DEPARTMENT OF DEFENSE

DEVELOPING CRITICAL TECHNOLOGIES/SCIENCE & TECHNOLOGY (DCT/S&T)

SECTION 14: MATERIALS AND PROCESSING TECHNOLOGY

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PREFACE

Developing Critical Technologies/Science & Technology (DCT/S&T) is a product of the Defense Critical Technologies Program (DCTP) process. This process provides a systematic, ongoing assessment and analysis of a wide spectrum of technologies of potential interest to the Department of Defense. DCT/S&T focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade U.S. military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

DCT/S&T is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. A key component is an assessment of worldwide technology capabilities. S&T includes basic research, applied research and advanced technology development.

SECTION 14—MATERIALS AND PROCESSING TECHNOLOGY

Scope

Highlights

- Projectile materials with performance comparable to depleted uranium and none of the environmental concerns.
- Armor system materials that provide increased ballistic protection without increased weight or cost.
- Materials to enable higher density microelectronic circuitry and increased reliability.
- New structural materials for lighter, stiffer platform structures with longer lifetimes and less maintenance.
- Lighter weight, high-temperature materials for more efficient, higher performance propulsion, and energy conversion.
- Coatings and sealants to protect components from erosive/corrosive/thermal environments.
- Tribological materials to provide longer lifetimes with less maintenance burden.
- New classes of materials and material architectures to create structures that will be able to sense and adapt to their surroundings.
- The use of familiar materials to create components and systems at ever smaller dimensional scales.
- Magnetic materials for radiation-hardened, highdensity data storage.

OVERVIEW

The periodic chart of chemical elements lists the building blocks available to humankind. These elements are manipulated alone or in combination with others to create all manmade functional and structural materials. The number of chemical element combinations and processing methods used to create and tailor those combinations for specific purposes is nearly endless and continues to grow. Classification and cataloging schemes for cataloging the resulting materials tend to follow functional lines, but are not always clearly delineated. For purposes of addressing current research that may result in materials advances of military utility and importance, the taxonomy in the table at the top of the page has been utilized. Although nano-science is a topic that has garnered much recent publicity, current nanotechnology research related to materials is not treated as a separate entity, but rather as subsets of the above taxonomy where appropriate. As this document is being prepared, additional research in the United States is being planned under the National Nanoscience Initiative. As a result, nanomaterials may have its own heading in a future taxonomy. Other materials topics not addressed in this section include optical materials, energetic materials, signature control materials, and manufacturing processes. Information on those can be found in Sections 11.2, 2.0, 18.0, and 12.1, respectively.

There are three underlying themes for materials research that may benefit defense:

- to potentially enable some sharp increase in capability over what can be achieved now;
- to provide a material or process that will make military equipment more affordable, either from a procurement or from a life-cycle cost perspective—preferably both; and
- to reduce the logistics burden through increased lethality, lighter weight, smaller size, better fuel efficiency, or reduced maintenance requirements.

The title of this chapter is meant to include research into (1) the identification of new materials, (2) the use of existing materials in new ways, and (3) the processes needed to produce materials that can subsequently be fabricated into useful components and/or structures. Materials technology research included in *Developing Critical Technologies* has been grouped into the seven categories reflected in the scope above. These seven areas are intended to capture the range of materials research and development (R&D) that may ultimately be of value to the military. Section 14.1 deals with materials technologies that may have a direct impact on system survivability in the face of enemy fire (armor) or that is directly related to lethality (anti-armor). Sections 14.2 and 14.7, Electrical Materials and Magnetic Materials, respectively, deal with materials research that may someday improve the sensing, targeting, and communication tools that underpin the concept of information dominance that is receiving so much attention in recent DoD plans, as well as provide lighter weight, more compact power-generation and propulsion equipment. Structural materials (Section 14.3) continue to be the backbone of defense platforms and infrastructure. Research into ways to make such platforms less expensive to purchase, maintain, and supply and also to make them more durable in peacetime and survivable in combat will always have a place in DoD research plans and needs. Special Function Materials (Section 14.4) covers research into the myriad topics related to lubricants, fluids, seals, sealants, and special coatings needed to ensure that systems can operate reliability at peak performance for sustained periods of time in both peacetime and combat. Smart Materials and Structures (Section 14.5) is meant to capture research into an area that represents the confluence of structural materials with embedded sensors, data processors, and actuators on a macroscopic scale. Micromachined Materials and Structures (Section 14.6) represents the combination of structural and electrical elements into various kinds of sensors, switches, and actuators on a micro-scale. These particular areas are relatively new arrivals on the research scene. The promise for defense application is high and they are the subject of much current research interest.

One aspect of the research process is to determine where the new materials and process technologies might best be utilized and what benefits they may provide. A result is that some technologies show up in more than one subsection. Diamond, for instance, appears in Section 14.2 as a high thermal conductivity material that could be used to support electronic components, and it appears in Section 14.4, Special Function Materials, as a potential wear-resistant coating. In addition, some “materials” technologies cut across traditional boundaries and appear in more than one section. For example, MEMS is discussed in this section and in Section 12, Manufacturing and Fabrication Technology.

The principal reason for including “Materials and Processing Technology” in *Developing Critical Technologies* is that most advances in the capability of military equipment of all kinds can be traced to a preceding advance in materials technology. Materials technology is also an area where the United States can engage in cooperative research programs with foreign investigators at the precompetitive level without undue risk of giving away the advantages included in our present generation of hardware. Of course, if we decline to utilize advances that are developed as a result of such collaboration, then our research partner will have an opportunity to move ahead of us in future generations of hardware.

TECHNOLOGY ASSESSMENT

Materials and the processes that convert them to finished products are fundamental to any industrial economy. The distribution of chemical elements in the earth’s crust does not give all countries equal access to all elements, but most raw materials that are not plentiful naturally can be easily purchased. Thus, research work on materials and processes hinges primarily on the availability of adequate research facilities and trained people. These two prerequisites are typically found in any country that has a viable industrial base and an educational system to promote academic training and research. Because the field of materials science is very broad and all encompassing, not all countries will have significant research programs in all topic areas. Regardless, in the overall assessment of materials and processes all industrialized nations will have most, if not all, of the requisite capabilities to perform research programs at the moderate or significant level in one or more of the research topics included in this section.

SECTION 14.1—ARMOR AND ANTI-ARMOR MATERIALS

Highlights

- Improved steels and low-cost titanium for fabrication and protection of armored vehicles and components.
- Combinations of metal, polymer, and uranium materials in composite and laminate forms for increased ballistic protection and/or reduced weight.
- Advanced processing of refractory metal alloys for penetrators and shaped-charge liners.
- Wear-resistant coatings and research to mitigate wear and erosion of gun barrels and electromagnetic launch rails.

OVERVIEW

This subsection covers passive armor materials. Metals, ceramics, and polymers and their composites, laminates, and hybrid combinations are included. Such armor materials being developed for future systems application are required to be highly effective in defeating or resisting penetration by a variety of ballistic threats at significantly lower areal densities than currently in use. Both transparent and opaque armor materials are required for enhanced survivability (and mobility) of individual warfighting personnel, tactical and combat system crew members, and platforms. For transparent armor materials, newer glass ceramics, polycrystalline ceramics, and ceramic/polymer hybrids are being developed to potentially replace traditional soda-lime glass technology. For ultra-lightweight opaque body armor, innovative ceramic and polymer composite combinations are being investigated to provide larger area coverage and higher threat protection with a reduced weight penalty. Growing concern about mobility of tactical vehicles is motivating research to exploit newer lightweight armor materials. Armor protection for rotary- and fixed-wing aircraft and satellite and spacecraft applications will require even further improvements in ultra-lightweight and highest efficiency opaque and transparent armor materials.

Research in anti-armor materials includes work in metals, ceramics, and polymers used in kinetic energy (KE) penetrators, sabots, shells, shape charge liners, and explosively formed projectile (EFP) warheads for improved lethality. This section also includes work on coatings and insert materials for reduced gun-barrel wear and erosion in conventional and advanced gun systems. Materials research specific to small tactical weapons that could be used against armor is not specifically covered.

LIST OF TECHNOLOGY DATASHEETS
14.1. ARMOR AND ANTI-ARMOR MATERIALS

ARMOR

METALS

CERAMICS

COMPOSITES

COMBINED SYSTEMS

ANTI-ARMOR

DATA SHEET 14.1. ULTRA-HIGH STRENGTH; INTERMEDIATE FRACTURE TOUGHNESS STEELS

Developing Critical Technology Parameter	Determine the ballistic properties of a commercial steel, AerMet 310, with yield strength >1.0 GPa (275 ksi); ultimate strength >2.14 Gpa (310 ksi); fracture toughness >66 MPa√m (60 ksi √ in.) The strength to density ratio of this alloy is comparable to Ti-6Al-4V, which could make AerMet 310 a direct competitor to titanium for lightweight, passive armor.
Critical Materials	Cobalt and chromium.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial aircraft.
Affordability	A commercially available product, AerMet 310 alloy may provide more survivable, more durable components that reduce system maintenance and associated logistics requirements.

BACKGROUND

The combination of strength and fracture toughness of this alloy provides an indication that it may also turn out to provide excellent ballistic protection. If the performance is indeed superior to other armor steels, it will enable the fabrication of lighter weight armored platforms of equivalent survivability. In addition, it is expected to find uses in aircraft and missile components and integral helicopter armor.

DATA SHEET 14.1. ULTRA-HIGH HARDNESS STEEL PLATE

Developing Critical Technology Parameter	Over the years, hardness has been determined to be a critical parameter in the performance of armor protection systems. High hardness in steel is attained through a combination of mechanical deformation and heat treatment. It is very difficult to achieve uniform hardness in thick steel plate. SSAB Oxelosund (Swedish Steel) is attempting to achieve through-thickness hardening of 4-in. thick plate in two grades: Rockwell C 40 and Rockwell C 48.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Executive protection.
Affordability	Slightly higher cost to achieve improved survivability.

DATA SHEET 14.1. LOW-COST TITANIUM

Developing Critical Technology Parameter	Low-cost titanium (less than $10 per pound) with mechanical properties equivalent to aerospace grade Ti-6A1-4V to replace steel in armored vehicles and other military structures.
Critical Materials	Low-cost titanium feedstock in the form of sponge or scrap.
Unique Test, Production, Inspection Equipment	Electron beam, single melt, cold-hearth furnace for material processing and laser solid freeform system for fabrication.
Unique Software	None identified.
Major Commercial Applications	Aerospace and marine components, corrosion-resistant industrial heat exchangers and food processing equipment, sporting goods, and specialized automotive components.
Affordability	The goal is to reduce the cost of titanium alloy and components fabricated therefrom so that titanium can be considered as a replacement for steel.

BACKGROUND

Future vehicles must be lightened to improve deployability, bridge crossing capability, and maneuverability while maintaining lethality and survivability. Development of lower cost alloy and “high rate” fabrication capabilities are key to weight reduction by means of replacement of steel with titanium in vehicle structures and components.

DATA SHEET 14.1. AMORPHOUS ZIRCONIUM-BASED ALLOYS

Developing Critical Technology Parameter	Properties of these glassy metal alloys such as Zr-Be (zirconium beryllium) are not yet defined, but initial testing indicates a potential for very high strength-to-weight ratios.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Precise composition and processing variables.
Major Commercial Applications	A Zr-Be alloy that also contains small amounts of copper, titanium, and nickel is being manufactured in small quantities for inclusion in club heads for golf equipment sold at the high end of the market.
Affordability	To be determined once properties and processing better understood.

BACKGROUND

High hardness typically accompanies high strength in metallic systems. Consequently, a material with a very high strength-to-weight ratio is a potential candidate for lightweight armor application. These new classes of alloys with amorphous (noncrystalline) microstructures are being investigated to determine if ballistic performance comparable to current systems can be achieved at lighter weight. If so, these materials will become candidates for use in personnel and vehicle armor systems.

DATA SHEET 14.1. OPTICALLY TRANSPARENT ARMOR

Developing Critical Technology Parameter	This research is striving to reduce the cost of large-size, high-quality, optical and infrared transparencies based on single-crystal Al_2O_3 (sapphire), polycrystalline $Al_{23}O_{27}N_5$ (ALON), or polycrystalline $MgAl_2O_4$ and various glasses.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Custom crystal growing apparatus (sapphire).
Unique Software	None identified.
Major Commercial Applications	Teller/cashier windows; executive protection.
Affordability	Increased survivability, reduced routine maintenance.

DATA SHEET 14.1. ARMOR CERAMICS

Developing Critical Technology Parameter	Reduce B_4C cost to a level sufficient to promote increased use; engineer multiphase ceramics with performance equal or better than B_4C.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Ceramic cutting tools, police and executive protection, automotive engine components.
Affordability	The objective of this research is to reduce cost to enable greater usage.

DATA SHEET 14.1. CERAMIC MATRIX COMPOSITES

Developing Critical Technology Parameter	Lightweight silicon carbide/silicon carbide composite with an areal density less than 6 lb/ft^2 for use in high-temperature armor applications.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Power generation; commercial satellite launch systems.
Affordability	Increased survivability.

BACKGROUND

Comparatively lightweight armor is needed that can be used to protect propulsion and power-generation equipment in vulnerable high-temperature locations.

DATA SHEET 14.1. METAL MATRIX COMPOSITES

Developing Critical Technology Parameter	Demonstrate the feasibility Al_2O_3/Al and SiC/Al in a functionally graded metal matrix composite format as armor materials. Characterize the ballistic performance of those combinations and ceramic distributions that look promising for use in armor systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Protection of impact-critical components from damage.
Affordability	If these materials are shown to be feasible for ballistic protection they are expected to be relatively low cost as a result of the relatively simple manufacturing processes envisioned.

BACKGROUND

A lightweight armor that will remain intact, capture fragments, and provide multihit ballistic protection is desired for a number of applications in military systems.

DATA SHEET 14.1. POLYMER COMPOSITE ARMOR MATERIAL SYSTEMS

Developing Critical Technology Parameter	An armor material that utilizes S–2 glass, Kevlar, Spectra, or polybenzobisoxazole (PBO) separately or in combination in a polymeric matrix composite for use in ultra-lightweight armor (3 to 4 lb/ft^2 areal density) with multihit capability.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Custom software may be required for NDE image enhancement depending on thickness and arrangement of components.
Major Commercial Applications	Police and executive protection, aircraft engine containment, and explosion-resistant cargo containers.
Affordability	Parts consolidation enabled by composite construction reduces part count and assembly expense. A 40-percent reduction in acquisition and life-cycle costs may be possible.

BACKGROUND

As with many of the other ballistic protection systems, the requirement that motivates the research is to substantially reduce the weight of the armor system needed to prevent penetration by a specific threat, be it projectiles or fragments. Such a system can be expected to be utilized for personnel protection, for specific air- and ground-vehicle applications, and as an applique to protect critical equipment.

DATA SHEET 14.1. ULTRA-LIGHTWEIGHT ARMOR SYSTEMS

Developing Critical Technology Parameter	The goal is to develop $\leq$ 3.5 lb/ft^2 areal density personnel armor that is effective against small arms threats.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Analytical models that predict system performance.
Major Commercial Applications	Law enforcement and executive protection.
Affordability	Decreased combat casualties.

DATA SHEET 14.1. LAMINATED/ENCAPSULATED COMBINED SYSTEMS

Developing Critical Technology Parameter	Combinations of S–2 glass, ceramics, metals, and one or more polymeric materials to achieve improved mass efficiency of a hybrid armor for protection against multiple threats; e-beam curing of polymer composite components is included for cost reduction.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specialized computed tomography equipment may be required for nondestructive inspection (NDI) of multicomponent systems.
Unique Software	Custom software may be required for NDE image enhancement, depending on thickness and arrangement of components.
Major Commercial Applications	Police and executive protection, aircraft engine containment, and explosion-resistant airline cargo containers.
Affordability	Combined systems can provide structural and armor functions simultaneously and thereby reduce parasitic weight, increase mobility, and decrease logistics fuel burden for ground vehicles and rotary-wing aircraft.

DATA SHEET 14.1. LAMINATED TRANSPARENCIES

Developing Critical Technology Parameter	Reduce thickness (and areal density) by 35 percent with a corresponding increase in optical properties achieved by means of reduced thickness.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Executive protection, industrial security, and safety glasses.
Affordability	Improved durability and survivability of vehicles and better personnel protection.

