical manpower and funds are available. However, this is one technology area where technical manpower is limited. Figure 44-5 displays the Group's forecast showing that a multibeam HPM device capable of a few gigawatts of peak power can be demonstrated by 2000, and a device capable of tens of gigawatts of peak power could be available in the 2010 time frame.

The multibeam klystron inherently will require ultra-high-current-pulse power conditioning systems and/or modulators. For example, a 1-GW HPM unit would need 10-kA, 200-kV, 10-μs precise flat-top modulators (a factor of 30 over present experience); an HPM unit capable of 10 GW peak pulse power would require 100-kA, 200-kV modulators at a 100-Hz pulse rate (i.e., a factor of 300 more pulse current than presently used). The development of these modulators must go hand in hand with the development of the new klystrons, since they would be needed to support any developmental test stands for the multibeam klystrons.

Development of long-life, rugged, and ultra-high-brightness thermionic electron cathode sources will be required at increased current density (50 to 100 A/cm^2). In parallel, development of field breakdown mitigation must occur for the structural elements in the tube and the cathode area and at the exit windows and the transmission waveguides that initiate an HPM distribution network for a phased-array beam projector. Beam dynamical analyses can be made reliably to set space-charge debunching limits and hence define the optimum building block for the multibeam klystron. The development of 60-dB suppressed, high-power, electronically steerable phased-array antennas will also be a crucial technology, for which reasonable design approaches already exist.

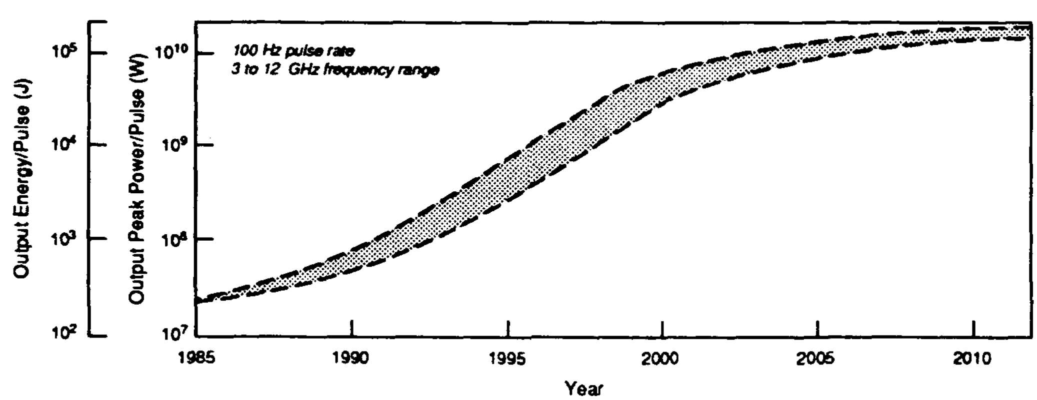

FIGURE 44-5 Technology projection for a multibeam klystron unit.

Advanced klystrons have been demonstrated with capabilities greatly exceeding the pulse-current levels of even the new tubes incorporated only a few years ago in a large phased-array beam-projection demonstration system. These or other new-concept microwave generators could be introduced periodically as appropriate into a systematic long-term technology evolution program. With substantial funding, a prototype HPM unit producing 1 MW average power at 10 kJ per 10-μs pulse at 100 pulses per second, combined with a steerable, multiple-antenna phased-array projector, could be demonstrated by 2005. It is also important that the Army pursue this technology to a level that will enable the full-scale determination of vulnerability of its own operational field equipment and weapons to such HPM beams in the hands of adversaries.

References

Institute for Advanced Technology. 1992. Briefings on Focused Technology Program; U.S. Army's Critical Component Development and Maturation Program for Electric Armaments. University of Texas, Austin.

Army Science Board. 1989. Initial Report of the Army Science Board Panel on Electromagnetic/Electrothermal Gun Technology Development, December 18, 1989, Assistant Secretary of the Army for Research, Development, and Acquisition, Washington, D.C.

AUSA. 1987. The 1987–88 Green Book. Status Report of Landpower. Arlington, VA: Association of the U.S. Army. Army [Magazine] 37(10):304–312, 412–438.

Anonymous. 1988. Aerospace forecast and inventories. Aviation Week and Space Technology 128(11).

Bill, R.C., G.J. Weden, and J.J. Coy. 1988. An overview of rotorcraft propulsion research at Lewis Research Center. Vertiflite. 34:24–31.

Botez, D. 1992. High-power monolithic phase-locked arrays of antiguided semiconductor diode lasers. IEEE Proceedings. Optoelectronics. 139(1):14–23.

Burkes, T.R. 1978. A Critical Analysis and Assessment of High Power Switches. Report NP30/78. White Oak, MD.: Naval Surface Weapons Center.

Checklich, G.E. 1989a. Power distribution technology projections. U.S. Army Tank-Automotive Command, Warren, Mich. Working paper.

Checklich, G.E. 1989b. Power technology projections. U.S. Army Tank-Automotive Command, Warren, Mich. Working paper.

Checklich, G.E. 1989c. Propulsion technology. U.S. Army Tank-Automotive Command, Warren, Mich. Working paper.

Defense Advanced Research Projects Agency. 1987. Electrical Energy Gun System Study. Report SC No. 24301-87. Washington, D.C.

Defense Nuclear Agency. 1992. Electrothermal chemical gun sets world record. Public Affairs Office, Defense Nuclear Agency, Alexandria, Va. Press release, March 2.

DOD (U.S. Department of Defense). 1987. Soviet Military Power, 1987, Report 088-000-00464-1. Washington, D.C. U.S. Government Printing Office.

DOD (U.S. Department of Defense). 1989. The Department of Defense Critical Technologies Plan for the Committee on Armed Services, prepared for the Senate Committee on Armed Forces. Washington, D.C.: U.S. Department of Defense, U.S. Congress, May 5.

Dugger, G.L. (ed.). 1969. RAMJETS. AIAA Selected Reprints. IV. Washington, D.C.: AIAA.

Estrov, A., and I. Scott. 1989. Planar Magnetics Lower Profile, Improve Converter Efficiency. Powerconversion and Intelligent Motion 15(5):16, 18, 20, 22, 24–26.

Fischetti, M. 1992. Here comes the electric car—It's sporty, aggressive and clean. Smithsonian Magazine. 23(1):34–43.

FMC Corporation. 1987. Electric Drive Study. 1. Report DAAE07-84-C-R-16. Warren, Mich.: FMC Corporation for U.S. Army Tank-Automotive Command.

Furgal, D. 1988. Power conditioning for multimegawatt space power systems. Briefing presented at Sandia National Laboratories, Albuquerque, N. Mex., June 2, 1988.

General Dynamics Corporation. 1987. Electric Drive Study. Report DAAE07-84-C-R-16. Warren, Mich.: General Dynamics Land Systems Division for U.S. Army Tank-Automotive Command.

Hansen, I.G. 1986. Description of a 20-kHz Power Distribution System. Cleveland, Ohio: NASA Lewis Research Center.

Haynes, D. 1989. Dealing with dc/dc converter reliability. Powerconversion and Intelligent Motion. 15 (4):67, 70–72.

Hesse, W.J., and N.V.S. Mumford, Jr. 1964. Jet Propulsion for Aerospace Applications. New York: Pitman Publishing Corp.

Hosney, A.N. 1974. Propulsion Systems. Columbia, S.C.: University of South Carolina Press.

IEEE (Institute of Electrical Engineers). 1989. Proceedings of the IEEE 4th Symposium on Electromagnetic Launch Technology. IEEE Transactions on Magnetics. New York: 25.

Jane, 1986. Jane's Weapon Systems. ed. R.T. Pretty. Jane's Publishing Company. New York.

JCS (Joint Chiefs of Staff). 1984. United States Military Posture, for FY 1985, Report 1984-433-138. Washington, D.C.: U.S. Government Printing Office.

Juhasz, A.A., K. Jameson, K. White, and G. Wren. 1988. Introduction to electro-thermal gun propulsion. Proceedings of the 25th JANNAF Combustion Meeting. CPIA Publ. 498. Laurel, Md.: Chemical Propulsion Information Agency, Johns Hopkins University.

Kerr, G.T. 1989. Synthetic Zeolites. Scientific American 261 (1):100–105.

Kintzer, E.S., J.N. Walpole, S.R. Chinn, C.A. Wang, and L.J. Missaggia. 1992. High-power strained-layer tapered traveling wave amplifier. Conference on Optical Fiber Communication, Vol. 5, 1992 Technical Digest Series (Optical Society of America, Washington, D.C., 1992), Paper TuH5, 5:44.

McClelland, R.C. 1987. Advanced Planning Briefing for Industry, 1987. Warren, Mich.: U.S. Army Tank-Automotive Command.

Mawst, L. J., D. Botez, T.J. Roth, G. Peterson, and J. Rozenbergs. 1991. CW high-power diffraction-limited-beam operation from resonant optical waveguide arrays of diode lasers. Applied Physics Letters 58(1):22–24.

Monastersky, R. 1991. Voyage into Unknown Skies. Science News. 139(9):136–137. March 2.

NASA (National Aeronautics and Space Administration). 1971. Exploring in Aeronautics. Washington, D.C.

NASA JPL (National Aeronautics and Space Adminstration Jet Propulsion Laboratory). 1986. Gun Propulsion: Emerging Army Technologies. Report on the Advanced Propulsion Technology Study conducted for the Army Materiel Command August 1986.

Nored, D.L. and D.T. Bernatowicz. 1986. Electrical Power System Design for the U.S. Space Station. Pp. 1416–22 in Proceedings of the 21st Intersociety Energy Conversion Engineering Conference: Advancing Toward Technology Breakout in Energy Conversion. Washington, D.C.: American Chemical Society.

NRC. 1992. STAR 21: Strategic Technologies for the Army of the Twenty-First Century. Main Report. Board on Army Science and Technology, National Research Council. Washington, DC: National Academy Press.

NRC. 1988a. Mobile Electric Power Technologies for the Army of the Future—Engines, Power Sources, and Electrical Aspects. Energy Engineering Board, National Research Council. Washington, D.C.: National Academy Press.

NRC. 1988b. Navy 21: Implications of Advancing Technology for Naval Operations in the Twenty-First Century. Naval Studies Board, National Research Council. Washington, D.C.: National Academy Press.

NRC. 1989. Advanced Power Sources for Space Missions. Report ADPPOW, Energy Engineering Board, National Research Council. Washington, D.C.: National Academy Press.

Oberle, W. 1988. A feasibility study of power curve-working fluid combination for optimal ET gun performance. Proceedings of the 25th JANNAF Combustion Meeting. CPIA Publ. 498. Laurel, Md.: Chemical Propulsion Information Agency, Johns Hopkins University.

Oberle, W., and K. Jamison. 1988. A systems perspective on electrothermal guns. Proceedings of the 25th JANNAF Combustion Meeting. CPIA Publ. 498. Laurel, Md.: Chemical Propulsion Information Agency, Johns Hopkins University.

Post, R.F., and S.F. Post. 1973. Flywheels. Scientific American 229:17–23.

Pretty, R.T., ed. 1985–86. Jane's Weapon Systems 1985-86. New York: Jane's Publishing Co.

Raytheon. 1987. Rectenna Technology Program: Ultra-light 2.45 GHz and 20 GHz Rectenna. Report prepared for National Aeronautics and Space Administration. Washington, D.C. NASA CR-179 558. March.

