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Basic research funding in universities and industry, first undertaken by the U.S. Government through the Office of Naval Research beginning in 1946, is shown to have provided a very large return on investment through positive influences on knowledge developed and applied, people trained and their career contributions, new companies and industries formed, and major new contributions to national defense posture.

RETURN ON INVESTMENT IN BASIC RESEARCH — EXPLORING A METHODOLOGY

Report to

Office of Naval Research
Department of the Navy

by

Bruce S. Old Associates, Inc.

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PREFACE

On December 28, 1978, Bruce S. Old Associates, Inc., submitted an unsolicited proposal entitled, "Basic Research Returns" to the Office of Naval Research (ONR). This resulted in the negotiation of Contract N00014-79-C-0192, dated June 15, 1979. Subsequently, the Contract completion date was extended because of surgery and other delaying reasons typical of projects of this type, with no change in total funding.

The Contract required one deliverable item: "a final report will be prepared, submitted and distributed by sixty days after completion of the work."

An oral report was also delivered at ONR after submission of the final report.

This report constitutes the written deliverable under the Contract. It describes the work in sufficient detail to permit the results to be evaluated and to decide whether additional work along lines pioneered in this small, exploratory Contract should be funded.

Work is continuing on a popular-styled report, which is *not* a deliverable under the Contract, but which could represent an important contribution. The popular summary report is aimed at attracting the attention of lay readers, particularly those concerned with or involved in the legislative process of budget review and *appropriations for R&D by the Federal Government.* Success in publication of such a summary depends upon editorial approval by the publications to which submissions are made. One important journal has already agreed to publish an article based on this study.

A

ACKNOWLEDGEMENTS

During this assignment about 100 scientists, engineers and administrators who participated in the projects under study were interviewed one or more times, or contacted by letter. (See list in Appendix A.) They generously provided much unique and valuable information which in most cases was verified through evidence from multiple sources.

Particular indebtedness is hereby expressed for careful reviews of draft material to Jay Forrester, Robert Everett, Norman Taylor and Norman Zimbel of Project Whirlwind; to Jerrold Zacharias, Malcolm Hubbard, Peter Demos, Fred Eppling and Jerome Friedman of the Laboratory for Nuclear Science and Engineering; to Morris Cohen and Marguerite Meyer for the detailed information they helped to gather on the ONR-funded research of Cohen and students; and to Albert Hill for his constructive overall review.

Finally, the interest and patience of Robert Lundegard of the Office of Naval Research, and his staff and contracting officers are greatly appreciated for making possible the completion of a research objective harbored for more than 10 years by the contractor.

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SUMMARY

Under the democratic system, the budget of a government is an expression of the objectives, aspirations, and social values of the people at a given point in time. Every year at budget time, those responsible for appropriations within the Federal Government question sharply the funding of basic research in the physical and social sciences by various agencies. They do so not because this portion of the budget is large, but rather because it is not possible to predict what new knowledge the basic research programs will create, or how soon, or where, the findings might ultimately be utilized. On the other hand, there is general agreement that creating new knowledge is a laudable activity for mankind.

How then do we exercise proper judgment regarding investment in basic research in an economy where competition for appropriations is always fierce and the life of the government in power is brief compared to any projected payback? One way might be to try to enhance our capability for making judgments by careful study of past experiences. This report attempts to show the returns on investment from three distinctly different basic research activities funded at the Massachusetts Institute of Technology (M.I.T.) by the Office of Naval Research (ONR), the first Federal agency to contract broadly for basic research beginning in 1946. It was hypothesized that sufficient time has now elapsed for the new knowledge created to have had some impact upon our society. The method used in this study is exploratory — it is anecdotal, not statistical.