BACKGROUND

Improved visibility along with lighter weight and decreased volume are needed for personnel protection. The same materials in thicker variations will provide increased survivability when used in transparencies for air and ground vehicles.

DATA SHEET 14.1. TUNGSTEN ALLOYS

Developing Critical Technology Parameter	Development of beneficial failure mechanisms by means of compositional control and/or processing that will enable tungsten to meet or exceed the performance of depleted uranium (DU).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	This technology avoids the environmental costs associated with DU penetrators.

BACKGROUND

Tungsten alloys provide superior performance without the hazards and cleanup costs associated with DU.

DATA SHEET 14.1. NANOSTRUCTURED REFRACTORY METALS

Developing Critical Technology Parameter	Tungsten shaped-charge liners consolidated to near-theoretical density with grain size $\leq$ 0.1 μm.
Critical Materials	High-quality, nanometer particle size, refractory metal powders.
Unique Test, Production, Inspection Equipment	Unique powder synthesis and consolidation equipment needed for reactive tungsten material.
Unique Software	None identified.
Major Commercial Applications	Electronic substrates.
Affordability	More effective munitions at higher unit cost but decreased quantity and logistic burden.

DATA SHEET 14.1. CONVENTIONAL REFRACTORY METALS

Developing Critical Technology Parameter	<100 ppm interstitial element content leading to improved high-strain-rate shear behavior in a tungsten or tantalum refractory metal alloy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Oil well drilling, mining, and demolition.
Affordability	More effective munitions at higher unit cost but with decreased quantities required and a lower logistic burden.

DATA SHEET 14.1. FUNCTIONALLY GRADED CERAMIC/METAL SYSTEMS

Developing Critical Technology Parameter	Functionally graded ceramic/metal coatings are being investigated as a means to obtain a 2× increase in lifetime of large-caliber gun barrels.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique processing equipment for placing graded coatings on the inside surface of gun tubes.
Unique Software	None identified.
Major Commercial Applications	Erosion- and corrosion-resistant components for chemical and oil industry; cylinder liners.
Affordability	Longer component lifetime and reduced logistics requirements both contribute to a more affordable weapon.

BACKGROUND

Hot and corrosive gases generated by the propellant in large-caliber guns erode the inside of the barrel and limit effective lifetime. Coatings are being sought that will decrease or eliminate barrel erosion, increase the lifetime of critical military weapon systems, and eliminate the current use of hard chromium plating. Functionally graded ceramic/metal coatings to protect gun bores are being investigated to address this problem.

DATA SHEET 14.1. TANTALUM BORE COATINGS

Developing Critical Technology Parameter	Tantalum metal coatings are being investigated as an approach toward obtaining a 2× increase in lifetime of large caliber gun barrels.
Critical Materials	Tantalum.
Unique Test, Production, Inspection Equipment	Unique processing equipment for reliable and repeatable application of tantalum coatings to the inside surface of gun tubes.
Unique Software	None identified.
Major Commercial Applications	Erosion- and corrosion-resistant components for chemical and oil industry.
Affordability	Longer gun-barrel lifetimes and reduced logistic support in terms of spare parts and replacement time.

BACKGROUND

Hot and corrosive gases generated by the propellant in large-caliber guns erode the inside of the barrel and limit effective lifetime. Coatings are being sought that will decrease or eliminate barrel erosion and increase the lifetime of critical military weapon systems. Tantalum metal coating to protect gun bores is one approach being investigated to address this problem. Use of tantalum also avoids environmental concerns associated with hard chromium plating.

DATA SHEET 14.1. OXIDE DISPERSION-STRENGTHENED MOLYBDENUM

Developing Critical Technology Parameter	Dispersion-strengthened molybdenum is being investigated as a protective coating that will provide a 10× increase in barrel life of medium-caliber weapons when used with high-impetus propellants.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Analytical models to predict effects of extreme thermal environments on various barrel materials and coating-system candidates.
Major Commercial Applications	If successful, this coating will provide an alternative to hard chrome wear-resistant coatings (and the environmental problems associated with chromium plating) in a wide range of industrial and automotive applications.
Affordability	Enables new capability.

BACKGROUND

The use of high-impetus propellants in medium-caliber guns has a very detrimental effect on barrel life because the higher temperature propellant gases result in increased erosion. A protective coating is needed to enable increased lethality for medium-caliber weapons without shortening the barrel life.

DATA SHEET 14.1. AMORPHOUS METAL MATRIX COMPOSITE

Developing Critical Technology Parameter	The deformation behavior of DU has a great deal to do with its effectiveness as a kinetic-energy penetrator. An amorphous metal alloy of zirconium beryllium, copper, titanium, and nickel exhibits a similar deformation mechanism. It is being investigated as a matrix material for a tungsten-rod reinforced composite to potentially replace DU.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Reduced logistic and environmental burden compared with DU.

BACKGROUND

DU penetrators are deemed to be an environmental hazard, and extensive efforts to retrieve DU from the battlefield have been required. The search for more environmentally acceptable and potentially better performing kinetic-energy penetrators has traditionally focused on tungsten (see Data Sheet 14.1 above). The deformation behavior of some recently identified amorphous metal systems approximates that of DU, which suggests that one or more of these materials (possibly in composite form) may be a suitable alternative.

DATA SHEET 14.1. HIGH ELECTRICAL CONDUCTIVITY ALUMINUM AND POLYMER COMPOSITES

Developing Critical Technology Parameter	High-purity aluminum is being utilized as a matrix for high specific strength and stiffness composites that have both the electrical conductivity and high compression strength needed for launch from an electromagnetic gun. Two approaches are being pursued. One is a high-purity aluminum matrix composite where the aluminum provides the electrical conductivity and the fiber provides strength and stiffness. The other is a high electrical conductivity carbon fiber in a thermoplastic polymer matrix.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Aluminum electric power transmission lines with an oxide ceramic fiber-reinforced aluminum core.
Affordability	New capability.

DATA SHEET 14.1. TRIBOLOGY IN SEVERE ENVIRONMENTS

Developing Critical Technology Parameter	Understand erosion mechanism(s) associated with hypervelocity launch to guide advances in materials technology and design that will enable multilaunch capability.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Extend the lifetime of experimental systems and enable development of practical electromagnetic launchers.

SECTION 14.2—ELECTRICAL MATERIALS

Highlights

- High electrical conductivity (including superconductors) for efficient conversion of electrical power to KE and for novel electronic components.
- Materials for improved thermal management and reliability of micro-electronic circuits and spacecraft.
- Wide bandgap semiconductors for electronic components that operate in harsh environments.
- Polymeric materials for insulation, conduction, and actuation.

OVERVIEW

Electricity is at the heart of "information dominance" envisioned by the Revolution in Military Affairs. None of the military command, control, communication, intelligence gathering, and computing networks or targeting and weapon-guidance systems will work without reliable supplies of electricity. Research on electrical materials affects modern military systems in two ways. The first is to provide power generation and storage capabilities that provide efficient, affordable, and reliable sources of electrical energy. Research in this vein is discussed in Section 7, "Energy Systems Technology." The second is to provide new materials and process technology that will be the basis for advanced systems and devices that utilize electrical energy for their operation. Those advances in materials and associated process capability used to fabricate systems and devices that require the flow of electrons to operate are the focus of this chapter. Even here there is some overlap with Section 7. For instance, the development of wide-bandgap semiconductors not only enables high-power switching and power conditioning (Data Sheet 7.3), it provides transistor material capable of operating in more stressing thermal and radiation environments than can be easily endured by materials in present day devices. Other topics covered in this section deal with material technologies that affect thermal management for electronic systems. The ability to control temperature has a significant impact on the reliability of electronics. If research on materials for improved thermal management is successful, these materials will permit increased power density without sacrificing reliability. What is not included in this section is research (primarily done by commercial companies) that is oriented toward processes to further decrease feature sizes of silicon-based electronics.

REFERENCES

"First Superconductor Wire Plant Planned," *Performance Materials,* Vol. 15, pg. 2, John Wiley & Sons (publisher), May 29, 2000.

"THZ-Spectroscopy with High-T_c Josephson Junctions," http://www-phys.rrz.µni-hamburg/

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LIST OF TECHNOLOGY DATASHEETS
14.2. ELECTRICAL MATERIALS

DATA SHEET 14.2. HIGH-TEMPERATURE SUPERCONDUCTING MATERIALS (BULK)

Developing Critical Technology Parameter	Lengths of conductor more than 100 m with critical current densities greater than 1,000,000 A/cm^2 at 77 K and zero magnetic fields. Engineering critical current densities of 10,000 A/cm^2 at 77 K and magnetic fields of 5 T.
Critical Materials	Yttrium barium copper oxide (YBCO), buffer layers, and substrates.
Unique Test, Production, Inspection Equipment	Wire producing capability.
Unique Software	None identified.
Major Commercial Applications	Power generation, motors, transformers, and transmission lines.
Affordability	These materials offer more efficient generation and utilization of electric power. More important is the system design flexibility and increased performance that may be realized by the ability to move large amounts of power to distributed electric propulsion and control systems.

DATA SHEET 14.2. HIGH-TEMPERATURE SUPERCONDUCTING MATERIALS (THIN/THICK FILMS)

Developing Critical Technology Parameter	Arrays of Josephson Junctions (1,000 to 10,000 junctions) with uniform properties (spreads in critical current and normal resistance less than 10 percent). Appropriate values of junction critical current and resistance (application dependent).
Critical Materials	Superconducting films and junction barrier layers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Process procedure manuals.
Major Commercial Applications	Communications and signal-processing components for wireless communication systems.
Affordability	The main promise is one of increased performance with little increase in cost. Regardless, affordability will be an application-dependent issue.

DATA SHEET 14.2. MULTIPLE QUANTUM WELL AND SUPERLATTICE LAYERED ELECTRONIC MATERIALS

Developing Critical Technology Parameter	Infrared (IR) detectors and focal plane arrays that have (1) multispectral IR sensitivity in 2 to 20-µm spectral band and (2) high sensitivity to long-wavelength IR radiation (>8 µm) at elevated operating temperatures (>40 K).
Critical Materials	Group III–V materials (such as AlGaAs/GaAs, AlInAs/InGaAs/InP, AlSb/InAs, and InGaSb/InAs for quantum wells) and materials such as HgTe/CdTe and InAs/InGaSb for super lattices.
Unique Test, Production, Inspection Equipment	High-vacuum, ultra-clean molecular beam epitaxy deposition equipment with in situ film-deposition monitors and advanced substrate temperature-control apparatus.
Unique Software	Computer-automated film-deposition protocols.
Major Commercial Applications	None identified.
Affordability	Yields of device quality material are presently extremely low.

DATA SHEET 14.2. DIAMOND SUBSTRATES

Developing Critical Technology Parameter	Natural diamond's thermal conductivity, in the vicinity of 2,000 W/m-K, is among the highest known. As such, it is an ideal material to serve as a substrate for high-power electronic devices that must dissipate a relatively large amount of heat to keep from destroying themselves. The goal of this research is to grow synthetic diamond in flat shapes suitable for electronic substrates and maintain a thermal conductivity of 1,500 W/m-K or more.
Critical Materials	Processing is critical—not materials.
Unique Test, Production, Inspection Equipment	Need well-controlled chemical vapor deposition equipment.
Unique Software	Process procedure manuals.
Major Commercial Applications	Would eventually migrate to a range of commercial electronic devices (e.g., personal computers).
Affordability	Too early to determine if market volume will make this technology "affordable."

DATA SHEET 14.2. HIGH THERMAL CONDUCTIVITY COMPOSITES

Developing Critical Technology Parameter	The goal of this research is to develop chip carriers and thermal planes that have (1) very high thermal conductivity for thermal management purposes and (2) a coefficient of thermal expansion closely matched to the chip or package to eliminate stresses that can fail the chip and/or the wiring connections.
Critical Materials	Processing is critical—not materials.
Unique Test, Production, Inspection Equipment	Carbon-carbon composite versions will require special high-temperature processing equipment.
Unique Software	Process manuals and instructions.
Major Commercial Applications	Commercial electronics of all kinds.
Affordability	High thermal conductivity composites will have to compete on the basis of cost when compared to other passive thermal management technologies and on the basis of cost, performance, and improved reliability when compared to active thermal management technologies.

BACKGROUND

Higher component density and more power dissipation requires improved thermal conductivity to transfer heat away from the chip to maintain reliable operation. The use of high thermal conductivity, carbon-fiber composites adds the ability to more closely match the thermal expansion of the chip by adjusting fiber content and architecture within the composite.

DATA SHEET 14.2. FERROELECTRIC THIN FILMS

Developing Critical Technology Parameter	Q >100 and loss tangent <0.015, large variation in the dielectric constant with applied DC bias, dielectric constant <500 for impedance matching purposes, and low leakage current characteristics for frequencies >10 GHz.
Critical Materials	Reproducible processing for bulk composite ferroelectric materials is critical.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Process procedure manuals and materials models: new device (antenna) designs with thin-film ferroelectric materials are critical to lowering conductor losses.
Major Commercial Applications	These materisls could be utilized for electronically tunable mixers, delay lines, filters, oscillators, resonators, and phase shifters for applications such as collision-avoidance sensors, satellite communications, and cellular communications. They may also be useful for uncooled (room-temperature) pyroelectric detectors for thermal imaging.
Affordability	Bulk ferroelectric phase shifters are now a fairly mature, commercially available technology. These bulk material components offer a 5:1 cost reduction compared with ferrites. Thick- and thin-film ferroelectrics are still being researched, and large-scale manufacturing has not been established. Affordability will ultimately be determined by the feasibility of process scale-up.

BACKGROUND

These materials are essential for tunable microwave communications electronics, miniaturization of RF electronics, and phased-array radar phase shifters.

DATA SHEET 14.2. WIDE-BANDGAP ELECTRONIC MATERIALS

Developing Critical Technology Parameter	Develop wide-bandgap SiC and GaN semiconductor materials for high-temperature/ high-power applications. SiC development goals include growing high-quality substrates with less than 5 micropipe defects per cm^2 in diameters up to 3 in. or more. Defect levels in GaN must be reduced by several orders of magnitude to achieve the desired performance and reliability. Shallow p-type dopants are required for both materials. A SiC solid-state, high-power switch capable of handling up to 1,000 V with current densities greater than 1,000 A/cm^2 is one goal of this development work.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Customized single-crystal growth equipment will be needed to achieve desired perfection, purity, and uniformity.
Unique Software	Process procedure manuals.
Major Commercial Applications	Initial applications include blue and UV lasers for high-density optical storage, high-frequency electronic devices for high-speed modems, cardiac defibrillators, and magnetic resonance imaging (MRI). The material can be expected to migrate to distributed control systems for a host of power-generation and propulsion systems.
Affordability	These materials are still being developed and limited manufacturing has been established. Scale up to 4-in. diameter will improve affordability in the short term. Ultimately, the market and manufacturing efficiency driven by the competing companies discussed below will determine affordability.

DATA SHEET 14.2. LOW DIELECTRIC CONSTANT INSULATORS

Developing Critical Technology Parameter	Ultralow dielectric constant materials are being developed to minimize electrical cross talk between conduction paths as the feature size of microelectronic components continues to decrease. A material with a dielectric constant <2.0 is being sought to optimize chip performance as the number of components per unit area increases.
Critical Materials	Not yet identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology is being developed solely to address high-density commercial integrated circuits.
Affordability	If successful, it will be used in large-scale commercial applications.

SECTION 14.3—STRUCTURAL MATERIALS (HIGH STRENGTH AND HIGH TEMPERATURE)

Highlights

- Much of the research emphasis in structural materials remains focused on lighter weight materials with equivalent or better properties than the materials they replace.
- Lower cost material production and fabrication processes are receiving emphasis as more advanced metal-, ceramic-, and polymer-based materials attempt to displace traditional materials in a range of military and commercial applications.
- Lightweight, high-temperature metals and metal matrix composites continue to lead U.S. efforts related to gas-turbine aeropropulsion.
- Research on lighter weight, multifunctional materials, such as aluminum foams, for spacecraft structure and thermal control emphasizes performance and system cost over initial material cost.
- The principal focus of research on ceramics and ceramic matrix composites is for power generation, industrial process, and heavy vehicle applications in the civil sector, although eventual use in propulsion and aerothermal applications is a longer term goal.