Rodler, W.E. Jr., and K.W. Shafer. 1987. Electric Drive Study. Report DAAE07-84-C-R017. Warren, Mich.: U.S. Army Tank-Automotive Command.

Sarjeant, W.J. 1989. Briefing to the Defensive Technologies Study Team on Space Power Technology. Briefing presented at the Institute for Defense Analysis, Washington, D.C., June 15, 1989.

Sarjeant, W.J., and T.R. Burkes. 1987. SDI power and power conditioning components. Unpublished discussion paper for the NAS-NRC (EEB) Committee on Advanced Space Based High Power Technologies.

Sarjeant, W.J. and R.E. Dollinger. 1989. High Power Electronics. Blue Ridge Summit, PA: TAB Professional and Reference Books.

Staffier, D.T. 1989. Technology: Problem Statement–Power Development Out of Synch with Systems Needs. EPRI and DEC Briefing. Littleton, Mass.: Digital Equipment Corporation.

Stephens, W.D. 1989. Army power information package. Working paper presented to the Propulsion and Power Technology Group, Committee on Strategic Technologies for the Army, July 12, 1989.

Stix, G. 1992. Electric car pool. Scientific American. 266(5):126–127.

Systems Planning Corp. 1989. Electrical Energy Gun System Study (Phase I). Report 89-C-07. Washington, D.C.: Defense Advanced Research Projects Agency.

Vitkovitsky, I. 1988. High Power Switching. New York: Van Nostrand Reinhold, Inc.

Welch, D.F., W. Streifer, P.S. Cross, and D.R. Scifres. 1987a. Junction semiconductor laser arrays—II. Experiments. IEEE Journal of Quantum Electronics QE-23(6):752–756.

Welch, D.F., P.S. Cross, D.R. Scifres, W. Streifer. 1987b. Single-lobe Y-coupled laser diode arrays. Electronic Letters. 23:270–272.

Wright Aeronautical Laboratory. No date. Integrated High Performance Turbine Engine Technology Initiative. U.S. Air Force Wright Aeronautical Laboratory. Turbine Engine Division.

PART VIII

ADVANCED MANUFACTURING TECHNOLOGIES

ADVANCED MANUFACTURING TECHNOLOGY GROUP

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Summary of Findings on Advanced Manufacturing Technologies

Advanced design and manufacturing systems adapted from civilian industry offer opportunities for the cost-effective design and production of military equipment. By 2020, specifications and quality standards will probably be so good and so reliable that many military specifications may be unnecessary. Distributed and forward production facilities will allow significant reductions in supply inventories, savings in procurement cost by responding to a specific order, rapid reaction to operational requirements, and replication of replacement parts in the field.

To take advantage of these technologies, radical changes in the current military procurement system may be needed. For example, the U.S. Army must be willing to have its equipment designed and produced in factories that also produce for the civilian sector. Other policy issues for manufacturing in 2020 include more single-source procurement, material and component availability within the United States, a focus on the development of manufacturing techniques for unique military items, industrial preparedness, adequate investment in production facilities for defense materiel, flexible production schedules to mesh with civilian needs, and environmental and legal considerations. Emphasis must be placed on designing products for producibility at the outset of the research and development (R&D) phase to ensure the low cost and availability of the production capability.

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Introduction

This assessment does not focus on individual process technologies. Instead, it focuses on manufacturing systems, independent of the products they make and the processes they employ. Each of the other Technology Groups in the Strategic Technologies for the Army (STAR) study has addressed producibility for their own technology, where applicable.

Manufacturing is generally considered in terms of a specific product or process technology, but the broader systems issues are often not recognized or understood. Key concepts in implementing advanced manufacturing techniques include:

- Systems provide the means of interconnection. Thus, systems technology is itself used to build systems by connecting individual system elements. Since the capability of interconnection can and should be used extensively and recursively, systems technology also provides the ability to connect smaller systems together to form a larger and more comprehensive system.
- Systems are product and process independent.
- Systems contribute significantly to the effectiveness of manufacturing.
- Systems greatly affect quality, cost, responsiveness, and yield.

Three major categories of systems are used in manufacturing:

1. *Energy systems* are the oldest and best understood resource optimization problem. When energy optimization was a pervasive problem early in the industrial revolution, optimization required the design and use of extensive belt and pulley systems to transmit energy. Similarly, wheel and gear devices were designed for processes such as the Jacquard loom and the cotton gin to permit human energy to be harnessed in operating the manufacturing processes. In addition, plant location was then greatly influenced by the availability of energy sources because of the need to optimize energy usage.
2. *Material management systems* are the current focus of optimization in manufacturing (e.g., just-in-time delivery, design for manufacturability, flexible manufacturing systems, total quality control).
3. *Information systems* will be the focus of optimization in the next generation of manufacturing. Early evidence can be seen in the work on networks, data bases, robots, smart processes, and decision support systems.

Manufacturing today is typically executed by automated machinery. This is not to say that humans have no role in the process or that they do not operate the machines at all. However, rather than having only humans and physical processes in the loop, manufacturing is now a tripartite arrangement—a machine, a human, and some form of computer control based on sensors, feedback, and so on. In many cases, however, humans must be brought into the situation only in exceptional circumstances.

This arrangement will yield levels of accuracy, reliability, and quality—in the product and the process alike—that could not have been realized or even imagined a generation ago. Products, designs, and specifications can be reproduced to higher degrees of accuracy and split-second timing than they were in the past. This has given new importance to reliance on computational models and to understanding of fundamental processes. It also highlights specific situations in which there is no understanding of what controls specific processes.

From the perspective of product or process technology, the focus is on the incremental improvements in key factors of manufacturing. Many developments that can be expected over the coming decades include:

- reduced cost for increased functionality (consider computers, for example);
- civilian specifications and quality standards that are so good and so reliable that most military specifications and standards will not be necessary (this implies a mixing of military and civilian production facilities, with major implications); and
- significant decreases in the time from concept development to the actual fielding of weapon system.

All of the improvements listed above are in the category of performing the usual process faster, smarter, and better. Other improvements in the manufacturing and procurement process can be expected, but many will require changes in requirements generation and design philosophy. Products *and* processes are involved. To the extent possible, the military should use civilian products and components. On the other hand, flexible civilian manufacturing processes will allow uniquely military products to be made in the same facilities with the same equipment. Major advances in manufacturing processes are likely to occur in equipment customization, streamlining of logistics equipment, and concurrent development.

EQUIPMENT CUSTOMIZATION

Since the quantities of an order must no longer be large to be economical, and since variations in products neither add cost nor reduce reliability, there will no longer be a need to design weapons, support equipment, and so on, to fit broad categories of use (desert sand and heat to polar ice and cold), to stand the test of 10 to 15 years (until the next generation of a product is developed), or to justify the value of an item by a broad-based need (across the Army). It will be possible to customize weapons and support gear to fit their intended uses. Imagine the benefit to a soldier's effectiveness of using equipment designed for the current task and conditions, not for all tasks and conditions that might arise in the next 10 years.

STREAMLINING OF LOGISTICS EQUIPMENT

The economic value of the equipment that must be kept on hand is directly related to the time it takes to resupply that equipment. When that time is measured in years, the Army must create a huge logistical system with, for example, the need for warehouses and complex schemes to determine which items should be reworked and which should be scrapped. Changing response times from years to weeks and adding the ability to customize are not simply new variable values for the old equation—they permit new strategies. Imagine the options that might be exercised if one could configure support equipment as easily as one could assemble skilled workers.

CONCURRENT DEVELOPMENT

The development of advanced computer systems has stimulated a fundamental change in manufacturing processes, affecting the design, fabrication, and measurement of components. New interfacing technologies will facilitate concurrent *and* coordinated development of defense systems. Concurrent development has been faulted in the past as the cause of design-performance disconnects and engineering shortcomings, but the creation of formal engineer–user interfaces early in the design process will allow the research, development, test, and evaluation (RDT&E) cycle to be accelerated. New platforms will make the transition from drawing board to fielding more rapidly as manufacturing, quality control, distribution, and maintenance are incorporated in system design.

Technical Description

Material transformation processes (metal removal, fabrication, electronic deposition, foundry, cutting, etc.) are all experiencing significant advances. Scientific models are being developed for the underlying transformations that will facilitate higher performance characteristics in the process itself. The development of low-cost, highly capable computer systems, coupled with a new, more capable range of sensor devices, has yielded significant new control capabilities. When one then considers advances in computer science, knowledge engineering, and human–machine interfaces, major advances in process capabilities become possible.

At the level of process technology, increases in feasible dimensions of one or two orders of magnitude will routinely be achieved. Self-correcting, 100 percent accurate process execution will be the norm, as will the ability to automatically program machines used in the manufacturing process. Information regarding what to make and the state of process variables will be routinely available and will be handled by process controllers.

These advances in process technology will accelerate two trends with respect to possible products. First, the concept of "designer materials" (the ability to tailor new materials atom by atom, to achieve a desired set of properties) will broaden to include the ability to design and fabricate "designer parts." Second, the information content of a product will continue to increase (consider the increase that has already taken place in the automobile electronics). In addition, the quick-reaction, highly accurate, repeatable nature of processes and control information will contribute to an increased ability to model various scenarios and predict systems performance.

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Current and Projected Status of Manufacturing Systems

CURRENT STATUS

All of the enabling technologies and subsystems for these manufacturing systems already exist. The key technologies are summarized here.

Intelligent Processing Equipment

Intelligent processing equipment includes a broad range of computer-controlled equipment capable of executing a wide array of manufacturing processes such as machining, forming, welding, heat treating, painting, testing, inspecting, assembling, fabricating composites, and handling materials. The fundamental concept is that the manufacturing process includes the ability to sense the desired characteristics or properties of a product and has enough local intelligence to control those properties. Industrial robots are the most visible products of this emerging technology, but they must be coupled with sensors and control systems in order to perform the desired process. The ability of intelligent processing equipment to maintain quality consistency will virtually eliminate the need for postmanufacture inspection.

Sensors and Control Systems

Sensors and control systems, coupled with artificial intelligence and an understanding of process variables, are critical to intelligent processing equipment. The mechanical elements of intelligent processing equipment include manipulators and actuators, precision mechanisms, machine vision systems, nonvision sensor systems, and assembly and inspection systems. The trend in manufacturing is toward more rapid product realization; increased flexibility; and integration of design, production, and quality control. Firms lacking intelligent manufacturing capabilities will be unable to compete in many markets.

Microfabrication and Nanofabrication

Microfabrication and nanofabrication involve the fabrication and manipulation of materials and objects at microscopic (microfabrication) and atomic (nanofabrication) levels. These techniques are essential in the production of semiconductor devices to achieve the densities necessary for the next generation of integrated-circuit chips. Expected applications include high-density integrated circuits, optoelectronic devices, quantum devices, textured surfaces for biotechnology, and production of nanoscale mechanical devices and sensors.

Microscopically applied films and surface treatments are being used in a number of areas. Coatings are applied, for example, to turbine blades in aircraft engines to reduce wear. Bearings can be treated to produce surface coatings that reduce friction. Films themselves can be fabricated as part of an integrated circuit. Cutting and drilling tools are coated to protect them against wear. A key production factor is the ability to fabricate a microscopically thin, dense, and uniform surface. Diamond films illustrate the promise of microfabricated films. The remarkable properties of diamond include its higher thermal conductivity (five times that of copper at room temperature), hardness that is orders of magnitude higher than those of many other coating materials, and greater electron mobility, making it suitable for a variety of electronic applications. The key to microfabrication is using this material in minute quantities to capitalize on its superior properties while also using the desirable qualities of other materials to which it might be bonded in various fabrication processes.