The three projects arbitrarily selected for study from among the 30 ONR projects then existing at M.I.T. were:

- Project Whirlwind — an engineering basic research project aimed initially at developing a high-speed computer for use in an aircraft trainer-simulator.
- Laboratory for Nuclear Science and Engineering — a large, multi-disciplinary laboratory aimed at expanding knowledge in nuclear science and engineering.
- Professor Morris Cohen and students — a single professor who from 1947 to date has had 40 consecutive graduate thesis students funded by ONR.

Information on the three projects was obtained through many interviews of key participants and a review of reports and literature.

An attempt was made to discover for each project what new knowledge has been created, where it has been utilized to the benefit of the nation, what people were trained, and what contributions they have made to society. Some of the more important findings follow.

No study of the returns on investment in basic research will uncover more than a *small fraction* of the total knowledge created and later applied to the benefit of society. The flow of knowledge through publication, the migration of people, and teaching is boundless. The application of knowledge is likewise unrestricted, as one use begets new and improved related uses in a branching chain reaction. Therefore, the information reported here on knowledge created and utilized and people trained and their contributions is only the "tip" of the iceberg. Even so, we find the small sample of basic research events studied has already given birth to an indescribably large "tip."

Project Whirlwind, directed by Jay W. Forrester (age 26) and Robert R. Everett (age 23), turned out to be a most successful basic engineering research project. In 1949, the objective was changed from development of a high-speed analog computer for an aircraft trainer-simulator to a high-speed digital general purpose computer. By the middle of 1951, the young, highly talented core team of about eight engineers had made the several key inventions necessary to place in operation the first real-time, synchronous, parallel digital computer. Among these inventions was the magnetic core memory by Forrester which replaced the more expensive and less reliable electrostatic tubes, and soon revolutionized the entire computer industry. Just at that time the newly developed Soviet threat of long-range bombers equipped with nuclear weapons forced immediate consideration of a new U.S. air defense system. At the instigation of Professor George E. Valley of the Laboratory for Nuclear Science and Engineering and a member of the Science Advisory Board of the Air Force, the Board established a committee to study the problem. A novel defense system concept was evolved that called for a high-speed computer to analyze vast amounts of input radar data, and Whirlwind was chosen. Project Charles was then formed to study the organization of an appropriate air defense laboratory. It recommended the establishment of the M.I.T. Lincoln Laboratory. After its formation July 26, 1951, Whirlwind was transferred to Lincoln and the Air Force took over funding from ONR. (This was fortuitous as ONR funding was about to be curtailed.) IBM was brought in, first as a subcontractor to M.I.T. and later as a prime contractor, to complete the design and initiate manufacture of components. By December 1953, Lincoln had in operation the Cape Cod system using Whirlwind to track and intercept "enemy" aircraft. This was the prototype for the Semi-Automatic Ground Environment (SAGE) air defense system. The first deployment of the SAGE system occurred July 1, 1959, at McGuire Air Force Base in New Jersey for the protection of the New York-Philadelphia area.

Since it was deemed inappropriate for a university to take responsibility for the continuing task of systems engineering for the nationwide air defense system, M.I.T., at the request of the Air Force, formed the independent, non-profit, public interest MITRE Corporation in July 1958, to carry out this requirement. SAGE played a key role in blunting the Soviet air threat.

But Whirlwind had a far broader impact on our society than air defense. Its ramifications far exceed the fondest dreams of its protagonists. (See Figure 2.)

First, Whirlwind stimulated the rapid growth of the computer industry. M.I.T. licensed all the major computer companies to utilize magnetic core memories, as well as many companies to manufacture cores. Royalties to M.I.T. from non-government sales amounted to about $25 million, as the magnetic core memory dominated computer design from about 1958 to 1973.

Second, Whirlwind personnel formed a number of new companies. While this report is not meant to develop quantitative returns on investment in basic research, it is difficult to refrain from pointing out that the government invested about $17.4 million in Whirlwind and has received back in corporate income taxes from just one of the computer companies founded on Whirlwind technology, Digital Equipment Corporation, over $600 million. If one were to estimate the other corporate income taxes and employee income taxes attributable to Whirlwind technology, the return to the government would be many billions of dollars!