OVERVIEW

Structural materials are essential to a wide variety of DoD spacecraft, aircraft, ground vehicles, ships, and submarines, along with their associated weapon, mechanical, and propulsion subsystems and support infrastructures. Investments in structural materials and process technologies must be continuous to sustain healthy core and infrastructure capabilities and to increase system lifetimes, thereby enhancing affordability. Structural materials technology includes development, synthesis, processing, and characterization of a broad range of high-strength and high-temperature monolithic and composite materials. The goal is to obtain improved capability in terms of cost reduction, improved supportability and reliability, cost-effective incorporation of multifunctional capabilities into structural components to decrease weight and volume requirements, and to improve stealth and survivability capabilities. Key endeavors include process development, synthesizing of new/improved materials, development of analytical modeling, characterization of microstructure, determination of properties, fabrication technologies, structural integrity, life prediction, and durability.

LIST OF TECHNOLOGY DATASHEETS
14.3. STRUCTURAL MATERIALS (HIGH STRENGTH AND HIGH TEMPERATURE)

DATA SHEET 14.3. COMPUTATIONAL MATERIALS AND PROCESS DEVELOPMENT

Developing Critical Technology Parameter	Computerized development (modeling and simulation) of alloys used in aluminum- and metal-working processes such as casting and forging.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard production equipment and facilities.
Unique Software	Structure and property databases and models for specific alloy families and industrial process models.
Major Commercial Applications	Optimized alloys and heat treatments for cost reduction in a host of commercial applications.
Affordability	Rapid optimization of alloy composition and processing for specific applications.

BACKGROUND

This technology has the potential to reduce the cycle time needed to optimize an alloy and associated processing procedures for a particular application and to minimize material usage and weight in defense hardware components fabricated therefrom. If this research is successful, it will be possible to specify alloy chemistry, heat treatment, and fabrication processes that are tailored to meet a specific application in a time frame within the normal purchase order cycle rather than after years of development and testing. This will also allow simultaneous optimization of material selection and component design to provide the most functional product at the lowest cost.

DATA SHEET 14.3. BERYLLIUM-ALUMINUM

Developing Critical Technology Parameter	Beryllium-aluminum alloys and processing. Large-size rolled sheet and increased strength castings are important development objectives.
Critical Materials	Beryllium
Unique Test, Production, Inspection Equipment	None identified, although precautions are needed to protect workers from beryllium dust during fabrication operations.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Some components have been shown to be less expensive than equivalent weight polymer matrix composites, plus they are machineable and weldable by conventional methods, albeit with environmental control.

DATA SHEET 14.3. DISCONTINUOUSLY REINFORCED ALUMINUM METAL MATRIX COMPOSITES

Developing Critical Technology Parameter	Discontinuously reinforced aluminum metal matrix composites with 380 MPa tensile strength at 315 °C and 33 MPa √m fracture toughness at ambient temperature.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Automotive engine blocks, commercial aircraft, fanjet engines, commercial spacecraft, automotive braking components.
Affordability	Large positive impact on sustainability at the expense of higher initial cost.

DATA SHEET 14.3. CONTINUOUS FIBER REINFORCED TITANIUM METAL MATRIX COMPOSITES

Developing Critical Technology Parameter	Advanced titanium, titanium aluminide, and orthorhombic titanium alloy matrix composites for elevated temperature (600 °C and above) structural applications.
Critical Materials	Silicon carbide monofilament reinforcing fibers. Superplastic titanium alloys.
Unique Test, Production, Inspection Equipment	Specially designed equipment is needed to apply matrix to the fibers and consolidate the coated fibers into sheet goods or shapes.
Unique Software	Process control software associated with production.
Major Commercial Applications	Uses of this technology in gas turbine engines for commercial aeropropulsion are envisioned.
Affordability	High initial cost because of sophisticated processing and limited manufacturing capability and product usage could be offset by reduced fuel consumption and maintenance requirements for military gas turbine engines.

DATA SHEET 14.3. GAMMA TITANIUM ALUMINIDES

Developing Critical Technology Parameter	Wrought gamma titanium (TiAl) alloys with strength that exceeds 400 MPa at 750 °C, elongation >1 percent, and creep resistance with less than 0.2 percent strain at 100 hours at a stress of 125 MPa at 750 °C.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specialized processing equipment and techniques and high-temperature gas turbine component test rigs.
Unique Software	None identified.
Major Commercial Applications	Tested as valves for high-performance automotive engines but no production at present. Also, tested in turbine engine components but not yet in production.
Affordability	Initial cost expected to be high due to difficult processing, limited manufacturing capabilities, and small market. Higher cost may be counterbalanced by improved fuel consumption in propulsion applications.

BACKGROUND

These high-temperature intermetallic materials have the potential to replace nickel base alloys for gas turbine engine components with operating temperatures up to 1,000 °C or 750–800 °C for long life at about half the weight.

DATA SHEET 14.3. ADVANCED INTERMETALLIC ALLOYS

Developing Critical Technology Parameter	Advanced aluminide and silicide intermetallic alloys with (1) stress rupture lives of 1,000 hours at 900 °C and 350 MPa stress for turbine disks and (2) 100 hours at 1,100 °C and 170 MPa for turbine blades with oxidation resistance equivalent to coated nickel base superalloys.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specialized processing equipment that is not yet fully developed and high-temperature component test rigs.
Unique Software	None identified.
Major Commercial Applications	Potential application in commercial power gas turbines after the technology is adequately demonstrated in defense applications.
Affordability	The initial cost of components fabricated from these materials will be higher because of difficult manufacturing processes and limited market. These costs may be counter-balanced by higher thrust-to-weight ratios in military gas turbine aero-engines and reduced fuel consumption.

BACKGROUND

The refractory metal aluminides and silicides being developed for gas turbine engine applications offer the promise of engine components with much lower weight and higher temperature capability than nickel-base superalloys. Such materials are key to increasing the thermodynamic efficiency of gas turbine engines by means of higher operating temperature and decreasing the weight of the propulsion system.

DATA SHEET 14.3. CERAMIC MATRIX COMPOSITES

Developing Critical Technology Parameter	This technology is focused on developing ceramic matrix composites for use under high stress at temperatures in excess of 1,100 °C in gas turbine engines, as hot structures in rocket engines, in divert and attitude control systems, as structural thermal protection systems, and for low observables.
Critical Materials	SiC fiber, preceramic polymers.
Unique Test, Production, Inspection Equipment	Sophisticated fiber placement, weaving, and knitting equipment to fabricate fiber preforms and equipment to infiltrate and consolidate those fiber preforms into dense ceramic composite shapes.
Unique Software	Design codes unique to ceramic matrices.
Major Commercial Applications	Ceramic matrix composites are being investigated for applications as hot gas filters, radiant burner screens, and immersion heaters in industrial process equipment. They may also find applications in gas turbine base power generation and auxiliary power units.
Affordability	Current high cost is dominated by fiber cost, which is a volume-driven issue. Once fiber cost decreases, affordability issues are similar to other composite materials. These high initial costs may be more than compensated for by added functionality.

BACKGROUND

As high-temperature structural materials, ceramic matrix composites are much lighter than metals and may be usable at temperatures in excess of 1,100 °C in high-stress environments.

DATA SHEET 14.3. POLYMER MATRIX COMPOSITES (PMC)

Developing Critical Technology Parameter	Polymer matrix composite (PMC) materials for (1) aerospace applications that are capable of retaining the physical properties associated with lower temperature PMCs over long-term exposure to temperatures of 370 °C or higher and for (2) ground and marine vehicle applications whose PMC material and processing costs are 50 percent less than current PMC are needed. Electron-beam-cured and microwave-cured PMCs are being pursued to meet this goal.
Critical Materials	Electron beam hardenable polymers.
Unique Test, Production, Inspection Equipment	Automated fiber- or tape-placement equipment, filament-winding machines, appropriately sized autoclaves, industrial-scale electron accelerators, or radiation sources for low-temperature curing of polymer resins.
Unique Software	Winding pattern optimization software "omni-wind."
Major Commercial Applications	Commercial uses are likely to be in transportation systems that include aircraft, trains, trucks, cars, and buses, as well as offshore oil platforms, all of which require reduced weight.
Affordability	High initial cost will continue to decrease as the volume of PMCs utilized increases. For instance, it is estimated that to gain acceptance in ground and marine vehicle structures, carbon fiber costs will have to be in the $3 to $5 per pound range. At least one carbon-fiber manufacturer has predicted the $5/lb price will be reached soon for large tow fiber.

BACKGROUND

PMC structures typically weigh about 25 percent less than an equivalent metallic counterpart. The ability to mold PMC in large units also eliminates the need to fabricate and join many smaller parts as is often done when building systems from metal. Elimination of fasteners and lap joints also provides some additional system-level weight reduction.

DATA SHEET 14.3. ULTRA-LIGHTWEIGHT METALLIC MATERIALS

Developing Critical Technology Parameter	Technology that will allow conventional aluminum, titanium, and polymer matrix composite materials to be replaced with ultra-lightweight, porous metallic materials that are half the weight with no increase in cost.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Some forms of controlled-porosity material require high pressure and precise temperature control to grow pores with precisely controlled geometry.
Unique Software	None identified.
Major Commercial Applications	Commercial applications for lightweight automotive structure (floorpans) are currently being investigated. Other commercial applications that may develop are likely to involve other transportation modes, as well as sound attenuation, thermal insulation, and building construction panels.
Affordability	Higher initial cost may be offset by the ability to form highly weight-efficient structures in complex shapes and large sizes. The number of such structures, especially if used by automotive companies, will reduce the cost.

RATIONALE

This technology will enable metallic structures that meet or exceed the structural efficiency of polymer matrix composites and/or that can be inexpensively formed into much more complex shapes than possible with conventional honeycomb-core sandwich panel construction.

DATA SHEET 14.3. HIGH THERMAL CONDUCTIVITY STRUCTURAL MATERIALS

Developing Critical Technology Parameter	Materials with thermal conductivity in excess of 1,000 W/(m-K) with a density of less than 50 percent that of copper and/or thermal expansion matched to silicon to increase thermal conduction and reduce thermal stresses in semiconductor packaging.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	High-temperature, controlled-atmosphere furnaces may be needed to fabricate some potential high thermal conductivity materials or components.
Unique Software	None identified.
Major Commercial Applications	Lightweight, integral thermal management for commercial spacecraft and low-cost alternatives to copper/tungsten thermal planes and other thermal dissipation components in electronic packaging.
Affordability	Low-cost, better performing alternatives to copper/tungsten are expected for electronic packaging applications. Multifunctional structures enhance spacecraft thermal management, eliminate large thermal sinks, and provide weight margin for extra expendables that extend the useful life of the spacecraft and provide substantial cost benefit.

DATA SHEET 14.3. NANOCRYSTALLINE MATERIALS AND STRUCTURES

Developing Critical Technology Parameter	The formation of materials composed of submicron (nanometer)-size grains that each contain only a few thousand atoms. A large portion of the overall volume of such materials is made up of grain boundary regions that have properties that differ significantly from those of the bulk material and provide increased strength and hardness.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Inert gas atomization equipment for the production of nanometer-size powder particles.
Unique Software	None identified.
Major Commercial Applications	No large-volume commercial applications were identified. If the resistance to wear indicated by early research can be maintained in large-scale components, commercial application should develop in the machine tool, automotive industry, and for component coatings.
Affordability	Because the processing needed to achieve nano-structured materials is more involved than typical fabrication processes, it can be expected to result in higher initial part cost. Affordability will therefore have to result from reduced maintenance requirements, reductions in the logistics associated with maintenance, and lowered operating costs.

BACKGROUND

Research to date indicates that nanometer-size grain materials are more resistant to deformation and wear than materials of the same chemical composition in more conventionally processed forms at ambient temperatures. At the same time, the ultra-fine grain size in many of these materials allows the materials to be affordably fabricated into complex shapes at elevated temperatures via superplastic forming.

DATA SHEET 14.3. STRUCTURAL CARBON-CARBON COMPOSITES

Developing Critical Technology Parameter	The goal is to develop lightweight, high stiffness materials for use at high temperature in solid-fuel rocket motors and reentry vehicles (RVs), and for use in space structures that are intrinsically hardened (survivable) to laser threats and that also provide improved thermal management capability to spacecraft designers.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Isostatic presses and controlled-atmosphere furnaces for production of carbon-carbon composite components and structural shapes.
Unique Software	None identified.
Major Commercial Applications	Any very lightweight structure for operation in a temperature or atmosphere regime where oxidation is not a problem.
Affordability	High initial cost provides increased survivability and extended lifetime of valuable space assets to achieve overall affordability. Labor-intensive processes currently limit uses to other aerospace high-value or nonstructural applications.

DATA SHEET 14.3. LIGHTWEIGHT, LOW THERMAL EXPANSION MATERIALS

Developing Critical Technology Parameter	Near-zero coefficient of thermal expansion (CTE) for lightweight, precision tolerance, spacecraft structure that does not require parasitic thermal insulation to maintain its shape as it moves in and out of Earth's shadow.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Spacecraft, reciprocating engine hot structures, and high-temperature industrial processing equipment.
Affordability	Increased system on-orbit lifetime and reliability and the avoidance of parasitic thermal management system weight and failure modes will have to compensate for the expected high cost of structures fabricated with these engineered materials.

BACKGROUND

Large spacecraft are vulnerable to structural deflection caused by uneven solar heating. Near-zero CTE structural materials enables the precision alignment of critical systems without the need for elaborate thermal-management schemes to avoid structure warping thermal gradients. Present near-zero thermal expansion materials such as Invar are iron-nickel alloys that are quite heavy compared to carbon-fiber composites. The use of negative thermal expansion carbon fibers to balance the positive expansion of polymer or light-metal matrices can result in a lightweight composite that undergoes very little thermal expansion. This saves valuable weight and eliminates complexity, thereby contributing to affordability and durability.

DATA SHEET 14.3. ADVANCED MONOLITHIC CERAMICS

Developing Critical Technology Parameter	Advanced ceramics are being pursued for their high-temperature capability, wear- and corrosion-resistance, and relative light weight.
Critical Materials	High quality powders.
Unique Test, Production, Inspection Equipment	Rapid prototyping manufacturing systems to support reduced product development cycles.
Unique Software	Design codes for application to brittle materials.
Major Commercial Applications	Cutting tools, gas turbine-generator sets, diesel engine components, wear parts, heat exchangers, and hot-gas filters.
Affordability	Except in specialized high-performance applications, production volumes will have to be increased to get price down to a competitive level. One key cost driver is final machining.

BACKGROUND

The promise of this technology is to increase the thermodynamic efficiency of power-conversion machines by having uncooled components capable of higher operating temperatures than can be obtained with most metals. Lighter weight and lower wear also benefit durability, particularly in reciprocating engine applications.

DATA SHEET 14.3. HIGH-STRENGTH, HIGH-FRACTURE-TOUGHNESS STEEL

Developing Critical Technology Parameter	Steel that has a combination of strength and fracture toughness that exceeds any other steel available on the market today. Controlled rolling parameters.
Critical Materials	Welding consumables.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software to control the processing.
Major Commercial Applications	None identified.
Affordability	This steel will almost certainly sell at a premium price. If the strength and fracture toughness enable lighter weight design, however, then less material will be needed and the cost may be competitive.

DATA SHEET 14.3. SUPERALLOYS

Developing Critical Technology Parameter	Large, affordable nickel-, cobalt-, or nickel-iron-based superalloy components for use in gas turbine engines which will operate at turbine inlet temperatures above 1,425 °C.
Critical Materials	Modifications to compositions of conventional alloys and associated processing; source materials for thermal barrier coatings compatible with the base alloy.
Unique Test, Production, Inspection Equipment	Specialized processing equipment and associated controls. High-temperature gas turbine component test rigs.
Unique Software	Chemical composition specifications and all related process procedure documentation.
Major Commercial Applications	Gas turbine engine components for aeropropulsion and power generation.
Affordability	Higher costs needed to achieve higher temperature engine operation and thermodynamic efficiency should be more than compensated for by increased range, speed, and payload and/or decreased fuel consumption.