Advances in microfabrication and nanofabrication have also enabled the development of new devices with microscopic dimensions that are capable of performing a range of functions. Their potentially low cost coupled with sensitivities that are orders of magnitude beyond the capabilities of devices now in use promise breakthroughs in many fields. Microsensors could be used to measure the flow, pressure, or concentration of various chemical species in environmental, medical, and mechanical applications.

Flexible Computer-Integrated Manufacturing

Flexible computer-integrated manufacturing (CIM) combines product, process, and manufacturing management information into a single interactive network, greatly reducing the number of "transactions" necessary to make a product. Whereas intelligent processing equipment focuses on the process and work-station level, flexible CIM incorporates various levels of factory automation and information systems into a single coordinated system. A group of work stations, organized around a set of common tasks or functions, constitutes a factory cell. Collectively, these cells feed parts into factory centers, which may be composed of subassembly, assembly, and final assembly operations. The CIM system oversees all of the factory's operations, including its work stations, cells, and centers, and ensures that the factory can be responsive to engineering and marketing inputs.

Some of the following associated tools and technologies are used to implement flexible CIM:

- Simulation models use interactive systems to simulate a task or set of subtasks to design more effective manufacturing systems, increase utilization rates, streamline factory layouts, and simplify scheduling.
- Computer-aided design allows the creation of three-dimensional designs and representations of solid objects.
- Computer-aided engineering is used to define, refine, and optimize the qualities of various products by allowing interactive design and analysis to simulate performance.
- Group technology emphasizes the identification of major similarities among items so that they can be grouped for more efficient production, thus minimizing tooling changes or the reprogramming of manufacturing systems.
- Computer-aided process planning establishes methodologies for determining processing sequences from part specifications, part characteristics, and/or assembly configurations; applies process models to determine economical operating conditions for each processing unit; and evaluates the impact of operating conditions within work stations and CIM systems on production rates and the economics of the entire production sequence.
- Factory scheduling tools are used to manage just-in-time material flow systems and other tasks.

Systems Management

Systems management includes the tools, practices, and sciences that will become increasingly important as advanced manufacturing systems become the standard. Systems management is directed at the intra- and inter-enterprise levels rather than toward specific manufacturing operations. The following technologies are already in use:

- Product data exchange tools provide the ability to exchange computer information within and among business units. Although these tools are still in the early stages of development, they represent steps toward allowing different computer-aided design and computer-aided manufacturing systems to communicate with one another and are essential if the benefits of CIM are to be fully realized.

- Data-driven management information systems involve the storage and use of designs, inventory and order information, and information on the capabilities of different machines to design and manage flexible CIM.

Concurrent Development of Doctrine, Systems, and Manufacturing Process

The Army's Concept-Based Requirements System is essentially a "sequential" model of the development process. This system worked in the past because those establishing the specifications understood the downstream processes and made good trade-offs, while designers understood the intent of the military specifications and were able to anticipate enemy countermeasures. But as systems become more complex—and as the gaps increase between tacticians, specifiers, designers, and producers—these informal mechanisms break down. Formal engineer–user interfaces early in the design process will allow the RDT&E cycle to be accelerated. New platforms will make the transition from drawing board to the troops more rapidly as manufacturing, quality control, distribution, and maintenance are incorporated in conceptualization and system design.

Concurrent Development Teams

In the commercial world, competition has forced U.S. manufacturers toward concurrent development, in which small teams of designers, market experts, and manufacturing engineers simultaneously define the concept, design the product, and create the manufacturing system to produce it. This process is possible because various elements of the development team interact with the product at different levels of abstraction. This management scheme for concurrent development increases the level of detail in team members' understanding of the environment in which the product will be used, the set of products under consideration, and the manufacturing processes to be employed. Imposing the concurrent development philosophy is a difficult process because it entails innovation in traditional workplace organization and interpersonal relations even more than innovation in technology.

Concurrent development requires that technical specialists be used in new roles. Team members bring their individual expertise to the team but also participate in the group's knowledge-sharing and decision-making processes. On an individual basis, team members must be able to communicate with all other members of the group. Many of the integrative and filtering functions of a management hierarchy are performed within the group. Lateral information flow replaces the up-across-and-down pattern of communication between technical specialists in a traditional management hierarchy. When this standard is applied to the Army, tactical personnel will have to acquire competence with technology and manufacturing processes, while technologists must acquire a degree of proficiency in tactics.

The best way to prepare personnel to fill broader roles is to rotate them through the different jobs involved so that they can acquire a broader perspective. This has meant rotating technical personnel through positions in design and manufacturing. For the Army, concurrent development would mean rotation of prospective team members through assignments in the areas of doctrine, systems, and manufacturing processes.

The traditional manufacturing organization, such as the Army's Concept-Based Requirements System, has been segmented by functional specialties. For example, there may be a finance group, a marketing group, and a manufacturing group, each of which does not interact with the others any more often than is necessary. The Army understands and currently employs this kind of teamwork at the tactical level. This is an important institutional experience upon which it can draw. But at the development level, the Training and Doctrine Command is functionally separate from the Army Materiel Command, and so on. The handoff of ideas and information across these functional boundaries is likely to be more problematic than it is within a traditional manufacturing organization because there is even greater separation between what the Army does as a "consumer" of defense products and what industry does as the "producer" of systems.

Lessons for the Army

These problems, though real, are not insurmountable. They have been encountered by private industry and surmounted. The Army can learn from both the successes and the failures in overcoming obstacles in the commercial sector. For example, automobile development teams have succeeded in combining marketing experts, design engineers, and production engineers on a team to produce a single model. By analogy, an Army weapons system development team would include tacticians, logisticians, design engineers, and production engineers. The team should always be organized around development of a particular system. Another lesson from industry experience is that development teams have been more successful when the team members share a common facility and have the same leader. This imposes the same standards of objective, design, and accountability across the individual participants. Experience has demonstrated that, where this design and organizational philosophy has been imposed, the management hierarchy has been substantially flattened. One positive consequence of this is that technical experts do not abandon technical roles for managerial positions where they cease to make design contributions. Working relationships with suppliers are changing from strictly buyer/seller to partnerships. Application of this emerging trend will have the most beneficial impact on the quality, availability, and support of Army equipment.

PROJECTED STATUS

There is still need for work on communication standards and on internal data representations. Internal data management may be a bigger task than it seems to be today. There is also a need for new organizational concepts. Anticipated progress in these areas will bring about the following benefits:

- continued reduced cost and increased functionality in manufacturing systems;
- civil-sector specifications that are acceptable for many military requirements;
- drastic reduction in time from concept to prototype to production; and
- design and product modifications that respond rapidly to operational needs.

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Impact on the Army in the Twenty-First Century

DISTRIBUTED AND FORWARD PRODUCTION FACILITIES

Current logistics methods require large quantities of finished goods to be stored at many locations in the supply system. However, using advanced design and manufacturing technologies, the Army will be able to collocate modules, subassemblies, and raw material with the computer-based intelligent manufacturing equipment so that it can produce finished goods where and when they are actually needed. Great savings can be realized by making items to a specific order. For example, clothes, food, and equipment can be manufactured and packaged to satisfy specific end-user preferences. This approach reduces the value of the total inventory and makes more equipment and supplies available to the end user.

The rate of replacement of weapon systems can be increased in the future by storing weapons as modules and data, rather than as finished systems. Upgrades will not require retrofitting but will merely require some minor changes in the choice of components to be used and the methodologies for assembling them. This capability will reduce the Army's dependence on large industrial complexes; in a very real sense, manufacturing activities will be distributed to many locations. In many cases, particularly in areas close to the combat zone and for uniquely military items, the Army would have to own and operate the manufacturing capabilities. If it is implemented well, this approach will result in a more robust and competitive industrial base. It also provides an opportunity to strengthen the machine-tool industry, a strategically desirable side effect.

RAPID REACTION TO OPERATIONAL REQUIREMENTS

The application of advanced design and manufacturing technologies will shorten by an order of magnitude the duration of the specify–design–produce cycle. It will be possible to customize equipment to a variety of specific adaptations by making small, modular engineering changes. This will create the need for a new corps- or division-level staff officer who understands field requirements and can communicate with manufacturers. This officer will have both military and manufacturing expertise and will serve as a filter, separating serious requests from frivolous ones. Field personnel will be involved in the process as well, with influence over equipment and weapon systems design and specifications and frequency of review. Specification and requirement processes can be expected to improve if field personnel are given the motivation and ability to affect weapons systems development.

PARTS COPYING

Three-dimensional sensor technology (x-ray tomography and others) will advance to the point that accurate measurements of a part's structure can be obtained in digital form. The ability to "grow" a three-dimensional part via etching and sintering is now in the embryonic stage. By combining these two technologies, a three-dimensional "copying machine" can be created. Today, such a machine would be able to produce only a narrow variety of products, with limited accuracy. However, by 2020 this concept will be a reality for a broad spectrum of parts.

Parts copying provides the user with a number of desirable capabilities, including:

- storing one part (the original) instead of many;
- making parts without an engineering description of the part;
- producing a solid new part based on damaged pieces that have been glued together (e.g., to "edit" the original part before copying it);
- substituting new materials into old designs;
- increasing or decreasing the scale of parts; and
- editing parts without going through the drawing stage (for instance, to add new mounting holes to a base plate).

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Issues in Manufacturing Technology

SOURCES OF SUPPLY

A requirement for multiple sources of major components by prime contractors or the establishment of dual-source manufacturing of end items may actually increase the cost of defense system acquisition. Long-term, mutually supportive prime vendor relationships develop better products and lower costs by:

- allowing a free exchange of technical information;
- providing an incentive for investment in cost reduction and productivity, which is supported by an enduring payback period; and
- reducing costs for proposal preparation, evaluation, and marketing.

Procurement of smaller quantities of defense systems may actually prohibit economic production by more than one source. Where small quantities are anticipated, source selection must weigh the probability of success by competing contractors, rather than pay for the insurance provided by maintaining multiple producers.

MATERIAL AND COMPONENT AVAILABILITY

U.S. manufacturers are increasingly dependent on offshore sources for basic manufacturing materials, processes, and components. This directly jeopardizes the readiness of U.S. defense forces and limits the ability to control the cost of defense systems. Broad-based management of critical materials will become increasingly important in order to ensure that new systems are not designed with the assumption that overly utilized materials will be available. Coordinated procurement of materials and components from selected sources in the United States will be necessary to retain access to critical manufacturing supplies, skills, and equipment. Automated design tools can be used to "reverse engineer" existing components to perform identically but with more readily available materials. Such tools must also be developed to reduce the cost of parts substitution. Similar tools would allow the original design team, working under a concurrent engineering concept, to select materials and conduct trade-off analyses, using availability criteria as well as current cost and predicted performance.

MILITARY VERSUS CIVILIAN RESEARCH AND DEVELOPMENT

Given the increasing commonality between military and civilian components and systems, many of the manufacturing technologies required to produce military items will be developed by the civilian economy. The major difference today in military requirements involves operating lifetimes, reliability, supportability, and flexibility of application. There are also significant differences between the military and civilian operating environments. Some unique military manufacturing requirements will exist for the following areas:

- *electronics*—electronic warfare and countermeasures, high-density power sources, expert systems (e.g., very-high-speed integrated-circuit hardware development language), high-frequency semiconductors (nanoelectronics), and radiation-hardened integrated circuits;
- *biotechnology and biochemistry*—chemical defense, rapid detection and characterization of microorganisms, novel materials, deployable bioproduction of fuel, and antimateriel applications;
- *advanced materials*—munitions, armor, and ordnance; and
- *optics and photonics*—cooled focal-plane arrays, optical and digital devices integrated on a common substrate, and diode arrays.

INDUSTRIAL PREPAREDNESS

The ability of the U.S. industrial base to respond to mobilization situations is severely limited by (1) reduced investment in the standby capacity of equipment that has been laid away, and (2) lack of investment in the technology base, which is essential to maintaining state-of-the-art facilities and processes. Implementation of widespread mobilization agreements, prepositioned technical data packages, and planned producer lists may not provide sufficient materiel fast enough to support an emergency situation. Advanced flexible manufacturing facilities that are capable of rapidly converting production from commercial to defense products must be developed. As a result of smaller defense orders—fewer units over shorter schedules—many defense contractors will not be able to survive on defense contracts alone. This will also likely be true for subcontractors. Using commercial designs or systems that meet at least baseline military design specifications will provide a surge production potential. While these systems may not fulfill all Army requirements for battlefield durability or countermeasure hardness, their immediate availability will improve Army crisis reaction capabilities.

CAPITAL INVESTMENT AND FACILITIES

In a free economic system, investment dollars flow to ventures that provide a competitive return for the level of risk perceived by the investor. Fluctuations in defense spending and "winner-take-all" competitions have decreased the likelihood that good-faith investments will provide competitive returns to their investors. Accounting and profit regulations have simultaneously reduced the actual returns that investors do receive.

The Army has been encouraging "self-investment" by industry, in order to reduce its up-front expense and commitment to a weapon system. This approach is also intended to take advantage of the competitive innovation that emerges when industry must make the decision to invest its own capital. However, such investments must be accompanied by agreements to manufacture equipment over a sufficiently long period of time to recoup the funds that have been committed.

Flexible manufacturing systems, which can readily be converted for the manufacture of other product lines, reduce the risk to industry; however, multiyear contractual agreements or, if necessary, indemnification clauses are still required to ensure modern, cost-effective production facilities for defense materiel. Inadequate investment will only drive up the eventual costs of defense systems. It will be even more difficult for smaller firms to devote the necessary capital investment and facilities. If they fail to do so, the parallel investment of prime contractors will be undermined.

FLEXIBLE PRODUCTION SCHEDULES

The Army must plan for deliveries over time, allowing equivalent commercial production lines to produce military equipment during periods of low demand for commercial goods. The result will be the better use of existing facilities for both markets.

DESIGN FOR MANUFACTURABILITY

Manufacturability must be incorporated into component and systems designs from the outset. Ultimately, the cost and availability of products will be driven by their ease, flexibility, and capability of production. Planning for production, and particularly production in multiproduct, flexible, shared facilities, must start with the initial product concept.

CONCURRENT DEVELOPMENT

Although integrated development teams have advantages, there are still obstacles that must be overcome if concurrent development is to succeed in the defense sector. One problem with applying concurrent development to the defense sector is that it is difficult—particularly with technologically complex systems—to specify performance until the design itself is understood. Design teams often attempt to address this problem by an interactive process, in which ideas are tried and then modified. However, this process is expensive and time-consuming. Changes made to one part of a complex system often trigger changes in other parts, leading to an uncontrolled cost-complexity spiral. Because the iterative process in defense RDT&E generally yields only locally optimal designs, and ignores potentially revolutionary ideas, the design team must periodically submit its ideas to review by experts not associated with its specific program.

The requirement for occasional outside review is even more important for defense programs. Because the nature of the threat can change rapidly, performance specifications for military systems cannot exist in a vacuum. Potential threats not only change rapidly but adversaries attempt to anticipate and preempt weapon developments. Hence, the assumptions on which the specifications were based may change radically, frequently to the point that initial design approaches are superseded. The requirement for including doctrine and threat analysis in the initial system design phase must be imposed throughout the development process. The parallel in the commercial sector—market research—is not so dynamic. Trends and desires in the civilian marketplace can be plotted and predicted in stable evolutionary terms and are not subject to radical change. Initial specifications for a new product will generally hold up throughout the development process, barring the introduction of superior products by rival firms. The basic problem for defense manufacturing can be illustrated with a traditional mechanical system. Specifications for a new tank might reasonably call for armor that will resist all existing enemy rounds. The designers might, therefore, choose a thick, hard ceramic material. However, the resulting tank might be too heavy to transport to remote theaters and too expensive to acquire in adequate numbers. Field commanders might actually prefer a larger number of more agile, somewhat more vulnerable tanks.

This problem is exacerbated when dealing with computational systems. Computational technologies can change the battlefield so fast that users rarely have a full understanding of the technology's capabilities or limitations. Even experts predict performance poorly because the hard part of programming is understanding the problem in precise, formal terms. It is difficult to predict how a new system will affect field operations. Branch schools will normally generate a requirement for an evolutionary system, ignoring new possibilities that extend across branches and may render their existing skills obsolete. Finally, the development cycle is simply too slow for computational progress.

For example, it is proving difficult to develop specifications for battlefield robot systems because no one has ever fought on a battlefield dominated by such systems. Even if the defense community could develop the right systems, they probably would not work without changes in tactics. The enemy may respond so successfully that the whole investment becomes obsolete (since computer programs are much less adaptable than humans), unless the military can adequately model and simulate the use of novel systems to be able to anticipate the opponent's response before specifications are established.

In short, it is not enough to demand "concurrency" in development (or other manufacturing goals such as Total Quality Management), as an addition to or substitute for the current informal development process. The demand is likely to overwhelm the design team with too many details at once; it may allow poorly grounded "intuitive" decisions and create new opportunities for failure. Instead, new theories for structuring design processes are needed. These theories must allow the modeling of environments, alternatives, and manufacturing processes at varying levels of detail. The models must be able to evolve as goals are modified, constraints are added, and decisions are made. They must allow incremental modifications yet encourage radical redesign. And they must permit the deep exploration of critical aspects of the problem, while other aspects remain abstract.

The use of such formal, layered models is established practice for U.S. software and digital hardware developers. However, for complete systems, and particularly for those involving mechanical components, short-term solutions must be based on methodologies imported from overseas, such as the Quality Function Deployment methods used in Japan or a variety of highly structured methods developed in Europe. In the longer term, U.S. researchers are beginning to produce new, theoretically based models of the design process. These efforts focus on various aspects of the problem: providing a rigorous basis for ordering design decisions so as to reduce the interactions, understanding the mechanisms by which design problems are divided into smaller problems, and generating abstraction hierarchies. Although no consensus has been achieved, rapid progress is being made.

In addition to technical advances, managerial changes will be needed. Small teams of imaginative tacticians and technologists must have the freedom and resources to explore new ideas. One solution might be a laboratory associated with a national training center, manned by a mix of soldiers, civilians, and contractor personnel. The individuals could test new ideas in software and hardware with advanced simulation technologies before large contracts are specified.

Finally, contemporary industrial practice suggests that projects must be commanded, not administered, by senior warrior-technologists. Successful industrial companies develop broad and deep expertise by rotating personnel among design, marketing, research, and manufacturing duties, and by using a flat hierarchy with relatively few, but broadly experienced, managers. They pick their best leaders to head projects, then give them wide latitude and authority. These leaders remain in place throughout the development process; they are rewarded with the organization's highest positions if they succeed and punished if they fail.

The lesson is that, as in war, concurrent development demands agility, synchronization, teamwork, and leadership. Creating the leadership to support such a development process will require substantial changes in the way the Army manages career tracks and rewards its officers: staff bureaucracies must be systematically decreased; command tours must be extended; command opportunities for technical experts should be increased; accountability for development failures must be strengthened; and project managers should have increased decision-making authority.

ENVIRONMENTAL AND LEGAL ISSUES

The outflow of toxic materials from stacks and waste pipes cannot be tolerated because of its impact on the environment. State environmental protection laws and federal guidelines continue to restrict effluent contamination. Such regulations are tightening where they already exist and are spreading to all jurisdictions. Defense manufacturers are already feeling the impact of recent regulations that restrict how they dispose of their most hazardous wastes. "Grandfather clauses" that allow continued production under new regulations will gradually expire.

The cost of installing total pollution control may become too great for fragmented, multiple manufacturing sites. Some consolidation of the most hazardous processes will therefore be required. However, careful design and new production technology can also reduce the amount of pollution by using processes and materials that do not result in toxic wastes. Advanced treatment methods, including the use of biological agents, may also reduce the impact of manufacturing on the environment. Court decisions (such as those involving U.S. Department of Energy facilities) will gradually get the attention of government and industry managers alike, motivating them to address these issues in order to keep the costs of defense systems from skyrocketing.

PART IX

ENVIRONMENTAL AND ATMOSPHERIC SCIENCES

ENVIRONMENTAL AND ATMOSPHERIC SCIENCES TECHNOLOGY GROUP

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Summary of Findings for Environmental and Atmospheric Sciences

Throughout history three primary factors have framed battlefield engagements: the relative capabilities of the opposing forces, terrain in the area of operations, and weather. Adverse weather combines with difficult terrain to limit mobility, lethality, and intelligence of enemy and friendly forces alike. Coping with adverse weather and weather-induced changes in terrain is one of the elements of friction on the battlefield that "distinguish real war from war on paper." Clausewitz added that this element is a "force that theory can never quite define," but which effective command can mitigate. However, as we approach the twenty-first century, field commanders bring with them to the battlefield more than experience and guile; dramatic advances in dynamic real-time terrain mapping and in small-scale weather forecasting will continue to improve the quality and accuracy of these hitherto elusive tactical inputs in planning impending or ongoing operations.

In general, militarily useful forecasts require not only time and position information commensurate with civilian meteorology but also information on the shorter scales of time *and* distance that are so important to combat operations. As combat operations become more sophisticated, emphasizing force mobility and high-technology sensor systems, it is increasingly important that the army have a comprehensive data base for:

- characterizing the environmental features of the land masses of the globe;
- determining the degree to which the condition of these features can and does depend on the weather;
- identifying the variability of the weather as a function of locale; and
- providing its forces with the capability to sense and interpret the current condition of the atmosphere and the terrain.

Ideally, the Army should have sensing and modeling equipment *in the field* that can provide timely and sufficiently condensed forecasts of the weather and evolving terrain conditions to be useful in planning an impending or ongoing operation.

The Persian Gulf war illustrates the importance of environmental and atmospheric circumstances in military planning. Operational plans and logistical support had to take into account the effects of dust as well as mud on equipment and soldiers. Weather also became a major input in the decision-making process which set the timing of the ground campaign. And, while target acquisition was generally facilitated by the desert conditions, the United States and its allies did have to face what was undoubtedly the most extreme use of battlefield obscurants in history: hundreds of oilfield fires.

The rather dramatic opportunities in environmentally responsive military planning are an outgrowth of two emerging technologies. One is the growing capacity of digital equipment to store vast quantities of terrain and atmospheric data, to selectively retrieve and process appropriate subsets of those data, and to rapidly display the combat implications. The other enabling technology is the evolution of sensors and vehicles (frequently airborne or space-based) that can acquire data over a broad area with dramatic precision. A vigorous adaptation of these technologies is absolutely essential to the optimal use of Army personnel and materiel and to the formulation of strategy and tactics.