BACKGROUND

Current alloy systems have reached limits of operability and alternative composite ceramics and intermetallic metallic alloys have not yet developed to the point that they can be utilized. Accordingly, extension of existing material and processing capabilities together with thermal-barrier coatings and blade-cooling designs, where a production base exists, is an attractive alternative for obtaining improved performance.

DATA SHEET 14.3. BIOMATERIALS AND PROCESS RESEARCH

Developing Critical Technology Parameter	Various ceramic, metallic, and polymeric materials or combinations thereof that can be used to fabricate orthopedic implants and/or provide scaffolding for bone growth (biomedical materials). Organic materials to serve as protection and provide the scaffolding for regrowth of burned or damaged skin. In addition, biologically based processes are being studied to develop materials, materials arrangements, or both, at finer size scales, more affordably, or both, than can be accomplished by tradiitonal process routes (biomimetic materials). Synthesis routes to approximate/duplicate naturally occurring materials such as spider silk and barnacle adhesive are but two examples.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Solid free-form manufacturing equipment to rapidly fabricate custom implants.
Unique Software	Proprietary manufacturing processes.
Major Commercial Applications	Much of this research is being driven by commercial interest in medical applications (biomedical materials) and potential applications that might come from biologically derived materials which mimic nature (biomimetic materials).
Affordability	Reduce the cost of medical care for injured soldiers through more rapid recovery.

BACKGROUND

Nature provides the model for materials that are particularly well suited for specific applications and frequently have a combination of functions and properties that are not easily duplicated with inorganic and organic materials derived from traditional manufacturing processes. Researchers are challenged to develop materials with similar functionality through traditional means and to develop processes that will enable large-scale production of synthetic versions of the materials found in nature that provide increased performance when used in military applications.

DATA SHEET 14.3. HIGH-STRENGTH/HIGH-MODULUS CARBON FIBERS

Developing Critical Technology Parameter	Carbon fibers with 600 psi or greater tensile strength and 60 Msi or greater tensile modulus at ambient temperature.
Critical Materials	PAN-based carbon fibers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Satellite and spacecraft structures.
Affordability	Carbon fibers that meet strength and modulus thresholds at competitive cost need to be developed.

DATA SHEET 14.3. SEVERE PLASTIC DEFORMATION (SPD)

Developing Critical Technology Parameter	Thermomechanical processing to achieve a reduction of grain size in polycrystalline bulk metals and intermetallics to the submicrometer level to yield material with high-strain-rate superplasticity and improved strength and weldability.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Equal channel angular extrusion (ECAE) machines.
Unique Software	None identified.
Major Commercial Applications	Net shape component fabrication of complex shapes and medical implants.
Affordability	Reduced cost for higher performance versions of standard materials for military hardware.

BACKGROUND

Application of the process could lead to conventional metallic materials with significant improvements in terms of endurance, strength, and fabricability. Low-temperature superplasticity could provide reduced cost of near-net-shape components for structures and machinery. Property enhancements could be retained at moderately high temperatures associated with aerodynamic heating. Technology could also be used as an alternative to isothermal forging for turbine and compressor disk applications.

DATA SHEET 14.3. BULK METALLIC GLASSES

Developing Critical Technology Parameter	Metal alloys that can be solidified in an amorphous (glassy) state rather than a crystalline state.
Critical Materials	Although no critical materials are involved, the control of the composition limits of the materials used in these alloy is relatively precise.
Unique Test, Production, Inspection Equipment	Casting molds that can provide closely controlled cooling rates are required to maintain the glassy state when producing structural shapes or cast components.
Unique Software	None identified.
Major Commercial Applications	Coatings to prevent friction, wear, and corrosion. These properties are already being exploited in commercial oil drill pipe by Amorphous Technologies, Inc.
Affordability	Not yet identified.

BACKGROUND

Amorphous metals have been shown to have unique magnetic and corrosion-resistant properties, but heretofore have only been made in thin cross sections by quenching liquid metal at very high cooling rates (approaching 1 million degrees per second). Recently, compositions have been developed that can be cooled into a glassy state at much lower cooling rates (few degrees/second). This allows casting of amorphous metal parts with cross sections that are several inches thick and opens up as yet unexplored possibilities for the application of these unique materials. The properties of these new alloys in both the glassy and very fine (nanocrystalline) devitrified forms are just now being investigated.

SECTION 14.4—SPECIAL FUNCTION MATERIALS

Highlights

- Corrosion control is critical to achieving extended lifetimes of current and planned platforms and equipment.
- Materials that promote system reliability and maintainability and/or reduce the need for routine maintenance have a direct impact on reducing life-cycle costs.
- Consideration of environmental impact is a key factor in many special function materials research projects.
- Technologies for sustainment and repair of low observability are essential for military effectiveness
- Materials for more efficient and reliable propulsion and power systems have a strong positive impact on fuel efficiency and logistical burden.

OVERVIEW

Special function materials are essential for all next-generation DoD weapon systems to maintain sustained operation at maximum capability. This broad range of materials includes hydraulic fluids/seals, fuel-system seals, turbine-engine lubricants/seals, solid lubricants, protective paints and coatings for camouflage and corrosion resistance, antifouling coatings for ships, rain/sand erosion-resistant coatings, electronic cooling fluids, gyro flotation fluids, fire-retardant materials, and chemical/biological-resistant materials and coatings. These materials not only control the performance of weapon systems but are also essential for enhanced sustainability, reliability, and maintainability. Overall, special function materials support all weapons systems including soldiers, land vehicles, small arms, artillery, ships, aircraft, spacecraft, launch vehicles, etc. This section identifies a number of research areas that are expected to benefit one or more of the aforementioned systems. Of particular note, the control of corrosion is critical to achieving extended lifetimes for legacy platforms. Consequently, research projects that address the detection, prevention, and management of corrosion in an environmentally benign manner are included in this section.

TECHNOLOGY ASSESSMENT

Military equipment traditionally operates closer to the limits of capability allowed by design than might be expected in similar commercial hardware. As a result, there is a need for materials that will withstand the conditions encountered at the upper limits of the operating envelope without failure. There are two trends evident in the research projects reported in this section. First, there is increasing emphasis on simplifying, reducing, and/or eliminating routine maintenance actions and the associated manpower and logistics requirements. Second, there is an emphasis on R&D that seeks to reduce or eliminate environmentally undesirable materials and processes from maintenance and repair actions. Much of the research in this area has a direct impact on overall system affordability in terms of reduced maintenance, increased lifetime, increased readiness, and/or improved survivability.

LIST OF TECHNOLOGY DATASHEETS
14.4. SPECIAL FUNCTION MATERIALS

DATA SHEET 14.4. SPACECRAFT LUBRICANTS

Developing Critical Technology Parameter	Extremely low (less than 0.1 percent and approaching 0-percent volatile condensable material) volatility liquid and solid-lubricant bearing coatings to triple the on-orbit lifetime of spacecraft reaction wheels and control-moment gyroscopes. Solid lubricant parameters include various ceramic composite and microlayered coatings of inorganic compounds and metals to achieve lubrication with the desired durability, repeatability, and coefficient of friction, μ, considerably less than 0.10.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Solid lubricants are deposited by techniques such as laser ablation, ion beam assisted deposition, and chemical-vapor deposition that may require specially designed equipment and fixtures to achieve even coatings.
Unique Software	None identified.
Major Commercial Applications	Developments that make it into production can be expected to transition to commercial spacecraft almost immediately and possibly to some terrestrial applications.
Affordability	Lubrication approaches that develop from this research should increase the reliability and lifetime of military space assets. A positive impact on life-cycle cost should result from advances in this technology.

BACKGROUND

Anything that serves to increase the reliability and extend the on-orbit lifetimes of very expensive space-based systems has a large impact on the overall affordability of these systems. The need to avoid contamination of sensitive optical systems and achieve low coefficients of friction are primary reasons for research on solid lubricants.

DATA SHEET 14.4. AIRCRAFT CORROSION PROTECTION: COATINGS AND APPLIQUES

Developing Critical Technology Parameter	Develop a nonchrome, corrosion-resistant, foundation coating with a 40-year lifetime and a corresponding topcoat or applique with at least an 8-year lifetime.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	In this case, coating systems being developed for commercial purposes are being evaluated by the military.
Affordability	If successful, the results of this research will reduce the frequency and environmental consequences of aircraft maintenance.

BACKGROUND

Periodic stripping and repainting of aircraft required for structural inspection and life extension is a huge expense for the military and generates large amounts of hazardous waste that require special handling. The goal of this research is to extend the life of the protective coatings and thereby reduce the costs and environmental consequences of aircraft cleaning and painting.

DATA SHEET 14.4. AIRCRAFT PAINT STRIPPING

Developing Critical Technology Parameter	Develop an environmentally compliant technique(s) for the rapid and complete removal of topcoats without damaging the underlying foundation coating or the airframe skin, whether aluminum or composite.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	High-pressure water systems.
Unique Software	None identified.
Major Commercial Applications	Commercial airlines can be expected to adopt technology developed by the military as they face similar environmental issues associated with paint stripping.
Affordability	Eliminate the cost burden associated with disposal of hazardous chemicals and chromate contaminated paint stripping media.

BACKGROUND

As with the extended lifetime coatings cited previously in this section, the goal of this research is to reduce the cost and environmental consequences associated with cleaning and repainting military aircraft or associated with required structural inspection and life-extension projects.

DATA SHEET 14.4. REPAIR OF METALLIC AIRCRAFT STRUCTURE

Developing Critical Technology Parameter	Polymer matrix composite materials can be bonded to metal aircraft structure to either repair damage or to increase the stiffness of the original structure to enhance capability. Research to extend environmentally friendly, sol-gel surface treatments to facilitate adhesive-bonded repairs for damaged metal-skinned aircraft is one component of this technology. Research is also being conducted to develop process parameters for an instructional handbook to guide the repair process.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Process instructions and field test procedures will have to be developed.
Major Commercial Applications	Civilian aviation can be expected to use the techniques developed for the military once they are proven to be effective.
Affordability	A fast, reliable process for field repair of damage will provide increased readiness.

BACKGROUND

The goals are to eliminate hazardous materials from the surface preparation steps involved with adhesive bonding and to reduce aircraft downtime needed to complete a field repair of battle or other forms of damage. Also, the information needed to guide bonded composite repair of metallic structure is not readily available and a handbook must be created to capture the relevant materials and process instructions for repair and/or enhancement of metal structure.

DATA SHEET 14.4. REPAIR OF BISMALEIMIDE COMPOSITE STRUCTURES

Developing Critical Technology Parameter	Develop materials, procedures, and tools for field repair of high-temperature (>315 °C), polymer composite structures.
Critical Materials	Bismaleimide resins.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Fast, reliable repair of damage increases aircraft readiness.

BACKGROUND

Quick, reliable processes are needed for repair of battle or other damage sustained by polymer composite structures operating at temperatures approaching 315 °C.

DATA SHEET 14.4. NONCHROMATED SEALANTS

Developing Critical Technology Parameter	Develop fluorinated polymer and polyioether-based sealant formulations that do not contain chromate compounds and that have performance superior to the current commercial chromate-containing formulations that are used to seal joints and seams on aircraft structure to prevent water ingress and crevice corrosion.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Such a sealant can be expected to rapidly transition to commercial aircraft fabrication.
Affordability	A successful nonchromated sealant will eliminate a source of hazardous waste that is generated when aircraft are disassembled for maintenance and the flying surfaces are cleaned before reassembly.

BACKGROUND

Waste that is generated during disassembly and cleaning of aircraft structural components is currently contaminated with chromate-containing compounds from the sealants used to prevent crevice corrosion in the joints. That waste must subsequently be handled as a hazardous material because of the chromate content. The goal of this research is to develop a new sealant formulation that will eliminate chromate from the sealant and avoid the hazardous waste problem.

DATA SHEET 14.4. LOW-OBSERVABLE GAP FILLERS

Developing Critical Technology Parameter	A revised filler formulation with increased shelf life, reduced cure time, and better adhesion and a more durable, longer lasting tape.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	The goal of this research is to reduce the maintenance required to maintain low radar cross section in low-observable structures.

DATA SHEET 14.4. HIGH-TEMPERATURE JET FUEL

Developing Critical Technology Parameter	+125 °C (225 °F) increase in the boiling point of a nontoxic fuel formulation. This is also referred to a JP–8 + 100.
Critical Materials	A satisfactory additive package is needed to stabilize the hydocarbon fuel at these higher temperatures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	The new formulation will undoubtedly be more expensive, but it will also enable increased aircraft capability.

BACKGROUND

The aircraft fuel load is used as a heat sink for cooling of critical aircraft electronics. Current fuels are at the limit of their capability to absorb heat and are thus limiting the capability of on-board electronic systems. A fuel formulation with a higher boiling point will remedy this limitation.

DATA SHEET 14.4. HYDRAULIC FLUIDS

Developing Critical Technology Parameter	Develop barium-free, corrosion-inhibited hydraulic fluids for aircraft and biodegradable fluids for both aircraft and submarines.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	A hydraulic fluid that meets military performance requirements but does not contain barium or other hazardous compounds will reduce disposal costs, decrease maintenance actions, and increase readiness.

BACKGROUND

New environmental regulations have classified barium-containing hydraulic fluids as hazardous materials. As a consequence it has become very expensive to dispose of used hydraulic fluid. Also, the barium-containing additives that provide corrosion inhibition are thermally unstable and cause sticking of valves and filter clogging at aircraft operating temperatures. Finally, spills of nonbiodegradable hydraulic fluid result in cleanup efforts that are time consuming and expensive. A new formulation that avoids hazardous additives, is biodegradable, and meets overall performance goals is needed to ensure conformance with environmental regulations and eliminate cleanup costs for spilled hydraulic fluid.

DATA SHEET 14.4. GAS TURBINE ENGINE LUBRICANTS AND SEALS

Developing Critical Technology Parameter	Lubricant and lubrication system seals capable of sustained operation at temperatures up to 345 °C (650 °F) with infinite lifetime at temperatures below 200 °C (400 °F) are being developed to meet this challenge.
Critical Materials	Perfluoropolyakylethers and perfluoro elastomers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial applications will be derived from military developments but cannot be predicted at this time.
Affordability	The increased engine operating temperatures enabled by higher temperature lubricants and seals should provide a decrease in specific fuel consumption of 5 percent or more.

BACKGROUND

The next generation of gas turbine engines will operate with an increase of turbine inlet temperature of approximately 120 °C (250 °F), which will produce a corresponding increase in the lubrication-system temperature. New lubricants and seals are needed to enable the increased temperatures and avoid requiring more frequent lubricant changes and seal replacement.

DATA SHEET 14.4. ANTIFOULING COATINGS

Developing Critical Technology Parameter	Fouling control coatings that provide effective performance while meeting a 12-year drydock cycle. Such coatings must be environmentally compliant with respect to volatile organic compounds (VOCs), hazardous air pollutants (HAPs), the Environmental Protection Agency's (EPA) application of Federal Rodenticide Act for Pesticides (FIFRA), and the United National Discharge Standards (UNDS). Silicone coatings that act as barriers to marine growth adhesion and coatings containing biodegradable pesticides that block growth of marine organisms are being investigated.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Predictive methods are needed to avoid extended field trials to assess overall coating performance and conformance with environmental regulations.
Major Commercial Applications	Ship hull coatings.
Affordability	The Navy spends about $80 million per year to remove and replace ship hull coatings. Minimized environmental impact and hazardous waste disposal costs, increased hull coating life, and fuel savings would accrue to a $200 million/year cost avoidance.

BACKGROUND

Approximately 1.5 million pounds of heavy metal (copper)-contaminated hazardous waste are created in the process of removing the paint and cleaning prior to repainting a single aircraft carrier. Marine coatings, including antifouling coatings, are also a source of HAPs. HAP emissions from shipyard were estimated at nearly 1,500 tons/year in 1992. An environmentally benign coating is needed to meet increasingly strict environmental regulations and to avoid the handling and disposal costs associated with current coating systems.