It is also essential to note one caveat: there are inherent limitations on the reliability of weather forecasting. These limits depend intimately on the region of interest, the accuracies needed, the access to frequent inputs from a sensor network that "feeds" the forecasting model, and the model itself. As an illustration, the Technology Group notes that (1) the weather rarely brings surprises in the Mojave Desert, but (2) there were at least three occasions during August 1989 on which the weather in the Boston area was diametrically opposite from the civilian forecast 12 hours earlier. Military planning and contingency force optimization do need ever-better forecasting, but no one should expect more than is permitted by the inherent limitations.

To remain at the forefront of future combat effectiveness, research and development (R&D) must proceed along the following lines:

- digital topography;
- terrain imaging sensors;
- terrain surface dynamics;
- atmospheric sensors and systems, with emphasis on remote sensors;
- mesoscale dynamic weather forecasting models (which accurately include the effects of moisture);
- transport and diffusion models; and
- atmospheric physics and technology of small-area weather modification.

Due to the breadth and complexity of these topics, the Group envisions the need for intensified cooperative research with the Air Force, Navy, National Weather Service, universities, and National Science Foundation, especially in the area of basic research.

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Terrain-Related Technologies

The Army's current Operations Manual for Air-Land Battle states:

> Terrain forms the natural structure of the battlefield. Commanders must recognize its limitations and possibilities and use it to protect friendly operations and to put the enemy at a disadvantage. Terrain analysis, intelligent preparation of the battlefield, and engineer operations are key to the operational use of terrain.

To fulfill the intelligence portion of this doctrine, Army units in the field must have at their disposal, and in a timely way, three kinds of data about the terrain:

1. the topographical characteristics of the domain of interest for the ongoing operation(s);
2. an up-to-date characterization of environmental features that are less permanent, such as roads, amount and type of vegetation, condition of the soil, and habitation; and
3. some capability to anticipate (forecast) changes in soil condition, as determined by current and expected weather, as well as by direct enemy actions, such as earthwork obstacles.

Data defining the relatively permanent topographical features of areas of interest can be gathered well in advance of any hostilities and stored digitally in central data bases, from which they can be retrieved quickly and in compact (digital) form. Remote sensing (via satellite and aircraft) and intelligence operations can also provide selective but increasingly comprehensive topographical information. Up-to-date information can also be gathered and transmitted to field units when confrontation in a given area is anticipated, or even after hostilities have begun.

For example, soil condition (including trafficability of roads) responds significantly to weather, in particular to precipitation. As a result, there must be an organic capability to infer from the data (i.e., soil type, water runoff patterns, and recent, current, and expected weather) valid expectations of changes in trafficability. In particular, it would be desirable to preprogram field equipment with a complex set of battlefield environmental analyses that could forecast tomorrow's trafficability implications of today's weather. This analysis would then be fed into the command decision-making process. Ongoing advances in sensor and communication capabilities, data processing, display, and microminiaturization (described in Part II, "Electronics and Sensors") all point to an opportunity to provide units in the field with dramatically better environmental information that is crucial to their mission.

DIGITAL TOPOGRAPHY

Classical representation of terrain topography on a flat map sheet has the intrinsic limitation of relying on both the cartographer who compiles it and the end user who reads it to interpret the correct terrain shape and features. Two recent advances in technology—the acquisition of digital imagery and the extraction of digital information from that imagery—have helped to overcome these limitations. However, these technological advances impose their own new problems, particularly the vast amounts of digital data that need to be stored. Traditional image films and map sheets, on the other hand, are excellent data storage media. But they are static and make data conversion, interpretation, manipulation, and transmission difficult.

The most critical problem to be solved involves the development of a three-dimensional global terrain data base structure that can be very rapidly queried to extract information on specific locations, and that can also be quickly updated with newly acquired imagery. Techniques are also needed to allow for on-line dynamic viewing and interrogation by field commanders, followed by the ability to generate hard-copy maps of selected areas of the data base.

The technologies needed to provide these capabilities would include (1) high-capacity, electro-optical storage media for the data base; (2) a powerful three-dimensional data base structure; (3) rapid processing of large data sets; (4) high-speed broadband data links; and (5) quick production of multicolor maps in the field from input digital data. Parallel advances in all five areas are needed to make fielded automated terrain analysis systems a reality. Also needed are off-the-shelf microprocessors that are highly efficient, powerful, compact, and capable of sophisticated parallel processing. The thrust of development will be reliable integration, not only between system components and central data bases (particularly extensive Geographic Information Systems) but also with data acquisition systems. One critical technology will be advanced artificial intelligence, capable of automated reasoning about terrain feature characteristics and their interaction with environmental factors. Detailed sensor data on local terrain and climatic conditions, and the ability to modify and update these data continuously, become integral components of the digital terrain data base. Local terrain topography will also be an important factor in weather prediction.

TERRAIN IMAGING SENSORS

Current imaging sensors are either passive (i.e., record essentially directional information) or active (record basically ranging information). Images thus obtained are two-dimensional representations of the three-dimensional world. Photogrammetric techniques can be employed to three-dimensionally reconstruct the object from overlapping images. In the future, imaging sensors will improve in both spatial and spectral resolution, with corresponding improvement in the ability to control the sensor's position and attitude during imaging. It would be a major breakthrough in sensor technology to record three-dimensional data about the terrain directly. As an interim evolution, the sensor data should be at least partially processed on board the acquisition platform, so that terrain information can be acquired upon subsequent interrogation.

One of the most critical current problems involves automated feature extraction from digital imagery. Most current techniques work with single images. Powerful methods of feature extraction that directly process multiple overlapping images would yield substantial improvement in robustness and reliability. Neural-network technology (discussed in Part II, "Electronics and Sensors") should be vigorously pursued, particularly as applied to the problem of automated feature extraction. Another emerging approach is so-called hyperspectral image exploitation, where imagery from a large number of spectral bands (over 200) is used for quick identification of features on the basis of possible uniqueness of electromagnetic signatures over the whole spectral range.

Multi-image registration based on object models is another critical problem, the solution to which will make possible quick-response presentation to the user. The continually evolving technology of digital stereo image correspondence and matching, used in machine vision, should be pursued as well. Robust methodologies combining signal or area-based matching, feature matching, and relational matching hold the most promise, particularly when incorporating model (data base) target or feature projection in image space. Supplementary knowledge-based information will enhance the reliability and accuracy of the resulting systems.

TERRAIN SURFACE DYNAMICS

The surface of the terrain where battles are fought is quite dynamic, sometimes changing quite significantly within a short period of time. Such changes may be induced by weather; they may also be engineered by the enemy as passive defenses. Soil conditions in particular, including the passability of roads, vary dramatically with weather (i.e., rain) and recent traffic; however, given sufficient data on soil type and runoff patterns, as well as recent and future weather, it is possible to make reliable predictions of road conditions.

Systems capable of producing this sort of real-time state-of-the-terrain analysis will be of immense value to the commander. Such a system will require accurate modeling, to which topography, weather data, and other current sensor data are inputs. To realize this, technological advances will be required in the areas of high-resolution sensors, direct observation, and near-real-time processing. Most promising will be hyperspectral sensing, which provides not only surface characteristics but also subsurface conditions. Very efficient, fast, and redundant techniques for detecting changes, as well as for target orfeature detection and interpretation, will be required. Technology requirements for these abilities are artificial intelligence (particularly neural networks), integration of the knowledge base, and fast exploitation of hyperspectral imagery.

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Weather-Related Technologies

Tactical and operational exploitation of surprise, mobility, and concentration of close air support and artillery firepower demands reliable knowledge and anticipation of the weather in the operational region by field commanders. Target acquisition, weapons guidance, surveillance, damage assessment, and combat mobility all depend significantly on recent and current weather. Accordingly, in the field, there must be the ability to acquire, receive, store, analyze, and use timely data on the state of the atmosphere. In particular, sensors dispatched or controlled within the battle area must be either (1) robust against enemy countermeasures or (2) redundant and expendable.

There must also be digital equipment and software, again in the field command center, to synthesize the data collected into an accurate, real-time picture of the weather conditions on and around the battlefield. Weather officers will operate with a data set generated by sensors that are typically distributed on a sparser grid than that on which the information is needed. A digital forecasting capability should include computational models of atmospheric behavior from which one can anticipate with some reliability the weather that will prevail on the field of operations from 12 hours to 2 days ahead and from which one can obtain "nowcast" (in contrast to "Forecast") interpolations to improve resolution.

There is, of course, an intrinsic limitation on the extent to which the weather can be predicted. The Army should contribute to improvements in weather forecasting especially on the shorter time and distance scales that are uniquely important to the Army; but it must do so with a clear awareness of the limited gains in resolution and in forecast time that can be realistically expected. These improvements are receiving increasing attention in the civilian arena.

ATMOSPHERIC SENSING

The Army is responsible for atmospheric sensing in support of its immediate area of operations in the territory immediately forward of the division tactical operations center. The Army must measure meteorological parameters as required for battlefield-scale weather forecasting or as needed to provide corrections by artillery meteorological teams. Three sequential processes are used to provide weather intelligence:

1. collection of environmental observation data;
2. automated collation, processing, analysis, and application of forecasts to predict effects; and
3. dissemination of intelligence products on weather and environmental effects to the user.

Environmental data from across the battlefield must be collected and transmitted to a processing point as the first step in the development of weather forecasts. A variety of environmental data are needed for different missions. For example, observations taken in the target area are important during aviation mission planning to determine whether to employ precision-guided or conventional munitions. Observations of winds and atmospheric stability are required to defend against the enemy's use of nuclear, biological, and chemical (NBC) weapons or to employ battlefield obscurants. Measurement of cloud heights is critical prior to the use of smart artillery munitions. Atmospheric moisture content can significantly affect infrared and laser systems. Prediction of wind velocities and wave or surf conditions is also vital to the conduct of logistics over the shore operations.

The advent of new weapon systems involving more sensitive and sophisticated guidance and target engagement subsystems or utilizing directed energy outputs will require even more environmental parameters to be measured. These measurements may be required along the path of propagation as well as in the target area; they must also provide information on target contrast and energy dissipation in order to enable expensive weapon systems to be used with maximum effectiveness. The spatial and temporal resolution of these environmental measurements must be compatible with the systems and models they support, but, in general, spatial resolution of a few kilometers and temporal resolution of 30 minutes will be adequate.

On the battlefield of the twenty-first century, most of this environmental information will have to be gathered with remote-sensing techniques. Sensors flown on unmanned air vehicles (UAVs) and perhaps dropped in the target area will be located throughout the battlefield. Revolutionary developments in autonomous terrain-following UAVs will be needed to provide coverage in the lowest levels of the atmosphere. It may be possible to extract environmental information from smart weapons—for example, cloud base heights and visibility in the target area. Surface-based sensors will also probe the atmosphere with electromagnetic or acoustic energy. The third type of remote sensing involves satellite-based, cloud-penetrating sensors that will take imagery in all wavelengths from the ultraviolet to the microwave. This will place increased reliance on satellite Light Detection and Ranging and radars. In order to meet the resolution requirements, however, revolutionary progress in microwave or millimeter-wave sensing will be required. Both active and passive remote-sensing techniques need to be investigated. At present, few atmospheric parameters can be measured using passive techniques, while active methods provide the enemy with a target. The development of passive remote-sensing technology for use on or near the battlefield represents a major theoretical and engineering problem.

Environmental data from all sources must be transmitted to analysis points, and space assets may be used to facilitate communication of environmental data. Because important decisions committing troops and material may be made on the basis of intelligence provided by these environmental sensors, redundancy in the collection of data could be of great importance. Thus, it may be ill-advised to discard any information available from any sensor. The collection, processing, and subsequent dissemination of the resulting intelligence will be an important part of the sensing technology.

Consequently, the problems faced in the future of atmospheric sensing involve four issues:

1. what must be measured;
2. where it must be measured;
3. how it must be measured; and
4. how covertly the measurement can be made.

A wide range of technology developments will contribute to solving these problems. The most fundamental will be (1) the means to transmit the resulting data to locations where it can be analyzed and (2) the data processing technology that will allow future battlefield systems to handle these large amounts of data. Also important are the developments in the laser and radar sources, particularly their tunability, power, pulse length, and lifetime. Multispectral methods are expected to dominate future remote sensing, which will require broadband tunability of sources (see Electronics and Sensor Technology Forecast). The spatial resolution needed, at the ranges over which systems will be required to operate, will demand substantial improvements in efficiency, power output, and reduced pulse lengths, in order to operate from remote platforms and still provide adequate data near the ground. Detector technology must also be improved because these broadband systems will always be noise-limited. Signal processing will have to be incorporated into the sensor itself to minimize the data communication loads as well as to decentralize the data processing functions. Also contributing will be improved position location technology, to locate the sensors automatically in space and time. New "smart" sensing methods will also have to be developed to address unforeseen requirements for data.

Evolving technologies that are also expected to contribute to solving these problems include the following:

- sensor-based intelligence and signal processing;
- battlefield data dissemination systems;

- knowledge of the physics of electromagnetic/acoustic energy interactions with the atmosphere;
- environmental sensing and data communication by weapon systems;
- small-signature, passive sensing systems;
- low-level sensing by autonomous terrain-avoidance UAVs; and
- cloud-penetrating satellite sensors.

WEATHER MODELING AND FORECASTING

Weather has always played a decisive role in warfare. Combined with the smoke, dust, and obscurants induced by or intentionally introduced to battle activity, weather will have a larger role and bigger impact on the outcomes of future battles. It is the single decisive factor affecting combat power over which the commander has little or no control. History provides many examples of battles won or lost because of the impact of weather.

The future battlefield will also be filled with sophisticated reconnaissance, surveillance, target acquisition, communications, and weapon systems. These systems all exploit some part of the radiant energy spectrum, from acoustic energy near 1 Hz to ultraviolet energy near 10^{15} Hz. The radiant energy associated with or sensed by these systems is affected by weather conditions that change constantly, yet frequently determine whether or not the systems perform satisfactorily.

Army tactical units must have the capability to receive, assimilate, and process weather information from space, upper atmosphere, and surface sensors and to prepare weather-related decision aids. Forecasts must be keyed to those areas of the battlefield that encompass the commander's area of interest, which revolves around how far his soldiers, or the enemy, can travel or shoot during the period of an operation. Thus, the period (and spatial extent, and resulting resolution) of the required weather forecast depends on the level of command and ranges from one-half day to several days, with a spatial resolution as small as 20 km.

Since the Army must be prepared to fight anywhere in the world and at all levels of conflict, its weather data collection and forecasting capability must also be capable of semi-autonomous operation. The Army cannot rely solely on civilian weather networks or centralized weather processing centers during wartime. Moreover, the standard weather forecasts should be augmented by predictions of the values of the larger set of relevant meteorological parameters.

Civilian weather forecasting is currently carried out using models with necessarily coarse spatial resolution. Along with the large-scale, first-principle modeling of the atmospheric physics, these models include parameterized representations of mechanisms whose phenomenology occurs on a smaller scale. However, most of the subscale phenomena, including precipitation events, are not well understood. Furthermore, the extreme sensitivity of atmospheric models to small changes in the choice of initial conditions puts inherent limitation on the accuracy and reliability of weather advisories beyond three to five days.

Improvements are certain to emerge in civilian forecasting, and the Army should interact with and draw upon these efforts. For example, development is now proceeding on meteorological models for regional use that have a smaller resolution scale and that rely for data on sensors that can be fielded, when needed, on a grid commensurate with that scale. It is worth noting that U.S., European, and Japanese meteorological centers are already beginning to utilize grids of 30 km or smaller in nested models.

Another development of potential interest to the Army is the use of computers to generate powerful displays of current and forecast weather conditions, including animated maps. Finally, the meteorological community is exploring the applications of artificial intelligence to weather forecasts, warnings, and decision aids. The following attributes of artificial intelligence promise to be the most important:

- machine encoding and processing of the plethora of rules and procedures used by meteorologists in making forecasts;
- the ability to identify and extract significant data and information available from a diverse set of origins;
- the fusion of knowledge of the state of the atmosphere derived from heterogeneous sources;
- rapid processing of decision-assistance information; and
- automation of quality assurance.

To take advantage of these emerging capabilities, it is exceptionally important that the Army retain a first-rate competence in atmospheric modeling and an up-to-date awareness of the state of that field. The Army must promptly incorporate advances into its own models and maintain an independent, innovative capability to improve these models, with a particular emphasis on (1) battlefield scale, (2) modification of conditions by combat, and (3) impacts on tactics and systems performance (e.g., infrared sights and night-vision goggles).

TRANSPORT AND DIFFUSION MODELING

The Army has a substantial and growing interest in transport and diffusion (T&D) processes, stemming from concerns over nuclear, biological, and chemical (NBC) hazards, NBC agents, obscurants, and pollutants. T&D processes govern the manner in which substances such as NBC agents spread and dilute. Mathematical modeling of T&D processes allows quantification of the impact of various NBC agents, smokes, and pollutants on Army personnel, systems, and operations.

Any prediction of the transport of contaminants (whether inserted by our own or by enemy forces) can only be as accurate or as reliable as our ability to understand and predict the dynamic and thermodynamic state of the atmosphere. The reliability of transport prediction is also limited, usually severely, by uncertainties in the initiation process and our primitive understanding of turbulent mixing (dispersion) processes. Nevertheless, Army units with responsibilities for the use of atmospheric contaminants or defense against them should soon be able to generate requirements for atmospheric models that can support realistic prognoses of contaminant transport and diffusion. Smaller digital equipment with larger capabilities will further reduce the burden of atmospheric modeling.

Over the next 30 years, T&D modeling will be a basic element for the following:

- predicting the chemical and biological capabilities of our enemies, which will help determine the adequacy of soldier protective equipment on the NBC battlefield;
- predicting the performance and effectiveness of U.S. countermeasures to chemical warfare;
- making real-time predictions of NBC threats (in combination with remote-sensing surveillance);
- the use of combined-arms war game simulations, where the reliability and accuracy are heavily dependent upon realistic modeling of the battlefield environment; and
- designing military weapons and vehicles, where T&D principles apply to chemical reactions and mixing that affect combustion and propulsion.

Besides its application to warfare, T&D modeling will be used for a variety of other tasks important to the Army and the nation. T&D processes govern the rate in which carbon dioxide and other pollutants enter and are removed from different layers of the atmosphere. The levels of these pollutants affect the manner in which the global climate is changing. T&D modeling also has application in treaty verification, allowing the calculation of the source location of agents. Similar calculation methods can be used to aid in the detection of drug manufacturing factories and the fields where the plants are grown to produce the drugs.

Breakthroughs in methodologies for solving nonlinear stochastic and probability equations for physics, chemistry, and meteorology, will allow more realistic modeling of T&D processes. During the next 30 years, the speed and storage capacity of computers will be increased by a factor of over 1000, and communications will show similar if less dramatic improvements. These advances will allow much greater incorporation of T&D processes and concepts into military applications.

WEATHER MODIFICATION

It would be of great value to the Army to acquire even a modest capability to modify the weather. Obvious examples would be clearing fog over a limited region or initiating precipitation—again over a selected but limited area. We are not aware of any particular progress that is encouraging in this regard, or even of any intensive effort that is currently being conducted. The status of research in weather modification is not sufficiently advanced to merit any significant Army investment. However, the value of such a capability would be so great that we recommend that the Army continue to reconnoiter this field of research and that it be prepared to join such an effort, if there were a reasonable basis for optimism.

General Background References

Bonner, W.D. 1989. NMC Overview: Recent progress and future plans. Weather and Forecasting 4(September):275–285.

Caughey, S.J., and P.W. Davies. 1989. Defence services branch 50th anniversary. Part I: Historical aspects. The Meteorological Magazine. 118(1405).

Ghil, M., R. Benzi, and G. Parisi (eds). 1985. Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics. Amsterdam: North-Holland Publishing.

Nile, F.E., M.G. Heaps, R.C. Shirkey, L.D. Duncan, and M.A. Seagraves. 1989. Propagation environments, effects, and decision aids. Proceedings of the Fall 1989 AGARD Electromagnetic Wave Propagation Panel Symposium on Atmospheric Propagation in the UV, Visible, IR and MM-Wave Region and Related Systems Aspects (Copenhagen, Denmark. Oct. 9–13, 1989).

Racer, I.R., and J.E. Gaffney, Jr. 1986. The potential role of artificial intelligence/expert systems in the warning and forecast operations of the National Weather Service. Paper no. AIAA-86-0419, presented at 24th Aerospace Sciences Meeting, Reno, Nev. January 6–9.

Ray, P.S. (ed.). 1986. Mesoscale Meteorology and Forecasting. Boston: American Meteorological Society.

TRADOC. 1987. Joint Operational Concept for Weather and Environmental Support to Army Operations. PAM 525-21 and MAC PAM 105-3. Headquarters, U.S. Army Training and Doctrine Command. Fort Monroe, Va 23651–5000, July 10.

Turton, J.D., and S.J. Caughey. 1989. Defence services branch 50th anniversary. Part II: Current commitments and the future. The Meteorological Magazine. 118(1405).

U.S. Army Intelligence Center and School. 1988. Draft Report on Weather Effects and Information Handbook, Fort Huachuca, Ariz. October.

APPENDIX A

THE COMMITTEE ON STRATEGIC TECHNOLOGIES FOR THE ARMY

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Appendix A

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John K. Harkins, Texas Instruments
Walter B. LaBerge, Lockheed Corporation (Retired)
Wilbert Lick, University of California, Santa Barbara
Edward M. Mikhail, Purdue University
Gregory A. Petsko, Brandeis University
Richard S. Shevell, Stanford University
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Ronald D. Sugar, TRW Space Communications Division
Richard P. Wishner, Advanced Decision Systems

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Catharine E. Little, Study Director, April 1990 to April 1991
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Donald A. Siebenaler, Senior Staff Officer, February 1991 to October 1991
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APPENDIX B

BIOGRAPHICAL SKETCHES
STAR SCIENCE AND TECHNOLOGY SUBCOMMITTEE

Appendix B

Biographical Sketches

DAVID H. BRANDIN Mr. Brandin is currently Senior Vice President of International Operations at Interop Inc. Prior to this he was Vice President of A.T. Kearney Technology Corporation and was responsible for all technology-oriented consulting activities in the information technologies (computing, communications, and electronics) and intellectual property rights. Before this, Mr. Brandon organized the Information Services and Systems Division, International Management and Economics Group at the Stanford Research Institute International (SRI) and founded the Computer Science and Technology Division, also at SRI. Mr. Brandin's specialties include research management in computer science, telecommunications, strategic and competitive software issues, international industrial and government technology strategy relationships, and the techno-legal issues in the information technologies.