DATA SHEET 14.4. SHIP TOPSIDE AND CORROSION-CONTROL COATINGS

Developing Critical Technology Parameter	Urethane-coating technology that will minimize the escape of VOCs during application and provide an environmentally compliant coating for the service life of the ship (20 to 30 years).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Plural spray equipment for coating application.
Unique Software	None identified.
Major Commercial Applications	Topside coatings for commercial ships.
Affordability	A coating that meets the 20–30 year durability goal will save significant amounts of maintenance over the lifetime of the ship.

BACKGROUND

Major sources of HAPs to which VOCs contribute are regulated by the National Emission Standards for Hazardous Air Pollutants. Increasingly strict environmental regulations are making it more difficult to keep the painting process (materials and application) in compliance with the standards. Advances in coating technology are needed to keep pace with evolving environmental regulations without sacrificing overall performance and effectiveness. Failure to achieve these advances will have one of two results. If coating performance is sacrificed to meet environmental standards, then costs will increase as intervals between required maintenance are subsequently shortened by premature coating failure. As an alternative, maintenance could be deferred until environmental standards can be met. Neither of these is acceptable.

DATA SHEET 14.4. DRAG-REDUCTION COATINGS

Developing Critical Technology Parameter	Research is being conducted on ribbed textured appliques that can be applied to ship hulls to reduce hydrodynamic drag.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Competition racing boats.
Affordability	Reduced fuel consumption will offset the additional cost that may be associated with these appliques.

DATA SHEET 14.4. PASSIVE ACOUSTIC DAMPING MATERIALS

Developing Critical Technology Parameter	Identify materials that will provide 90-percent acoustic energy extraction in much less than a half wavelength thickness over a 0 to 25 °C temperature range and a 100 to 14,000 kPa (15 to 2,000 psi) pressure range.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Custom equipment may be required for fabrication and installation of these materials.
Unique Software	None identified.
Major Commercial Applications	Structural damping and machinery mounts.
Affordability	Affordability is achieved through increased survivability.

DATA SHEET 14.4. APPAREL

Developing Critical Technology Parameter	Develop lighter weight (30 percent) apparel to protect against known chemical and biological warfare agents with enhanced flexibility and body heat release to achieve longer wear time.
Critical Materials	Fabrics with very low permeability to air and liquids and high thermal transfer capability.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Protective clothing for law enforcement, civil defense, fire department personnel, and chemical industry workers.
Affordability	Better protection increases soldier survivability and decreases casualties.

BACKGROUND

Effective protection against chemical and biological threats will reduce casualties and increase capabilities to operate on contaminated battlefields.

DATA SHEET 14.4. CHEMICAL-AGENT-RESISTANT COATING (CARC)

Developing Critical Technology Parameter	New forms of CARCs (paints) used on vehicle bodies and airframes that give off much lower amounts of HAPs when they are applied and which will have minimal color change after weathering and cleaning.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Reduced environmental consequences and associated costs when applying coatings contribute to affordability, as do reduced decontamination time and soldier exposure in the event of chemical attack.

BACKGROUND

Lower VOC coatings are needed to meet environmental restrictions that are being placed on the repair and maintenance of equipment.

DATA SHEET 14.4. FIRE-RESISTANT POLYMER MATRIX COMPOSITES

Developing Critical Technology Parameter	The goals are (1) to develop fire-tolerant, load-bearing structures for ship and submarine applications that are a minimum of 30 percent lighter than current metallic structures by 2015 and (2) to develop similar fire-tolerant polymer composite structures for armored vehicles. All fire-tolerant materials developed by this research must have low oxygen depleting potential (ODP).
Critical Materials	Modified phenolic phthalonitrile resins and phosphonitrilic polymers.
Unique Test, Production, Inspection Equipment	Cone calorimeter for heat release; structural survivability test chamber developed by NSWC-Carderock.
Unique Software	Composite fire hazard analysis tool (CFHAT) that was developed to predict fire growth in organic polymers and composites.
Major Commercial Applications	Commercial marine, aircraft, and building construction.
Affordability	Lighter weight structure should translate into better fuel efficiency and maneuverability, which will reduce fuel logistics and increase survivability, respectively.

BACKGROUND

Lightweight, polymer composite structure pays dividends in terms enhanced vehicle/ship/submarine mobility and increased fuel efficiency and maneuverability. Better fire resistance is required before these benefits can be realized for enclosed structures.

DATA SHEET 14.4. INTUMESCENT PROTECTION COATINGS

Developing Critical Technology Parameter	Technology is being developed to eliminate HAPs, VOCs, and exotic ingredients (especially metals) in coatings that protect flammable substrates by melting and producing a gas that expands the coating into an insulating foam.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Fire-resistance-testing apparatus.
Unique Software	None identified.
Major Commercial Applications	Large-scale "fireproofing" of commercial structures.
Affordability	Passive coatings that increase platform survivability will delay replacement costs; those that increase durability will require less maintenance in the course of normal duty.

BACKGROUND

An environmentally compliant fire-protection coating system is needed to block the flow of heat between enclosed compartments in platforms such as ships and thereby protect the crew and extend the time to structural failure in the event of fire.

DATA SHEET 14.4. PROTON EXCHANGE MEMBRANES (PEM)

Developing Critical Technology Parameter	PEMs which allow the passage of protons (H^+) ions and allow very little methanol fuel to leak through. The membrane must be a proton conductor and must be stable in an acid solution.
Critical Materials	Polymeric proton conducting membrane and associated electrode assemblies.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	There is considerable commercial interest in this technology, and any major improvements in PEM fuel cell performance that result from this research are almost certain to have immediate commercial application.
Affordability	Current membranes cost $800 to $1,000 per kW, primarily because of the required platinum catalyst loading of approximately 10 mg/cm^2. Costs are expected to drop into the $50 to $100 range by 2005 as ways are found to decrease precious metal content. For high-power applications in large fuel cells, the precious metal catalyst will have to drop to approximately 1 mg/cm^2 to compete with other power production options.

BACKGROUND

Batteries are a significant logistics burden for the digital battlefield. The energy content of liquid fuels such as methane is such that the logistics burden can be significantly relieved if a fuel cell power source that can be easily refueled is developed to replace batteries.

DATA SHEET 14.4. DIAMOND AND HIGH THERMAL CONDUCTIVITY CERAMICS

Developing Critical Technology Parameter	Crystalline diamond, cubic boron nitride, aluminum nitride, silicon nitride, and silicon carbide are grown at relatively low pressures (~1 atm) and temperatures (<1,675 °C) by a variety of chemical vapor deposition techniques. Aluminum nitride and silicon carbide are also produced as powders and consolidated by conventional methods.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Sophisticated deposition systems that may combine plasma and/or ion beam processing with chemical vapor deposition (CVD).
Unique Software	None identified.
Major Commercial Applications	Heat sinks; cutting tools; surgical blades; wire drawing dies; and high-power transistors, electrical components, and electronic components.
Affordability	High initial cost is more than compensated for by the capabilities that can be achieved and the extended lifetimes of critical components.

DATA SHEET 14.4. THERMAL BARRIER COATINGS FOR AEROPROPULSION

Developing Critical Technology Parameter	Thermal barrier coatings with thermal expansion better matched to superalloy substrates to reduce thermal stresses and improve thermal shock and fatigue resistance. Also, increased hot-corrosion and oxidation resistance are needed for the bond coat that anchors the thermal barrier coating to the substrate.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial aircraft turbines have the same requirements for better fuel efficiency and reduced maintenance as the military, and these coatings would transition to commercial engines in short order.
Affordability	The increase in operating temperature enabled by thermal barrier coatings improves fuel efficiency, and a longer life coating will reduce maintenance costs.

BACKGROUND

Thermal barrier coatings have been used for more than 30 years to extend the operational life of static aircraft gas turbine engine components. Improvements in the composition and microstructure of these ceramic coatings have allowed the application of thermal barrier coatings to more highly stressed rotating parts. Research is now needed to extend further the useful lifetime of these coating systems to reduce maintenance costs.

DATA SHEET 14.4. HEAT SHIELD AND ABLATIVE MATERIALS

Developing Critical Technology Parameter	Alternative heat shield materials with performance equivalent to past rayon-based materials.
Critical Materials	Qualified rayon or carbon fiber.
Unique Test, Production, Inspection Equipment	Arc jet material test facilities.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Although decreased cost is a desirable attribute, it is not an overriding consideration in this case.

BACKGROUND

A new source of fiber is needed to ensure the future availability of high-performance heat shields with extended shelf lives and assured reliability.

DATA SHEET 14.4. AMMUNITION COATINGS

Developing Critical Technology Parameter	The goal of this research is to develop nontoxic coating formulation for high-rate production of military ammunition without exceeding EPA guidelines for release of VOCs and exposure to heavy metals.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Enables compliance with environmental regulations in ammunition-manufacturing operations.

BACKGROUND

Coatings and primers used in the interior and exterior of military munitions to protect energetic materials from deterioration caused by the natural environment contain VOCs and heavy metals that are known to be toxic. New formulations that reduce VOCs to acceptable levels and that are nontoxic are needed to facilitate the continued production of military ammunition at various manufacturing sites.

DATA SHEET 14.4. CHEMICAL AND BIOLOGICAL SENSOR MATERIALS

Developing Critical Technology Parameter	Polymers that selectively adsorb and release specific gaseous species that can be translated into chemical agent concentrations in the sub-part-per-million level when utilized in surface acoustic wave sensors.
Critical Materials	Hexafluoroisopropanol (HFIP) functional arene rings to activate the interactive portion of the selective polymer.
Unique Test, Production, Inspection Equipment	Surface acoustic wave sensors.
Unique Software	None identified.
Major Commercial Applications	Chemical and vapor detection and identification sensors for industry.
Affordability	These polymers are used in small quantities and cost is not a major issue. The surface acoustic wave devices they are relatively inexpensive when compared to other measuring instruments of similar sensitivity.

SECTION 14.5—SMART MATERIALS AND STRUCTURES

Highlights

- Demonstrations show that smart materials and structures technology has potential for controlling aerodynamic, hydrodynamic, and optical surfaces. It can be used for vibration damping and resonant frequency tuning of structures, and it may be applicable for use in robots and stealth.
- Defense use of smart materials and structures requires significant reduction in system cost and complexity.
- The current approach to development of smart materials and structures emphasizes composting known constituents.
- Synthesizing new materials and structures at atomic or molecular level with smart functionality will require new discoveries beyond what is available now.

OVERVIEW

Broadly speaking, smart materials and structures are those that can sense external stimuli and respond with active control to those stimuli in real or near-real time. Sensors, actuators, signal processors, and the physical links that are needed to connect them are the components of a smart structure or device. Sensors enable smart structures or devices to acquire the information needed to initiate tasks. They may measure physical quantities (displacement, velocity, acceleration, position, force, temperature, etc.) or chemical species (identify and quantify gases and chemicals). Sensing methods include optical, microwave, magnetic, acoustic/ultrasonic, chemical, and mechanical. Sensors and actuators are connected to a processing unit by sophisticated communications link techniques including wiring, radio, sound and ultrasound, chemically induced electrical phenomena (as in biological organisms), and fiber optics.

DoD research has emphasized structures that perform mechanical tasks for application to systems such as aircraft, torpedos, and submarines. Visual and acoustic tasks can also be undertaken, with the photochromic darkening of glass being an example. In the future, the development of microactuators will open the field to many additional tasks. For instance, optical microactuators are envisioned for the direct manipulation of matter by light or the indirect optical actuation utilizing light to heat solids or gases that upon expansion cause actuation.

Smart materials change or modify their physical properties in response to the environment. Physical properties of smart materials may include color, physical dimensions, elasticity, or they may include other functions and properties, such as the ability of the material to “push back” in response to a force field. They may utilize a centralized signal-processing unit along with distributed sensors and actuators, or they may utilize a distributed sensing or signal-processing scheme.

Being considered are six categories of actuators: electrical, magnetic, thermal/phase change, optical, mechanical/acoustic, and chemical/biological.

Electrical actuation relies on the coulombic attraction/repulsion between charged bodies. Electrical actuators include a variety of actuation schemes. Electrostatic actuation uses attraction between dissimilar charges to exert a force on a deformable/mobile body. Piezoelectric actuation, on the other hand, relies on the change in the dimension(s) of piezoelectric materials when a voltage is applied across them. Electrotheological fluids provide a fully reversible process where a composite contains polarized particles that stiffen when exposed to an electric field. Polyelectrolyte gels (a polymer matrix swollen with a solvent) can expand or contract up to 500 percent when exposed to an electric field.

Magnetic actuators include magneto-elastic and magnetorestrictive schemes, where the material dimensions change when a magnetic field is applied. More recently, magnetically acutated shape-memory alloys that provide larger displacements have been discovered and are being investigated.

Thermal actuators rely on the difference in the thermal expansion coefficients of different materials, thermally activated phase changes, or a combination of the two effects. For instance, the thermal expansion coefficient may undergo a drastic change when the phase of the material changes as a function of temperature. Certain materials, known as “martensites,” such as perm-alloys, have the interesting property of “remembering” their shape: after plastic deformation and upon heating they return to their pre-deformation shape. These methods are being exploited for large displacement/force applications.

Optical schemes are divided into direct and indirect optical methods. Direct optical methods use light to interact with the active parts of the actuator and cause actuation. Indirect optical methods take advantage of the heating power of the light or its ability to generate electrical current or to change the resistivity in photo-responsive materials.

Mechanical schemes use one type of mechanical motion, such as linear displacement, to generate another type of physical motion, such as rotation. Mechanical actuators are extensively used in everyday life, and they cover a wide range of actuators, such as those in water faucets, where the rotational motion is converted to a linear displacement that causes the opening of the valve. Mechanical methods may also rely on levers and gear boxes to amplify small displacements. In fluidic systems, a rich variety of structures exist that take advantage of channels with different cross sections to achieve amplification and switching.

Acoustic methods take advantage of the momentum and displacement that can be generated by acoustic waves and mechanical vibrations in gases and solids. In these actuators, either a mechanical rectifier is used to rectify the displacement and cause it to generate a linear displacement or the acoustic energy is concentrated and used to vaporize liquids that, upon condensation, constitute the output of the liquid pump.

Actuators that employ chemical reactions to generate force and displacement are numerous. Almost all the mechanical energy that biological (life) organisms generate uses chemical reactions. The car engine is a classic example of harnessing a chemical reaction (i.e., oxidation of the fossil fuel) to generate force and displacement. Explosives, since they rely on the generation of pressure waves and large forces by spontaneous chemical reactions, are another example of chemical actuators. Biological actuators, such as muscle, usually involve a chemical component that is used to generate the necessary forces and displacements. In these actuators, there is a fatigue factor that is related to the rate at which the chemicals (also called nutrients) can be replenished and byproducts can be removed and discarded. Another issue in biological actuators is the “mode” of operation or performance that is usually related to the rate and duration of work extraction. At slower rates, aerobic behavior is usually observed. As the rate increases, an anaerobic regimen sets in and energy stored in the actuator itself is taken up. As we move towards more complex systems with a multitude of actuators, such as a distributed and bimodal operation scheme may prove quite useful.

Smart materials and structures programs are developing and demonstrating new classes of materials which have the capability to both sense and respond to environmental stimuli with active control of their response. Such “smart materials” offer many new and enhanced capabilities to DoD systems, particularly in performance, durability, and reliability. Smart materials will provide designers and engineers with significant new capability to control geometric shape, materials movement, aerodynamic and hydrodynamic flow, damping and vibration, and other capabilities which can be designed attributes of the material/structure system.

The focus of the effort on smart materials and actuators relative to potential defense applications is on processing and manufacturing of advanced materials, materials combinations, and components that will enable new capabilities at an affordable cost for all advanced military systems. Defense requirements for robustness, reliability, and high response rate focuses research efforts on advanced actuator materials and devices. The use of induced-strain actuators has experienced a great expansion in recent years. With the emergence of smart and adaptive structures technology design in mechanical systems, there is a need for improved materials and devices to produce large mechanical displacements with highly efficient electrical-to-mechanical energy conversion. Through the use of displacement amplification, induced-strain actuators may achieve dynamic output strokes similar to those of conventional hydraulic actuators. The key to achieving this is to develop higher performance actuation materials and demonstrate innovative, low-cost production, forming, and fabrication technologies to produce both the active materials and the devices. The new actuator devices designed and fabricated from these materials will focus on achieving a high authority, high response rate in compact, lightweight packages. This includes the development of mesoscale actuators for direct incorporation into smart structures, as well as bulk actuator materials. In addition, a number of innovations have demonstrated the feasibility of a variety of potentially pivotal processing improvements, which, if brought to maturity, will increase actuator performance and reduce costs sufficiently to create strong non-DoD demands.

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LIST OF TECHNOLOGY DATASHEETS
14.5. SMART MATERIALS AND STRUCTURES

DATA SHEET 14.5. VIBRATION SUPPRESSION

Developing Critical Technology Parameter	Reduce the dynamic instabilities and vibration currently affecting noise levels and service life of military rotary-wing aircraft. Use smart material and structure design technology to provide 10-dB reduction in blade vortex interaction and blade tracking noise while landing by means of control of trailing edge flaps or active twist of helicopter rotor blades. These developments are expected to provide an 80-percent reduction on airframe vibrations and a 10-percent gain in rotor performance (lift/drag).
Critical Materials	Piezoelectric stack actuators and piezoelectric fibers for active "composite" structures.
Unique Test, Production, Inspection Equipment	Actuator bench and spin test; full scale rotor whirl test; 80 × 120 wind tunnel; sophisticated lay up, curing, and handling equipment.
Unique Software	Computer-aided design/computer-aided manufacturing (CAD/CAM) and operating algorithms.
Major Commercial Applications	All transportation and operating machinery and precision machine tool control.
Affordability	Expensive to develop and acquire and provide training. Trade-off is increased performance and survivability.

BACKGROUND

Reduction in vibration and acoustic signature reduces detectability when operating in Earth's environment. Vibration control on Earth-orbiting satellites can reduce jitter and improve sensor performance. Improvements in passenger/crew comfort and fatigue life of structure and electronic components as well as weapons accuracy are possible.

DATA SHEET 14.5. SHAPE-ADAPTIVE STRUCTURES

Developing Critical Technology Parameter	Shape-adaptive structures provide aerodynamic/hydrodynamic flow control. Aircraft wing warping, camber shaping/control-surface deformation, and ship propeller shroud shape modification all provide enhanced performance in their environments. For aircraft, improved lift could provide up to 8-percent increase in allowable take-off weight, 30-percent increase in weapons payload, 40-percent reduced drag on an F–18. Enhanced thrust with less cavitation for shrouded ship propellers is anticipated with active shape control.
Critical Materials	Shape-memory alloy torque tubes and wire and other high-strain, high-force actuator materials are required (see Data Sheet 14.5, Actuators).
Unique Test, Production, Inspection Equipment	Actuator bench test. Full-scale wind and water tunnel facilities and sophisticated lay up, curing, and handling equipment.
Unique Software	CAD/CAM and operating algorithms.
Major Commercial Applications	Aircraft and ships and unmanned vehicles.
Affordability	Cost will have to be balanced against improvements in range, performance, fuel efficiency, and survivability.

DATA SHEET 14.5. HIGH-RATE SHAPE CONTROL

Developing Critical Technology Parameter	Control aircraft engine inlet airflow at various Mach speeds, altitudes, angles of attack, and angles of slip to reduce drag and radar cross section. Expected performance improvements are 20-percent increase in range; better maneuverability, flutter and buffet control; and reduced signature.
Critical Materials	Shape-memory alloys and piezoelectric motors required (see Data Sheet 14.5, Actuators).
Unique Test, Production, Inspection Equipment	Actuator bench test. Wind tunnel for large test pieces. Sophisticated lay up, curing, and handling equipment.
Unique Software	CAD/CAM and operating algorithms.
Major Commercial Applications	All advanced aircraft.
Affordability	Cost comparison to correct adjustable inlet schemes has not yet been made. Performance improvements ultimately will have to be balanced against acquisition and operating costs.

DATA SHEET 14.5. ACTUATORS

Developing Critical Technology Parameter	Goal is to achieve actuators with maximum efficiency and minimum weight and size that can be manufactured at minimum cost and that can be integrated into useful structures and devices. Linked to sensors and supplied with an energy source—electrical magnetic, thermal, optical, mechanical, acoustic, or chemical/biological—they must operate in real time and reliably provide high force, energy, and power densities.
Critical Materials	Shape-memory alloys; piezoelectric, electromagnetic, and hydraulic systems currently in use; as well as evolving new magnetic shape-memory alloys, photochromics, pyroelectric gels, electrorheological fluids and solids in new or modified forms and composites.
Unique Test, Production, Inspection Equipment	Requires sophisticated tools and test equipment.
Unique Software	CAD/CAM and simulation algorithms.
Major Commercial Applications	Ultrasonic motors, sporting equipment, acoustic control, aeroelastic control, power transformers, commercial aircraft, ships and land vehicles, robotics, prosthetics, and nondestructive flaw detection in structures.
Affordability	Where major systems applications (submarine, aircraft, missile, satellite) are involved, the introduction of smart materials and structures to improve capability requires large-scale demonstrations and acceptance of risk, as well as expense, for whatever increased capability is projected.

SECTION 14.6—MICROMACHINED MATERIALS AND STRUCTURES [INCLUDING MICROELECTROMECHANICAL SYSTEMS (MEMS)]

Highlights

- There has been considerable advancement within the last 5 years in adapting micromachined structures for military applications.
- The principal focus of research on materials and structures in the commercial sector is for fluidic, chemical, optical, and communication applications where the highest return on investment is anticipated.
- Harsh environmental conditions (mainly temperature and chemical) for military systems is a driving force for the research in new materials and processes for micromachined structures and in materials development for packaging of micromachined structures.

OVERVIEW

This section describes selected developing critical materials and processing technologies for micromachined structures. Current military applications are utilizing materials and processes commercially demonstrated or under development for commercial applications. In many cases, the materials and processing technology is "dual use," although specific products (e.g., automotive accelerometers) may not be "dual use." Current commercial materials and processing technology will not be sufficient to meet all projected military use of micromachined structures.

The need for new technology (e.g., sensors), new processes (e.g., greater dimensional control), and new materials (e.g., materials capable of operating in harsh environments) will provide impetus for advances in processing micromachined structures. This section discusses process technologies used to manufacture micromachined structures, as well as particular classes of structures based on materials used.

LIST OF TECHNOLOGY DATASHEETS 14.6. MICROMACHINED MATERIALS AND STRUCTURES

DATA SHEET 14.6. MEMS PROCESSES

Developing Critical Technology Parameter	Develop and reliably fabricate structures with a minimum dimension on the order of 0.1 µm using MEMS processing.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test and inspection equipment to measure dimensions with submicrometer resolution and accuracy on miniature three-dimensional (3–D) structures, where structural dimensions range from 0.1 to 500 µm in any given dimension. Test equipment to measure material properties on specimens having a minimum dimension on the order of 1 µm in any dimension.
Unique Software	Robust structural design software based on fabrication process used and coupled with physical, chemical, and biological phenomena in which the final devices are deployed.
Major Commercial Applications	Accelerometers (automotive airbags, toys), pressure sensors (automotive, blood, etc.), inkjet printheads, digital micro mirrors, and wireless and optical communications.
Affordability	Commercially viable yields from MEMS processes require significant investment to ensure robust, repeatable manufacturing processes. Analog Devices, Inc. (ADI) and Bosch have achieved yields in the mid-high 90s percent.

BACKGROUND

Wafer-level processing to manufacture devices is being developed. Technology issues affecting development of MEMS devices include development of (1) microstructural characterization methods; (2) standard material property test methods; (3) standard device response/performance test methods; (4) quantitative relationships between microstructure, processing, properties, and performance; and (5) modification of existing MEMS processes that allow a broader range of materials to be manufactured. Advances in the five technology areas cited will lead to advances in process monitoring and control methods and in verification of design and modeling tools used. Progress in the MEMS process monitoring and control and in design and modeling tool verification will lead to a reduction in MEMS device development time and cost. Progress in modification of existing processes will allow MEMS devices and components to be considered for more applications, especially in harsh environments. Discussion of new process methods is introduced in later sections.

Current MEMS wafer-level processes include bulk processes, where the structures are produced from the substrate by material removal, and surface processes, where the structures are produced from material deposited onto the substrate. The most common bulk processes include wet chemical etching, deep reactive ion etching (DRIE), and laser etching. Surface processes are subdivided into surface micromachining and high-aspect-ratio micromachining (including Lithographie, Galvanoformung, Abformung—LIGA). Surface micromachining produces structures with heights on the order of 1 to 10 µm. High-aspect-ratio processes produce structures ranging from 10 µm and up, with LIGA producing structures on the order of 100 µm or greater.

Device and component MEMS processing will require either integration of electronics with MEMS devices by process integration or integration of electronics with MEMS devices by hybrid integration techniques. An example of one hybrid integration technique would be solder bonding of a MEMS device chip and an electronic chip using patterned solder or flip-chip techniques.

Component-level processing (packaging processing) compatible with or an integral part of the MEMS wafer-level device processing is being developed. Component-level processing addresses two main technical issues: (1) protection of the MEMS mechanical device from the environment and (2) integration of the packaged MEMS component into the larger system (form, fit, and function). In an increasing number of cases, the integration of the packaged MEMS component includes a means for calibration of the MEMS component. The majority of cost in a MEMS component is in packaging, characterization, and certification. Compared with electronic components, MEMS components must interface directly with the environment while being protected from damage due to this interface. For example, a MEMS flow sensor must interface with the medium in which flow is occurring, but must be protected from erosion due to the flow.

DATA SHEET 14.6. MESOSCALE MACHINING PROCESSES

Developing Critical Technology Parameter	Process development related to manufacturing structures having dimensions on the order of 1 µm and larger using scaled-down versions of traditional machining processes. The machining processes include drilling, milling and electrodischarge machining (EDM). Integration of these mesoscale machining processes with other micromachining process technology such as MEMS.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test and inspection equipment to measure dimensions with submicrometer resolution and accuracy on miniature 3–D structures where structural dimensions range from 1 to 500 µm in any given dimension. Test equipment to measure material properties on specimens having a minimum dimension on the order of 1 µm in any dimension. Production equipment designed for manufacture, handling, and assembly of individual micromachined structures produced by mesoscale machining.
Unique Software	Improvements to computer numerical control (CNC)-type software enabling submicrometer dimensional control.
Major Commercial Applications	Optical and fluidic applications.
Affordability	These processes are serial, not batch processes. As a consequence, unless volumes are increased above most projected volumes for microsystems, cost will be moderate to high compared with batch processes. These processes may be only method to produce some components, so higher cost would be accepted.

BACKGROUND

In the past, the United States has focused efforts in the production of micromachined structures almost totally on MEMS manufacturing. The rest of the world adopted a broader view of micromachined structures and included not only MEMS processes, but also machining processes based on “scaled down” machining or mesoscale machining processes. The United States is beginning to develop mesoscale manufacturing processes because they address limitations of the MEMS processes, such as materials used and geometry of structures that can be produced. One drawback of the mesoscale processes is that they are serial processes, not batch processes such as the MEMS processes are. Thus, the cost benefits achieved with batch processes are not realized with the mesoscale processes. Also, mesoscale processes will produce parts that require assembly to produce a device. Assembly of these parts will require development of cost-effective assembly processes.

Mesoscale machining processes include microelectrodischarge machining (microEDM), focused ion beam (FIB) machining, micromilling, microdrilling, and laser micromachining. These mesoscale machining processes allow fabrication of structures with sizes on the order of micrometers to hundreds of micrometers in at least one dimension.

DATA SHEET 14.6. SILICON STRUCTURES

Developing Critical Technology Parameter	Process optimization methods to enable high-volume, high-quality production. Modification and development of manufacturing processes used on 4-in. diameter substrates scaled-up for production on 6-in. diameter substrates.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test and inspection equipment to measure dimensions with submicrometer resolution and accuracy on miniature 3–D structures where structural dimensions range from 0.1 to 500 µm in any given dimension. Test equipment to measure material properties on specimens having a minimum dimension on the order of 1 µm in any dimension.
Unique Software	None identified.
Major Commercial Applications	Accelerometers, inertial measurement, display technologies.
Affordability	Affordability of bulk and surface micromachined components will be achieved when process optimized. It is anticipated that newer bulk micromachined components (e.g., DRIE components) will be higher priced compared with surface or wet bulk micro-machined structures because of the serial fabrication of structures etched from the wafer. This is in contrast with wet bulk micromachining processes where structures are etched at the same time across the wafer.

BACKGROUND

Silicon structures are most commonly produced using MEMS processing. MEMS processing builds on microelectronics manufacturing processing. The silicon structures can be made from single crystal, polycrystalline, or amorphous silicon. Typically, single-crystal structures are produced using wet chemical etching or DRIE. Structures that may be produced include diaphragms used in pressure sensors, nozzles used in inkjet printheads, and v-grooves used for optical fiber alignment. Recently, fuel atomizers made in single-crystal silicon using a DRIE process have been packaged and demonstrated. Finally, higher aspect ratio, higher mass, single-crystal silicon structures are being used in inertial-sensing devices to provide a different bandwidth with increasing structural robustness compared with other silicon inertial-sensing devices. Single-crystal silicon is considered mechanically stable up to temperatures approaching 500 °C.

Polycrystalline silicon (or polysilicon) and amorphous silicon structures are fabricated using surface micro-machining processes. These structures are typically from 1 to 10 µm high (or thick). Structures that may be produced include beam structures and spring-supported structures. The beam structures are used for atomic force microscopy (AFM) structures, for optical structures (e.g., grating light valve), and for temperature sensing/thermal actuation structures. Spring-supported structures are used for inertial sensing and resonant structures (e.g., micromechanical filters). Polysilicon typically is considered mechanically stable up to temperatures approaching 250 °C.

Silicon is a material that is in wide use in the semiconductor electronics industry. Therefore, the cost of silicon wafers is low. Also, many of the process steps in the manufacture of surface micromachined structures are similar to microelectronic fabrication process steps. The cost of developing equipment for silicon MEMS fabrication is consequently lower because the silicon MEMS processing can be carried out in microelectronic processing equipment.

DATA SHEET 14.6. SILICON-CARBIDE (SiC) STRUCTURES

Developing Critical Technology Parameter	Development of process to produce reliable, robust SiC structures that can function in temperatures approaching 600 °C. Methods for characterizing material and material response to harsh environment exposure.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test and inspection equipment to measure dimensions with submicrometer resolution and accuracy on miniature 3–D structures where structural dimensions range from 0.1 to 500 µm in any given dimension. Test equipment to measure (1) material properties in a wide variety of environments on specimens having a minimum dimension on the order of 1 µm in any dimension and (2) corrosion and erosion of materials and structures.
Unique Software	Thermal modeling software to predict thermal response on dimensional scale of micromachined structures.
Major Commercial Applications	High-temperature pressure sensors, fuel atomizers, and microturbines.
Affordability	The development of robust, reliable processes to ensure high yield is essential. It is anticipated that these structures will cost more than silicon micromachined structures because of the demanding applications for these structures. The cost should still be reasonable because of the batch fabrication nature of the processes currently being used.

BACKGROUND

SiC structures are being developed for harsh environments where silicon structures would not survive. SiC is expected to operate at temperatures approaching 600 °C. SiC films also have demonstrated chemical inertness, wear resistance, and radiation resistance. SiC micromachined structures could be used in high-temperature applications in automobile and aerospace engine applications. Also, SiC is being explored in the use of miniaturized power sources, such as a MEMS micro-turbine engine. While this data sheet focuses on SiC structures, it is worthwhile to note that SiC is being considered as a “coating” material for microfabricated structures to provide the environmental protection afforded by SiC without having the total structure fabricated from it.

SiC can exist as one of several polytypes. The most common polytypes are 3C (C = cubic lattice structure), 4H (H = hexagonal lattice structure), and 6H. The 6H polytype is used in CMOS integrated circuits designed for higher temperatures because it produces high-quality oxides and higher quality ohmic contacts compared with the other polytypes. Although it is not commercially available, there is growing interest in producing MEMS components from the 3C polytype. The 3C polytype can be epitaxially grown on a large-area silicon substrate using an atmospheric pressure chemical vapor deposition (APCVD) process. The SiC can be grown as single crystal or as polycrystalline films. The 3C–SiC can be patterned using a thin film of aluminum as a masking layer. The aluminum can be patterned using lithographic processes. As an alternative, SiC devices can be created using molding and chemical-mechanical polishing.