GEORGE F. CARRIER Professor Carrier is presently Professor of Applied Mathematics at Harvard University. His current work is in the areas of dynamics of tsunami and atmospheric vortices, growth and propogation of large fires, phenomena in internal combustion engines, and centrifugal phenomena. His subspecialties include fluid mechanics and the combustion process. Professor Carrier is a member of the National Academy of Sciences and of the National Academy of Engineering and is a Fellow of the American Academy of Arts and Sciences.

YET-MING CHIANG Professor Chiang is currently Kyocera Professor of Ceramics at the Massachusetts Institute of Technology. His research experience has covered such topics as the effects of microstructure and grain boundaries on the properties of electronic ceramic systems including high T_c oxide superconductors, strontium titanate, and barium titanate; processing of high-thermal-conductivity aluminum nitride for packaging applications; interfacial reactions in ceramic composites; and synthesis of spin-on superconducting thin films from polymeric precursors. Professor Chiang's current research interests include defect structure–property relationships in nonstoichiometric and multicomponent ceramic materials; chemistry, structure, and properties of ceramic grain boundaries; microstructure development in ceramics; reaction-formed structural ceramics and composites; and analytical electron microscopy of ceramics.

RUTH M. DAVIS Dr. Davis is currently President of the Pymatuning Group, Inc. Prior to this, she worked for various private and government firms including the U.S. Department of Defense, the National Bureau of Standards, the Department of Commerce, and the Department of Energy. Dr. Davis has done research in such areas as automation, electronics, computers, and energy. She is a member of a number of professional societies including the National Academy of Engineering, the American Association for the Advancement of Science, and the National Academy of Public Administration. In 1972, Dr. Davis was awarded with a Gold Medal from the Department of Commerce and in 1984 she received the Ada Augusta Lovelace Award.

LAWRENCE T. DRZAL Dr. Drzal is currently Professor, Department of Chemical Engineering, and Director of the Composite Materials and Structures Center, College of Engineering, at Michigan State University. He has served as Associate Editor for the *Journal of Adhesion* as well as reviewer for a number of journals. Dr. Drzal has done consulting for such organizations as the National Academy of Sciences, Naval Surface Weapons Center, and ALCOA. In 1979, he received the Charles J. Cleary Scientific Materials Research Award from the Air Force Materials Lab, and in 1981 he was presented with the Air Force Scientific Achievement Award. Dr. Drzal is a member of many organizations including the American Chemical Society, the Society for the Advancement of Material and Process Engineering, and ASM International, and is the author or co-author of numerous publications.

JERRY W. ELVERUM, JR. Mr. Elverum is retired from the Applied Technology Division of TRW's Space and Defense Sector. For almost 40 years, he played important pioneering roles in rocket engine research, most of the nations' ballistic missile programs, space systems of all kinds, and in the development of high-energy lasers and other directed energy devices. Mr. Elverum received a "Special Achievement Award" from the ASME in 1971 and the "Outstanding Engineering Merit Award" from the Institute for the Advancement of Engineering in 1972. He is a member of the National Academy of Engineering.

ROBERT R. EVERETT Mr. Everett has been a pioneer in the development of digital computers. He has worked at the Massachusetts Institute of Technology on such development, as well as for The MITRE Corporation. Currently, Mr. Everett is a Senior Scientist of the Air Force Scientific Advisory Board and a member of the Federal Emergency Management Agency's Advisory Board, the Defense Science Board, the Strategic Defense Initiative Advisory Committee, and Chairman of the Federal Aviation Administration Research, Engineering, and Development Committee. He is a member of the National Academy of Engineering and has received The Department of Defense Medal for Distinguished Public Service and, in October 1989, from President Bush, the National Medal of Technology, the nation's highest honor in this area, for his work in real-time computer technologies and applications.

EDWARD A. FRIEMAN Dr. Frieman is currently Director of Scripps Institute of Oceanography. Previously, he served as Vice Chairman of the White House Science Council and a member of the Defense Science Board. Dr. Frieman has done research in theoretical plasma physics, hydromagnetics, hydrodynamics stability, and astrophysics. He is a member of NAS and the American Association for the Advancement of Science.

DONALD Y. FREDRICKSON Dr. Fredrickson is currently doing private consulting. From 1974 to 1975, he served as President of the Institute of Medicine. He has also worked in such places as the School of Medicine at George Washington University and the National Institute of Health. Dr. Fredrickson has been presented numerous awards, among them the Distinguished Service Award in 1971 and the Lorenzini Medal in 1980.

J. CHRISTIAN GILLIN Professor Gillin is currently a professor of psychiatry at the University of California, San Diego, and staff psychiatrist at the San Diego Veterans Administration Medical Center. He served with the U.S. Public Health Service for 14 years and in various capacities at the National Institute of Mental Health. He is presently a captain in the U.S. Naval Reserve and, in addition to his other positions, is director of the Mental Health Clinical Research Center at the University of California, San Diego. His specialties include affective and sleep disorders, and he has conducted research in the field of psychopharmacology.

CHRISTOPHER C. GREEN Dr. Green is currently head of the Biomedical Science Department at General Motors Research Laboratories. Prior to working at General Motors, Dr. Green spent 16 years with the Central Intelligence Agency where he served in various positions, including analyst with the Life Sciences Division, Chief of the Biomedical Sciences Branch, Deputy Division Chief, and Senior Division Analyst with the Office of Scientific and Weapons Intelligence. In this last role, he gained multidisciplinary research and management experience in medicine, comparative biology, bioengineering, animal and human physiology, endocrinology, and the life sciences. Dr. Green is the author of over 50 peer-reviewed technical publications.

ALFRED B. GSCHWENDTNER Dr. Gschwendtner is presently Leader of the Opto Radar Systems Group at the Massachusetts Institute of Technology's Lincoln Laboratory. Prior to working with this group, his work at Lincoln Laboratory was in such areas as penetration aids for strategic offense, infrared systems for strategic defense, image processing, optical fire-control systems, optical discrimination technology, and binary optics technology. The areas Dr. Gschwendtner is currently researching are coherent laser radars, smart weapons, automatic target recognition, neural networks, infrared search and track systems, and multisensor fusion.

JOHN K. HARKINS Mr. Harkins has worked with Rockwell International and the Army Research Institute. At his current position with Texas Instruments, he is doing planning and business development for the Strategic Development Defense Systems & Electronics Group. He spent seven years on the Advanced Scientific Computer project at Texas Instruments, working in such areas as software systems engineering, project management, and business development. In 1980, Mr. Harkins developed a concept for *electronic delivery of technical information* for the Army Research Institute. He has since spent much time working with DoD Science and Technology personnel on various programs including the Infrared Focal-Plane Arrays Program and the Defense Advanced Research Projects Agency's Strategic Computing Programs.

JONATHAN I. KATZ Dr. Katz is currently an Associate Professor with the Department of Physics at Washington University in St. Louis. He has done consulting for such groups as The MITRE Corporation, the Stanford Linear Accelerator Center, and Los Alamos Scientific Laboratory, and has served on committees of both the National Aeronautics and Space Administration and the National Research Council. Dr. Katz is a member of a number of professional societies including the American Physical Society and the American Astronomical Society. He is the author of a book, titled *High Energy Astrophysics*, as well as over 70 other publications.

WALTER B. LABERGE Dr. LaBerge is a member of the National Academy of Engineering and has served as chairman or member on several National Research Council committees, including his current position as Chairman of the Study Committee on STAR. He was one of the principal inventors of the Sidewinder air-to-air missile and led a team that designed the NASA Houston Mission Control Center for Apollo.

From 1973 to 1975, Dr. LaBerge served as Assistant Secretary of the Air Force, Research and Development, which he left to become Assistant Secretary General of NATO in Brussels, Belgium. In 1986, he was appointed Under Secretary of the Army, a post he held until 1979. Dr. LaBerge is currently retired from the Lockheed Corporation where he held various positions including Executive Assistant to the President; Vice President, Planning and Technology; and head of the Research and Development Division.

JOHN J. LEWANDOWSKI Dr. Lewandowski is currently an Assistant Professor in the Department of Materials Science and Engineering at Case Western Reserve University. After completing his Ph.D. at Carnegie-Mellon University, Dr. Lewandowski did postdoctoral work at the University of Cambridge with the support of a NATO Postdoctoral Fellowship in Science and an ALCAN Research Fellowship. In addition to teaching, he has done consulting for a number of organizations including Dow Chemical and the United States Air Force Materials Laboratory, High Temperature Materials Group. Dr. Lewandowski has been the recipient of several awards, among them, the ASM Bradley Stoughton Award for Young Teachers and Presidential Young Investigator from the National Science Foundation. He is the author or co-author of numerous publications.

WILBERT LICK Dr. Lick has spent much of his career in academia, working at such universities as Harvard and Case Western Reserve and is currently at the University of California, Santa Barbara. He has done work or consulting for such organizations as the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, and Rockwell International Science Center. Dr. Lick is the author or co-author of numerous articles and a book, *Difference Equations from Differential Equations.* He was the recipient of a Guggenheim Fellowship in 1965 and the Fulbright-Hays Award in 1978.

JAMES G. LING Dr. Ling is President of Ling Technologies, a firm dedicated to expediting the use of federally developed technology and products by American industry. Prior to this, Dr. Ling served in the Air Force from 1954 to 1975 when he retired from active duty with the rank of Colonel. After his retirement, he joined The MITRE Corporation as a Group Leader in the Energy Resource and Environmental Systems Engineering Department. Dr. Ling went on to work for the U.S. Department of Energy as director of Program Implementation in the Office of Field Operations Management (Energy Research) and later for the Office of Science and Technology Policy, Executive Office of the President, where he served as Assistant Director for Institutional

Relations as well as Acting Assistant Director for Life Sciences. He was responsible for overseeing all federal laboratories and was Executive Secretary for the White House Science Council's Federal Laboratory Review Panel. Before leaving the federal government to start his own company, Dr. Ling worked on the staff of the President's Blue Ribbon Commission on Defense Management as Advisor to the Chairman.

ANTHONY F. LOPRESTI Mr. LoPresti is currently a consultant, retired from the Ford Aerospace Corporation. He retired from government service in 1987. He has more than 35 years of air defense problem solving experience ranging from field engineering to future weapons concepts. Mr LoPresti was the principal TRADOC Air Defense contact for the MICOM Advanced System Concept Office and was a co-developer of the TRADOC "Architecture for the Future Army."

GORDON J.F. MACDONALD. Dr. MacDonald is currently Vice President and Chief Scientist of The MITRE Corporation. He works, as well, as senior advisor to the country's national security agencies and is conducting research on such topics as new methods of signal processing, the nature of acid rain, and climate change. Dr. MacDonald has taught graduate and undergraduate courses in physics, geophysics, environmental studies, and government. His research in such fields as upper atmospheric physics, the nature of the earth's interior, weather modification, and the history of the moon and planets has led to the publication of over 120 papers and monographs as well as a book, *The Rotation of the Earth*, which he co-authored with Walter Munk and which received the American Academy of Sciences Monograph Prize for 1959. Dr. MacDonald has also published over 100 classified reports and papers and a number of unclassified papers on topics such as naval strategy, communications, command and control, air defense issues, and nuclear weapons, which have stemmed from his work on national security affairs.