Compared to silicon processing, SiC micromachined structure (mainly MEMS) processing is immature. It has good potential since it is a batch fabrication process and SiC electronic components are being used for higher temperature applications. Other mesoscale manufacturing methods have not been applied to produce SiC structures.

DATA SHEET 14.6. METAL STRUCTURES

Developing Critical Technology Parameter	Control of material composition enabling (1) expansion of operating temperatures for metal micromachined structures and (2) fabrication of smart materials enabling additional actuation methods (e.g., shape-memory alloys). Compatibility of fabrication process for metal structures with other micromachining processes. Process optimization methods to enable high-volume, high-quality production.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test and inspection equipment to measure dimensions with submicrometer resolution and accuracy on miniature 3–D structures where structural dimensions range from 0.1 to 500 µm in any given dimension. Test equipment to measure material properties on specimens having a minimum dimension on the order of 1 µm in any dimension. Metal structures produced by mesoscale machining requires production equipment designed for handling and assembly of individual micromachined structures.
Unique Software	Improvements to CNC software and image analysis software to ensure applicable to measurements on 3–D structures.
Major Commercial Applications	Mechanical relays, optical components (e.g., mirrors), and micromechanical actuators.
Affordability	Commercially viable yields from metal structure fabrication processes require significant investment to ensure robust, repeatable manufacturing processes. Affordability will depend on compatibility of metal structure fabrication processes with other micromachining processes.

BACKGROUND

Metal structures are produced using MEMS and mesoscale manufacturing processes. MEMS processes that produce metal structures include surface micromachining, optical LIGA, X-ray LIGA, and mesoscale machining processes. In manufacturing, structures ranging from 0.1 to 500 µm high can be produced with aspect ratios ranging from 1:1 to 50:1, depending on the process used. Structures have been made from aluminum, copper, nickel, iron-nickel alloys (permalloy), and nickel-titanium shape-memory alloys (nitinol). In many cases, to realize the full potential application of these materials, the processing of the metal structures must be compatible with the processing of other micrometer-scale structures and with the processing of electronics.

Unlike surface micromachining processes where a deposited film is lithographically patterned after deposition to form the micromachined component, in the LIGA process the component is formed by electroplating metal into a lithographically defined polymer mold that is attached to a substrate. The lithographic exposure of the polymer can be achieved by using high-energy X rays from a synchrotron source (X-ray LIGA) or by using UV light in a more standard lithographic process (optical LIGA). The X-ray LIGA process was developed to produced high-aspect-ratio structures (up to 50:1). The optical LIGA process is being developed to produce metal structures with aspect ratios between the ratios achievable by surface micromachining (less than 1:1) and by X-ray LIGA (50:1).

The use of metal structures has expanded the actuation mechanisms beyond electrostatic actuation used in the majority of silicon-based devices. Using metal structures, actuation mechanisms include electrostatic, thermal, electromagnetic, and shape-memory transformations. One challenge in the use of alloys is the careful control of composition during processing. Another challenge is demonstrating that the micrometer-scale structures produced from alloys exhibit the similar properties that make the alloys useful in bulk form.

DATA SHEET 14.6. POLYMER STRUCTURES

Developing Critical Technology Parameter	Material stability in selected environments, multifunctionality, and potential cost advantages compared with other micromachined materials and structures are being investigated.
Critical Materials	Development of new polymers chemistries enabling functionality.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None needed for nonfunctional polymers. Software containing models that capture the sensitivity and time response of functional polymers will be needed.
Major Commercial Applications	Drug delivery systems, spectrometers, micropumps and microvalves, chemical detection systems.
Affordability	Nonfunctional material and processing will be cheaper than other micromachining materials and processes. Integration of polymer processing with other micromachining processes may control cost. Because functional polymers are early in development and demonstration, it is difficult to determine cost at this time.

BACKGROUND

Polymers are used extensively in many commercial applications that do not utilize micrometer-scale structures. The advantages of plastics compared with other materials used in micrometer-scale structures include chemical resistance, biocompatibility, and batch fabrication by means of several processing routes. At present, the use of polymers in micrometer-scale structures mainly is in the area of microfluidics. The polymers fall into one of two categories: functional or nonfunctional. Polymers are used in chemical/biological sensing and analysis devices and in waveguide (optical) components. Also, functional polymers are being used in actuators. Polymers being used include PTFE (Teflon), parylene, polyimide, poly(dimethylsiloxane) (PDMS), and SU–8. The batch fabrication of miniature plastic parts is seen as necessary for cost-effective solutions for many microfluidic applications, especially in the biomedical field.

The polymers can be cast or injection molded into silicon or metal molds produced by micromachining fabrication techniques (e.g., surface micromachining, DRIE, or LIGA). Also, the plastics can be surface micro-machined on a substrate by depositing a plastic film and then patterned using lithographic techniques. Polymers can be produced by photopolymerization using UV or near-UV radiation lithographic processes. In many cases, the processing of the polymer structures is compatible with components made before or after the plastic structure fabrication. The issue in many instances is ensuring a proper process flow so that subsequent processing does not damage the polymer structures. In many cases, other materials are being embedded in the polymers to produce actuators (e.g., rare earth magnetic powder particles embedded in polymers to produce magnetic actuators).

In microfluidic devices/systems nonfunctional polymers make up the walls of channels and act as coatings for other materials and components that provide the structural support or that provide the actuation, such as pumping of fluid. Functional polymers are polymers that respond to changes in the local environment (e.g., pH in the fluid) and perform an action such as deflecting a membrane to open or close a valve. This class of polymers is called hydrogels.

DATA SHEET 14.6. CERAMIC AND LAYERED STRUCTURES

Developing Critical Technology Parameter	Materials for higher temperature (>600 °C) and chemically harsh environments. Materials and fabrication process technology for producing ceramic and layered structures with 0.1 µm minimum dimension.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Development of test and inspection equipment capable of performing test and inspection at appropriate scale in harsh environments.
Unique Software	None identified.
Major Commercial Applications	MEMS used in harsh environments including pressure, temperature, and chemical sensors.
Affordability	May overlap with some areas of silicon-based micromachined structures. If so, there may be some cost savings in packaging, compared with silicon-based micromachined structures.

BACKGROUND

Other material structures include ceramic (beyond typical ceramic MEMS materials) and layered micromachined structures. This category of structures is expanding as the applicability of micromachined structures is increased and the limitations of other micromachined materials are recognized. Advancements in the development of materials and structures in this category will be driven by specific needs.

Ceramic hybrid electromechanical systems utilizing micromachined structures have been fabricated using the technology available for manufacture of ceramic hybrid structures in the electronics industry. The ceramic-hybrid technology can result in laminated assemblies of ceramics, metals, and glasses that can be patterned, fired, and etched to produce the micromachined structures. One example of the manufacturing process that may be used to produce a micromachined structure is a combined stamping, deposition of metals and dielectric materials, assembly of the layers, lamination of the material stack based on the low-temperature cofired ceramic (LTCC) process technology, and wet-chemical etching to release the mechanical structures (e.g., a cantilever beam).

Also, electrically conductive metal-glass composite structures have been developed. These structures are used as conductive elements or parts of micromachined structures. In addition, the integration of integrated circuit (IC) processing and micromachining is resulting in the development of metal-/silicon-/ceramic-layered micromachined structures. The composite response of the layered structures to external loading, including mechanical and thermal, may result in new micromachined device development. In reality, many current micromachined structures are layered structures. This section has presented structures or components that were specifically developed for or depend on the layered material behavior for their functionality or performance.

SECTION 14.7—MAGNETIC MATERIALS

Highlights

- Ferrites and rare-earth permanent magnets are increasingly important to DoD applications, and their use has outpaced that of Alnico.
- New materials are being developed for thin films and nanostructures, which offer substantial improvement in data storage capability.
- Tailoring properties of magnetic materials for specific applications based on theory as well as experiment is continuing at a strong pace.

OVERVIEW

A. GENERAL

Magnetic materials are essential to a large variety of DoD electrical, electronic, and mechanical equipment. Iron, cobalt, nickel, and their alloys are examples of ferromagnetic materials. In ferromagnetic materials, the unpaired electron spins are aligned. These spins could have different values at different sites, known as magnetic sublattices. The ferromagnetic materials exhibit an external (macroscopic) magnetic moment due to the alignment of the sublattices. Ferrimagnetic materials have unpaired electron spins that are held in a pattern with some sublattices aligned up and some aligned down. In these materials, there are more sublattices aligned in a direction (up or down) resulting in an external (macroscopic) magnetic moment. Examples of ferromagnetic materials include magnetite (Fe_3O_4), $CoFe_2O_4$, and $Y_3Fe_5O_{12}$. A subset of ferrimagnetic materials is the antiferromagnetic materials. In this case, the materials have sublattices with an equal number aligned up and down. Consequently, these materials have no resulting external magnetic moment. There are also paramagnetic materials that have unpaired spins that are random and diamagnetic materials that have no unpaired spins. These materials can be temporarily magnetized when exposed to a magnetic field.

Ferromagnetic and ferrimagnetic materials are the most common materials used in DoD equipment. The onset of magnetic ordering for ferromagnetic, ferrimagnetic, and antiferromagnetic materials occurs below a material-specific critical temperature. This critical temperature is called the Curie temperature (T_c) for ferromagnetic and ferrimagnetic materials. In antiferromagnetic materials, this critical temperature is known as the Neel temperature (T_N).

Paramagnetic materials, which have randomly oriented (unaligned) spins (S), and diamagnetic materials, which do not have magnetic moments (spin $S = 0$), can be magnetized temporarily when they are exposed to a magnetic field. Paramagnetic materials such as aluminum are weakly attracted to both poles of a magnet. Diamagnetic materials are repelled by both poles of a magnet. Helium, bismuth, and water are diamagnetic.

There exists a large array of well-defined magnetic materials available to designers for most applications. These are two major classes of ferromagnetic and ferrimagnetic materials known as magnetically hard and magnetically soft materials. Magnetically soft materials can be easily magnetized and demagnetized while magnetically hard materials are generally permanent magnets and show a high resistance to demagnetization. The following are the most important characteristics of magnetically soft materials:

- low hysteresis loss (low resistance to demagnetization),
- low eddy current loss from electric currents induced by flux changes,
- high magnetic permeability and sometimes constant permeability at low field strengths,
- high magnetic saturation induction, and

- minimum or definite change in permeability with temperature.

Cost, availability, and ease of processing are other factors that influence choice of material. Magnetically soft materials made in large quantities include high-purity iron, low-carbon steels, silicon steels, iron-nickel alloys, iron-cobalt alloys, and ferrites. Control of impurities, alloy additions, grain size, grain orientation, coating, and processing variables are critical to meeting specifications. Special properties of ceramics and amorphous materials, as well as thin-film deposits, are important considerations for many applications. Not all desirable magnetic characteristics are found in a single material, and trade-offs have to be made for particular applications. As operating conditions, such as rotational speed, corrosion, temperature, and weight limitations, become more extreme, mechanical considerations of selected materials, such as strength/weight, creep at elevated temperature, and ability to be fabricated are increasingly important and the subject of new R&D. Major applications of magnetically soft materials include not only rotating equipment and transformers, but also specialty applications of communications and computing, such as filters, loading coils, magnetic amplifiers, and switch and storage devices. Ultrasonic and shielding are of great interest.

Permanent magnets have traditionally included a variety of metals, intermetallics, and ceramics having a high magnetic induction. Chief magnetic characteristics are the following:

- high induction,
- high resistance to demagnification,
- maximum energy content, and
- permeability approaching 1.0.

There are literally scores of permanent magnet materials superior to the magnet steel commercially available and used extensively even today. They consist primarily of ferrites and alloys of iron, cobalt, and/or nickel, plus a variety of other metals such as copper, tungsten, molybdenum, platinum, aluminum, titanium, vanadium, and rare earths. Over 95 percent of permanent magnets other than magnet steel currently produced are variations of the following families: Alnico, strontium, barium ferrite, neodymium-iron-boron, and samarium cobalt.

Semihard magnetic materials (square hysteresis loops and medium coercive forces) were developed for memory and reed switch applications based on the 90 Co-10 Fe binary and could contain platinum, gold, beryllium, titanium, molybdenum, or gold.

Permanent magnets are used in dynamic applications (magnetos in engines, small dc motors, and torque drives), as well as static applications (radio speakers, meters, telephones, temperature controls, games, toys, etc.); magnetrons; and inertial-guidance systems for space requiring long-term stability and resistance to changes in magnetization with time, temperature, shock, noise, vibration, and their environmental effects. Development of materials which minimize these reversible and irreversible conditions is the subject of continuing R&D. With the advent of thin-film technology, magnetic material deposited on tape and disks has advanced the safe operating area (SOA) of computers recording and communication. To a large extent, storage of data technology and high-definition television using electro-optic materials and lasers has overtaken the capabilities of magnetic material media, although considerable research is still being done in that field. Electro-optic materials are covered in Section 11.3. The development of smart materials and structures (covered in Section 14.6) has enhanced the need for improved magnetostrictive materials as actuators, and work is continuing in this area.

In other applications raw materials are generally reduced to fine particulates before manufacturing; any development in this area is important to many materials, for example, in the preparation of magnetic particles contained in paint or coatings with high relative permeability in the frequency range of electromagnetic to be absorbed.

In many cases, the mission requirements of individual weapons systems dictate the specific capabilities of magnetic materials and thin-film coatings in components. Advances in commercial applications, however, have a great impact on the military, both for capabilities and cost reduction.

B. NEW TRENDS IN MAGNETIC MATERIALS

A combination of advances in theory and experimental techniques of processing materials has led to the development of new and exotic magnetic materials. Some of these materials are captured in the data sheets. Deeper understanding of the structure and behavior of magnetic materials on the level of quantum mechanics, coupled with techniques for dealing with and producing nanostructures, self-assembly materials, thin films, and other two-dimensional (2–D) structures, has produced magnetic materials, some of which are already used in industry. Other exotic magnetic materials are still in the research phase. For example, the quantum Hall (QH) effect is important for basic research in the laboratory (e.g., for the measurement of the basic unit of resistance), but as yet, important military or commercial applications have not been realized. On the other hand, the giant magnetoresistive (GMR) effect, frozen ferrofluids, and other magnetic composites are already finding applications in industry.

LIST OF TECHNOLOGY DATA SHEETS
14.7. MAGNETIC MATERIALS

DATA SHEET 14.7. ULTRAHIGH-PERFORMANCE SOFT MAGNETIC MATERIALS FOR HIGH-TEMPERATURE TURBINE APPLICATIONS

Developing Critical Technology Parameter	Soft magnetic material (alloy, composite, matrix, ceramic, etc.) capable of sustained high [550 mPa (80 ksi)] mechanical, magnetic, and electrical performance at temperatures as high as 550 °C, while experiencing less than 1 percent creep over 5,000 hours and minimizing electrical losses
Critical Materials	Cobalt, rare earth, and ceramic coatings.
Unique Test, Production, Inspection Equipment	Dynamic creep testing, core-loss testing at elevated temperature. Laminate bonding equipment.
Unique Software	None identified.
Major Commercial Applications	Integral starter generators (ISGs), integral power units (IPUs), magnetic bearings, and alternative fuel vehicles.
Affordability	Not determined.

DATA SHEET 14.7. HIGH-SATURATION, HIGH-STRENGTH, SOFT ALLOYS FOR HIGH-TEMPERATURE USE

Developing Critical Technology Parameter	Sheets with a saturation magnetization up to 24 kG, low coercivity, high yield strength, low creep, and high resistivity.
Critical Materials	Iron and cobalt.
Unique Test, Production, Inspection Equipment	High-dielectric coating and equipment for heat treat annealing for peak magnetic characteristics.
Unique Software	None identified.
Major Commercial Applications	Starter/generators and IPUs for commercial aircraft. Automotive generators and actuators. More Electric Aircraft (MEA) IPU. Laminates for starter/generator and IPUs for MEA.
Affordability	Not an issue.

DATA SHEET 14.7. HIGH-TEMPERATURE PERMANENT MAGNETS

Developing Critical Technology Parameter	Bulk hard magnets capable of operation at 450 °C with coercivities exceeding 15 kOe at that temperature. Energy products stable as temperature increases. Magnetics for magnetic bearings and actuators.
Critical Materials	Samarium oxide, cobalt, and other minor constituents.
Unique Test, Production, Inspection Equipment	Samarium cobalt magnets must be sintered and heat treated; it can take up to 3 days to perform this process.
Unique Software	None identified.
Major Commercial Applications	Magnetic bearings and traveling-wave tubes.
Affordability	Not an issue.

DATA SHEET 14.7. HIGH-PERMEABILITY ALLOYS

Developing Critical Technology Parameter	Sheets with initial relative permeability (for fully annealed materials) of 120,000 or more and a thickness of 0.05 mm or less, typically but not limited to Ni-rich Fe-Ni with Mo concentrations of 4–6 percent.
Critical Materials	80 nickel family (e.g., Molypermalloy), 50 nickel alloys (e.g., Deltamax), and most permeable alloys.
Unique Test, Production, Inspection Equipment	High-frequency induction furnace.
Unique Software	None identified.
Major Commercial Applications	Fully commercial.
Affordability	Not an issue.

BACKGROUND

Good magnetic shielding, necessary for proper functioning of electronic equipment, relies upon a material with a high permeability-to-weight ratio.

DATA SHEET 14.7. MAGNETOSTRICTIVE ALLOYS

Developing Critical Technology Parameter	With saturation magnetostriction >500 ppm or magnetomechanical coupling factor (k) >0.8, primarily but not limited to rare earth alloys.
Critical Materials	Terbium, dysprosymium, $Tb_xDy_{1-x}Fe_2$ (TERFENOL), and METGLAS (Iron-based).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Noise and vibration control, materials testing, sound distribution, and acoustics.
Affordability	Not an issue.

BACKGROUND

These materials (particularly TERFENOL) could be used to eliminate noise in aircraft cabins and vibrations that upset instruments and machinery.

DATA SHEET 14.7. MAGNETIC AMORPHOUS ALLOYS

Developing Critical Technology Parameter	Strips with a composition of at least 75 percent by weight Fe, Co, or Ni; a saturation magnetic induction (Bs) of 16 kG or more; a strip thickness of 0.02 mm or less; or an electrical resistivity of 0.0002 ohm-cm or more.
Critical Materials	Cobalt, nickel.
Unique Test, Production, Inspection Equipment	Equipment for rapid solidification, 10^5 °C/sec.
Unique Software	None identified.
Major Commercial Applications	Magnetic switches, inductors for linear accelerators, high-voltage pulse transformer (HVPT), and pulse power transformer (PPT).
Affordability	Not determined.

BACKGROUND

Large-scale cores made from strips of amorphous and nanocrystalline alloys have the potential to be developed into high-average-power pulsed accelerators with the applications listed above. Amorphous and nanocrystalline alloys also have the possibility of almost completely eliminating hysteresis loss.

DATA SHEET 14.7. MAGNETIC NANOCRYSTALLINE ALLOYS

Developing Critical Technology Parameter	Strips with a composition of at least 75 percent by weight Fe, Co, or Ni; a grain size <50 nm; a saturation magnetic induction (Bs) of 16 kG or more; a strip thickness of 0.02 mm or less; or an electrical resistivity of 0.0002 ohm-cm or more.
Critical Materials	FeSiB- and FeCuNbSiB-based alloys.
Unique Test, Production, Inspection Equipment	High-dielectric coating and equipment for heat-treat annealing for peak magnetic characteristics.
Unique Software	None identified.
Major Commercial Applications	Power and high-frequency transformers and other electronics.
Affordability	Not an issue.

BACKGROUND

Large-scale cores made from strips of amorphous and nanocrystalline alloys have the potential to be developed into high-average-power pulsed accelerators with the applications listed above. Amorphous and nanocrystalline alloys also have the possibility of almost completely eliminating hysteresis loss.

DATA SHEET 14.7. FINE PARTICULATE MAGNETIC MATERIALS FOR PAINT OR COATINGS

Developing Critical Technology Parameter	Raw materials are generally reduced to fine particulates before manufacturing, and any development in this area is important to all materials. Magnetic particles contained in paint or coatings with the following property: relative permeability >10 in the frequency range of electromagnetic energy to be absorbed.
Critical Materials	Magnetic material to be processed.
Unique Test, Production, Inspection Equipment	Vacuum induction heater, rolling mill, and large/small jaw crushers.
Unique Software	None identified.
Major Commercial Applications	Fabrication of required magnetic materials.
Affordability	Not an issue.

DATA SHEET 14.7. ULTRAHIGH-DENSITY MAGNETIC RECORDING MATERIALS

Developing Critical Technology Parameter	Increase the data density per square inch beyond 40–100 gigabits attainable with cobalt/platinum/chromium alloys.
Critical Materials	Hard magnetic materials such as alloys of iron/platinum or cobalt/samarium.
Unique Test, Production, Inspection Equipment	Thermally assisted writing, magnetic alignment of grains, and thin-film deposition including pulsed laser.
Unique Software	Error-correction software.
Major Commercial Applications	Flexible magnetic media heads and hard disk drives for information storage systems.
Affordability	Not determined.

BACKGROUND

The need for magnetic materials onto which disk drives can write and read smaller and smaller bits presents a continuing opportunity and need. Hard disk drive industry is the dominant one for data storage. The hard disk drive is dependent on the hard disk drive media and overcoming the limitations of super paramagnetism. A 40 Gbit/in.^{2} area density media increase means that one double-sided 3.5-in. hard disk media can store about 50,000 books. Goals are to increase capability well beyond this limitation.

DATA SHEET 14.7. MAGNETIC NANOPARTICLE COMPOSITES

Developing Critical Technology Parameter	A nanocomposite of magnetic nanoparticles dispersed in a solid matrix in such a way that the nanoparticles are free to rotate inside a small cavity but not free to leave the cavity. The particles can line up with a magnetic field. At present, the matrix consists of frozen methanol (T<<200K). A room-temperature polymer to replace the methanol is being investigated. These frozen ferrofluids reduce power consumption and therefore have higher efficiency. They may replace iron cores in transformers, which generate heat and use power inefficiently. The particles in a nanocavity are formed from a ferrofluid by subjecting it to lower temperatures and oscillating magnetic fields. This process forces the particles to flip and produce a cavity for their free rotation. The resulting nanocavity allows the particles to rotate but not to wander.
Critical Materials	Iron, cobalt in nanoparticle structure.
Unique Test, Production, Inspection Equipment	The process of freezing the ferrofluid and forming the nanocavity.
Unique Software	None identified.
Major Commercial Applications	Nanoscale magnetic compass. Gyros. Magnetic switches. High efficiency transformers. Better permanent magnets. Better GMR materials.
Affordability	Not determined.

BACKGROUND

Transformers are used by the military in many applications. This technology will provide efficient transformers. On a smaller scale, electronic applications of GMR materials and magnetic switches are anticipated.

DATA SHEET 14.7. HIGH-PERFORMANCE MAGNETO-OPTIC SUPERLATTICES

Developing Critical Technology Parameter	Current magneto-optic recording discs use a layer of a rare-earth transistor alloy as the active medium. Advantages are low noise and excellent hysteresis properties. A major disadvantage is the low resistance to oxidation with subsequent deterioration of useful properties. This has to be defeated by properly designed coatings and dopants by fabricators. Tb/Bi/FeCo and Tb/Pb/Fe/Co superlattices have been predicted by electronic structure calculations to have superior properties using as the figure of merit the reflectivity times the Kerr rotation. Successful experimental results have been reported with three repeating layers of $Fe_{(1-x)}$ of 5A, a Tb layer of 5A, and a PbO_2 Bi layer with 1–3A thickness. The superlattices are compensation point materials with square hysteresis loops and good coercivities. These materials show magneto-optic Kerr rotations, ellipticities, and figure of merit far exceeding conventional systems, especially at blue wavelengths, expected to be important for future applications. Some of the materials have been measured to have a figure of merit 70-percent higher than TbFeCo over wavelengths of 400 to 800 nm.
Critical Materials	Tb/Bi/FeCo and Tb/Pb/FeCo superlattices.
Unique Test, Production, Inspection Equipment	Preparation of thin films.
Unique Software	None identified.
Major Commercial Applications	Magnetic recording. Disk storage. Computers.
Affordability	Not determined.

BACKGROUND

This technology will provide more efficient and higher density storage and computer input/output readout.

DATA SHEET 14.7. BONDED NEODYMIUM PERMANENT MAGNETS

Developing Critical Technology Parameter	Bonded neodymium magnets can be manufactured to have good mechanical and strength characteristics, as well as good magnetic properties, in small packages. Because of this, their use in consumer and military electronics is growing. As new computer-related technologies, disk drives, displays etc., emerge, bonded neodymium magnets are expected to take over the market.
Critical Materials	Rare-earth compound $Nd_2Fe_{14}B$—over 80 percent of the world's supply of this material is located in China. Epoxy resin.
Unique Test, Production, Inspection Equipment	Equipment for rapid solidification needed to produce isotropic $Nd_2Fe_{14}B$ powder, where a fine jet of molten material must be cooled on the order of 10^5 K/sec. No unique equipment needed once powder is available.
Unique Software	None identified.
Major Commercial Applications	High performance stepper, dc, servo, and linear motors; actuators; loudspeakers; headphones; switches; relays; magnetic imaging for medical and geophysical applications; holding systems; magnetic bearings; magnetic couplings; hard disk drives; and airbag crash sensors.
Affordability	Not an issue.

BACKGROUND

Bonded neodymium-iron-boron magnets have extraordinary strength and are relatively inexpensive. Because of their strength, the magnets can meet the same mechanical requirements as another type of magnet, but in a far smaller package. As a result, bonded neodymium magnets are gaining use in an extremely large range of commercial goods, as listed above.

DATA SHEET 14.7. MAGNETIC MATERIALS FOR ENHANCED MAGNETOCALORIC EFFECT

Developing Critical Technology Parameter	Magnetic cooling has been practiced for over 65 years, but has been restricted to the milli-Kelvin range. Recently, the process of magnetic refrigeration has been extended with nanocomposites to higher temperatures. On a volumetric basis magnetic refrigeration may provide an entropy change two orders of magnitude higher than a gas in a reversible order-disorder process. Efficiencies approaching the Carnot cycle are expected. Also, a more environmentally safe process is envisioned. Two types of materials are under consideration: paramagnetic materials for low temperatures (T <20 K) and ferromagnetic materials for higher temperatures. Magnetic nano-composites may bridge both regimes. The commonly used material for magnetic refrigeration has been $Gd_3Ga_5O_2$ (GGG), with an effective temperature upper limit of 15 K. Iron-substituted gadolinium garnets $Gd_3Ga_{3.2}Fe_{1.75}O_{12}$ (GGIG) materials have the potential to increase working temperature and/or to reduce the field requirements for cryogenic magnetic refrigeration. Oriented single crystal $Dy_3Al_5O_{12}$ materials have superior properties but are still limited to <20 K. On the other hand, other materials like $Gd_3Ga_{(5-x)}Fe_xO_2$ show promise for cyclic cooling well in excess of 20 K. Magnetic simulation calculations have been found useful in the study of the cooling effect in various materials over the Kelvin range. When a magnetic field is applied, the GGG structure shows complete linear behavior of the magnetization, while the GGFO structure containing Fe shows nonlinear behavior.
Critical Materials	$Gd_3Ga_{(5-x)}Fe_xO_2$, $Dy_3Al_5O_{12}$, $Gd_3Ga_aO_2$, $Gd_3Ga_5O_{12}$, and $Gd_3Ga_{3.2}Fe_{1.75}O_{12}$
Unique Test, Production, Inspection Equipment	Low-temperature measurements.
Unique Software	None identified.
Major Commercial Applications	Refrigeration for electronic components.
Affordability	Not determined.

BACKGROUND

This new material will increase the magnetic refrigeration capability by reaching higher working temperatures.

DATA SHEET 14.7. GMR SPIN VALVES

Developing Critical Technology Parameter	GMR spin valves are useful for controlling electrical transport (current) with magnetic fields. To this application a key goal is magnetic materials that are nonvolatile, radiation hard, low power, high density, and low cost. These materials can be used to fabricate (1) advanced magnetic memories that are high speed, low power, and low cost and (2) very small magnetic sensors with picotesla sensitivity at low frequency and low cost [two orders of magnitude less power and two to three orders of magnitude less expensive than superconductive quantum interference device (SQUID) or spin-resonance sensors]. Specular electron scattering (SES) at the top surface of bottom spin valve contributes to the GMR effect. GMR of spin valves can also be increased with the use of oxygen. Surprisingly, the best GMR materials are not produced in the best vacuums. Oxygen increases the GMR because it decreases the ferromagnetic coupling between the magnetic layers and decreases the sheet resistance between the magnetic layers of the spin valve. Single spin valves (on Cu layer) could also exhibit GMR effects as large as those found in superlattices.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Electronics industry and current control. Nondestructive evaluation. Magnetic anomaly detection, Mars geomagnetic probe, and land-mine detection. Magnetic spectroscopy.
Affordability	Not determined.

DATA SHEET 14.7. SPRING MAGNETIC FILM

Developing Critical Technology Parameter	Exchange spring magnets consist of soft and hard magnetic phases on the nano-scale, coupled at the interfaces. The soft phase boosts the magnetization of the composite, thereby enhancing the energy product. Future applications will be based on nanodispersive composites obtained through bulk processing or by mechanical alloying.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetron sputtering.
Unique Software	None identified.
Major Commercial Applications	Information storage, recording.
Affordability	Not determined.

BACKGROUND

This material can be used in the manufacturing of artificial magnetic structures and for information storage.

DATA SHEET 14.7. SELF-ASSEMBLING MAGNETIC MATERIALS

Developing Critical Technology Parameter	Magnetic particles in the nano regime (4 nm) have been observed to automatically arrange themselves into well-ordered arrays. Each particle is separated from the others by a predetermined distance. Controlled reactions can be used to provide the specific particle size and the required separation between the particles. With self-assembly, nature does the work. In the reaction, the Pt and Fe separate from the organic parts and form spherical nanoparticles. These nanoparticles are separated from each other by a layer of surfactant barrier, which upon heating turns into a hard shell. At the same time the heating/annealing transforms the particles into a useful form (face-centered tetragonal) that retains its magnetization. The particles are about half the size of currently used grains and 10 times more uniform in size. This material could provide new and massive data storage capability. It is estimated that two orders of magnitude increase in data storage density could be achieved.
Critical Materials	Iron carbonyl and platinum acetylacetonate.
Unique Test, Production, Inspection Equipment	Preparation of the magnetic nanoparticles.
Unique Software	None identified.
Major Commercial Applications	Computer. Increased storage capability.
Affordability	Not determined.

BACKGROUND

New storage capability will provide unprecedented data handling and computational power for many applications.

DATA SHEET 14.7. QH–EFFECT MATERIALS

Developing Critical Technology Parameter	The QH effect exhibits a sequence of energy gaps which in the limit of low temperatures produces electron transport without dissipation, not unlike superconductive materials. It behaves in other unusual ways. For example, it provides, in a very reproducible way, a measure of the quantum-mechanical limit of quantum resistance. The Hall conductivity in the "superconductive state" is given by $\sigma_{XY} = \omega^2/h$ with great precision and independent of microscopic details. The integral QH effect (v = 1,2 ...) is due to an excitation gap when the Landau levels are completely filled. The fractional QH effect occurs when one of the levels is partially filled. At v = 1, the Quantum Mechanical system exhibits a peculiar type of spontaneous magnetic ordering. Unlike iron, this ferromagnet is 100-percent polarized because its kinetic energy has been frozen into discrete Landau energy levels. Ordinary magnetic materials are manipulated by subjecting spins to magnetic forces. In the QH effect materials, one can manipulate spins by applying electric potentials. This is extremely useful in practice. The QH effect at present is used as a laboratory tool to study properties of materials. Its application to practical devices is still in its infancy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Micro techniques. Nanostructures fabrication. Thin-film techniques.
Unique Software	None identified.
Major Commercial Applications	Computers in space. Quantum computers.
Affordability	Not determined.