BERT W. MAIDMENT, JR. Dr. Maidment is currently director of the Life Sciences Department at the Midwest Research Institute, where he is responsible for the technical and administrative direction of R&D activities in the areas of analytical systems development, biological and pharmaceutical analysis, biobehavioral sciences, product chemistry and analysis, and toxicology and metabolism. He has worked in both the private and government sectors for such organizations as the Central Intelligence Agency as Executive Secretary of the Science and Technology Intelligence Committee, and Johnson and Johnson Research in the Pharmaceutical Research Department.

LOUIS C. MARQUET Dr. Marquet is currently Vice President for Directed Energy Systems at Nichols Research Corporation in Vienna, Virginia. Prior to this work, he spent a number of years doing government work for such agencies as NASA and the Defense Advanced Research Projects Agency, where he served as Director of the Directed Energy Office, with responsibility for advanced research efforts in directed energy technology and applications, including high-energy lasers, energetic particle beams, and submarine laser communications. Dr. Marquet also served as a member of the Systems Subpanel of the Fletcher Defense Technologies Study Team, which paved the way for the Strategic Defense Initiative Program. He later was appointed the first Deputy for Technology of the Strategic Defense Initiative project offices, in which capacity he managed all the technical research projects within the program.

BRIAN P. MCCUNE Dr. McCune is Managing Partner, Technology Group, at Montgomery and Associates. Previously, he was President of McCune & Associates, Inc., a consulting firm he founded in 1992 to provide services in advanced decision-making computer systems and high technology, generally to government, aerospace and defense, and commercial clients. Dr. McCune is a nationally recognized expert in artificial intelligence, software systems, information retrieval, decision support systems, distributed computing, and technology transfer. His professional experience includes such positions as a software engineer, a computer science researcher, and a manager of software R&D. Dr. McCune is a member of a number of professional societies including the American Association for Artificial Intelligence and the Institute of Electrical and Electronics Engineers.

THOMAS C. MCGILL, JR. Dr. McGill is presently Fletcher Jones Professor of Applied Physics at the California Institute of Technology. His current research interests are in the broad area of microstructures for modern electronics. Some of his contributions include: the first application of superlattices to sensors in the infrared; the invention and development of new two- and three-terminal devices based on tunneling; and the use of modern epitaxial techniques to produce visible-light emitters. Results of Dr. McGill's research have been reported in over 250 research publications and numerous technical presentations. Dr. McGill has served as a member of the Defense Advanced Research Projects Agency's Materials Research Council and as chairman of its Steering Committee.

EDWARD M. MIKHAIL Dr. Mikhail is currently in charge of graduate instruction and research in photogrammetry, data adjustment, and digital mapping at Purdue University. Prior to this, he spent three years with private industry as an analytical photogrammetrist and two years as an instructor at Cairo University. Dr. Mikhail has done consulting for both the government and industry, including the U.S. Army Map Service, the U.S. Department of Justice, the Defense Mapping Agency, Ford Aerospace Systems, General Dynamics, and General Electric. Dr. Mikhail has authored or co-authored five books and has written or presented over 150 papers and reports. In 1976, he received the Photogrammetric Award of the American Society for Photogrammetry and Remote Sensing, their highest technical award, and in 1978 and 1979 he received the coveted Alexander von Humboldt Senior Scientist Award.

WALTER E. MORROW, JR. Dr. Morrow is currently Director of the Massachusetts Institute of Technology's Lincoln Laboratory. He has done research in such areas as ionospheric and tropospheric radio communication and propagation, orbital scatter communication, orbital dipole experiment, communication satellites, and lunar and planetary radar studies. Dr. Morrow is a member of the National Academy of Engineering and the Institute of Electrical and Electronics Engineers.

ROGER N. NAGEL Dr. Nagel is currently the Harvey E. Wagner Professor of Manufacturing Systems Engineering at the Iacocca Institute at Lehigh University. He was the founding director of the Manufacturing Systems Engineering graduate program at Lehigh, as well as director of the Center for Design and Manufacturing Innovation. Dr. Nagel teaches courses and advises students in the areas of manufacturing planning and control, computer integrated manufacturing (CIM), robotics and intelligent machines, networks, and information systems. He also conducts graduate seminar courses in special topics such as linking strategy and technology in the enterprise and measuring flexibility in modern manufacturing systems. His current research activities and interests include the strategic use of information in manufacturing enterprises, intelligent control systems, information modeling systems, and the technologies of CIM. Dr. Nagel was one of three principal designers of the Synthavision system; developed pseudo solid methodology, now widely used in medical radiography; was one of the principal architects of the National Bureau of Standards Automated Research Facility; and initiated and was the first leader of the Initial Graphics Exchange Specification project at the National Bureau of Standards. Dr. Nagel is a member of the National Research Council's Manufacturing Studies Board.

GREGORY A. PETSKO Dr. Petsko is currently a Professor of Biology and Chemistry at Brandeis University. Prior to working at Brandeis, he taught at the Massachusetts Institute of Technology and Wayne State University School of Medicine. Dr. Petsko is a member of such societies as the American Association for the Advancement of Science, the American Chemical Society, and the American Society for Biochemistry and Molecular Biology. He has authored or co-authored close to a hundred publications and has been the recipient of the Siddhu Award from the American Crystallographic Association for outstanding contributions to x-ray diffraction and the Pfizer Award in Enzyme Chemistry from the American Chemical Society, among others.

W. JAMES SARJEANT Mr. Sargeant is currently Director of the Space Power and Power Conditioning Institute and James Clerk Maxwell Professor of Electrical Engineering at the State University of New York at Buffalo. He has been a member of or directed various research, design, and development groups within national laboratories and industry in the areas of pulse power components and impulse measurement systems. Dr. Sarjeant has lead government-sponsored research projects and technical advisory committees in the field of power and power conditioning.

THEODORE W. SCHLIE Dr. Schlie is currently an Associate Professor of Technology Management in the College of Business and Economics at Lehigh University where he teaches and does research in the fields of innovation management and policy, production/operations management, business policy and strategy, and international competitiveness. Dr. Schlie is also Associate Director for Research at Lehigh's Center for Innovation Management Studies where he is responsible for administering a nationwide research grants program in the area of innovation management, funded by a number of industrial sponsors. He is also Director of Field Research Projects for the National Technological University's new Masters Degree Program on the Management of Technology, and is a consultant to a number of industrial and government clients. Dr. Schlie has conducted and supervised technology policy studies for the National Science Foundation, the Department of State, the Agency for International Development, and other federal agencies. He is a member of several professional societies and holds elective offices with the American Association for the Advancement of Science and the American Society of Public Administration. Dr. Schlie has published extensively in the fields of science, technology, and innovation policy and management.

RICHARD S. SHEVELL Professor Shevell is currently an Adjunct Professor of Aeronautics at Stanford University. Prior to this, he worked for Douglas Aircraft Company for 28 years. There, he held various positions including Chief, Aerodynamics Section; Director, Advanced Design; and Aerodynamicist. Professor Shevell has served on various committees such as the National Aeronautics and Space Administration's Aeronautics Advisory Committee and the AGARD Flight Mechanics Panel. He is a Fellow of the American Institute of Aeronautics and Astronautics.

SHEN Y. SHEY Dr. Shey is a member of the Senior Staff, Optics Division at Lincoln Laboratory at the Massachusetts Institute of Technology. There, he has contributed to the R&D of high-power laser (HPL) technology and systems, including HPL propagation measurements, precision pointing and tracking, and laser amplifier development for optical radar experiments. From 1985 to 1989, Dr. Shey received a leave of absence from Lincoln Laboratory to take an assignment with the Defense Advanced Research Projects Agency (DARPA). At DARPA he was Director of the Directed Energy Office. Dr. Shey has done work in the private sector at such places as the Boeing Company Aerospace Group, and the Raytheon Company Power Tube Division.

GEORGE E. SOLOMON Dr. Solomon retired from TRW, Inc. after over 20 years with the company. At the time of his retirement, he was Executive Vice President and General Manager of the Electronics and Defense Section. Dr. Solomon is a member of the National Academy of Engineering, Sigma Xi, and the Aerospace Industry Association.

JOSEPH F. SOUKUP Dr. Soukup is currently a corporate vice president of Science Applications International Corporation (SAIC). He serves as program manager for SAIC on several life sciences contract efforts and as an independent advisor to the U.S. government on life science and technology. Since 1978, Dr. Soukup has supported numerous government and private-sector entities including the Defense Nuclear Agency, Office of Naval Reasearch, U.S. Army Medical R&D Command, Armed Forces Medical Intelligence Center, the Central Intelligence Agency, and others, with expertise in biomedical and life sciences. Dr. Soukup has authored or co-authored over 35 papers and reports, including scientific papers and presentations, government contract reports, and special assessments.

JOHN D. VENABLES Dr. Venables is presently retired from Martin Marietta Laboratories. During his time at the laboratories, Dr. Venables used his background in physics and materials science to investigate the properties of transition metal carbides, domain structures in pyroelectric materials, electromigration effects in thin mechanisms in MgO refractories and nitrogen ceramics, the relation between radiation damage in quartz and the stability of quartz oscillators, and basic bonding mechanisms in adhesively bonded structures. From this work has come the discovery of several important phenomena, including ordered structures in the transition metal carbides, and it has provided new insights into adhesive bonding mechanisms and factors controlling the durability of adhesive joints. Dr. Venables' work has led to over 60 published technical papers, four patents, and numerous invited lectures.

JOHN B. WACHTMAN, JR. Dr. Wachtman is currently Professor of Ceramics and Director of the Center for Ceramics Research at Rutgers University. Prior to working at Rutgers, he spent over 30 years with the National Bureau of Standards in various positions including Director of the Center for Materials Science and Scientific Advisor to the Director. Dr. Wachtman has conducted research in the mechanical properties and effective utilization of inorganic material. He is a member of the National Academy of Engineering and has received awards from the Department of Commerce, the American Society for Testing and Materials, and the American Ceramic Society, among others.

ALLEN C. WARD Dr. Ward is currently working at the University of Michigan at Ann Arbor. Throughout his career, he has done work in computing, management, and design. His design work has included the construction of a computer power interface box and a high-speed robotic gripper as well as the conceptualization of a very small, autonomous rough-terrain vehicle and a read-write head cable attachment system. From 1986 to 1988 Dr. Ward worked as a consultant to the U.S. Army Training and Doctrine Command, advising them on combat developments in robotics and artificial intelligence.

RICHARD C. WILLIAMSON Dr. Williamson is currently the leader of the Applied Physics Group at the Massachusetts Institute of Technology's Lincoln Laboratory. His research efforts have focused on optoelectronic switches, electro-optic analog-to-digital converters, and optical computing. Dr. Williamson has also done work on the development of surface-acoustic-wave devices and their application to signal processing, as well as on ultrasonic studies of critical phenomena and phase transitions in monatomic fluids, superfluids, and liquid crystals. He has published articles in the areas of ultrasonic instrumentation and measurement, optical devices and signal processing, surface-acoustic-waves, and physics of critical phenomena at second-order phase transitions. Dr. Williamson has five patents in the areas of optical and surface-acoustic-wave devices. In 1985, he received the Career

Achievement Award from the Institute of Electrical and Electronics Engineers for his work in ultrasonic physics, devices, and applications.