Third, Whirlwind first demonstrated numerically controlled tools, computer-aided design and manufacturing and computer time sharing (dedicated purpose). These are all big businesses today.

Fourth, Whirlwind use in research work by faculty and students provided the genesis for the M.I.T. Computation Center which was formed in 1955. In the words of the Dean of Engineering, "The digital computer promises not only to change the content of what we teach to students, but also to revolutionize the methodology whereby we do it."

And, finally, the people trained during Project Whirlwind have migrated to important positions in teaching, in industry, and in government, and their efforts are now building second and third generation contributors to our society in increasing numbers.

A truly amazing series of paybacks.

The formation of the Laboratory for Nuclear Science and Engineering (LNS&E) was announced December 19, 1945, by President Karl T. Compton of M.I.T. in anticipation of ONR funding in the summer of 1946. It was to be a multidisciplinary laboratory involving the Departments of Physics, Chemistry, Metallurgy, Biology, Chemical Engineering, Electrical Engineering and Mechanical Engineering. Professor Jerrold R. Zacharias (age 40) was appointed Director, and helped recruit a number of promising young scientists, between the ages of about 26 and 41 to assume leadership roles.

This talented initial group of about 30 staff scientists attracted to M.I.T. a large number of excellent staff and graduate students, as well as many visiting scientists. Over the 1946-1958 period, during which ONR had the prime contract for LNS&E, a total of about 400 staff and students participated at an overall cost of about $14 million.

The outstanding work of this group in generating and publishing new knowledge has been widely recognized by society. (See Figure 3.) Three have become Nobel Laureates; 21 were elected to the National Academy of Sciences, and nine elected to the National Academy of Engineering. About 113 have become professors in 56 universities and they are creating ever-expanding generations of new students. Finally, approximately 105 have become officials in 74 corporations in many segments of industry.

The new knowledge created within LNS&E continues to be applied in a wide variety of ways including nuclear medicine, nuclear reactor design, pattern recognition devices, metabolism studies, tumor location, tomography, photometric and thermometric titration, chemical analyses at submicrogram levels, solvent extraction, scintillation materials formulation, oil and gas reservoir discovery techniques, etc. What additional new applications will evolve is totally unpredictable.

There have also been substantial direct returns to the Defense Department. In April 1948 Professor Clark Goodman participated importantly in the underseas warfare conference which influenced the decision to pursue aggressively the nuclear propelled submarine project led by Captain H. G. Rickover, and then taught many naval officers in the first U.S. course on nuclear power. As a result of the dedication and talent of many individuals within LNS&E, several key air defense and anti-submarine defense projects were organized and successfully implemented. Project Charles, which was established in 1951 due to the efforts of Professor George E. Valley, led in turn (as we have noted under Whirlwind) to the formation of the M.I.T. Lincoln Laboratory and then to MITRE Corporation which installed the SAGE continental air defense system. Project Hartwell, which studied the security of overseas transportation against the USSR submarine threat, was organized in 1950 by Professor Jerrold R. Zacharias. It led to the development of the Lofar anti-submarine defense system, the anti-submarine helicopter, the high-speed Mariner class freighter and other important defense concepts. Project Lamplight was organized in 1954 by President James R. Killian and Professor Zacharias to review the current status of submarine detection. Four participants in various aspects of these studies went on to become science advisors to presidents of the United States — James R. Killian, Jerome B. Wiesner, Edward E. David, Jr., and H. Guyford Stever. One former student, H. Mark, became Secretary of the Air Force, and Valley served as Chief Scientist of the Air Force. And numerous individuals continue to serve in important advisory positions to the government.

Individuals from LNS&E have also been responsible for the establishment of several corporations and these continue to represent a return to the Treasury through taxes. In addition, the many defense systems suggestions originating in LNS&E special studies have had an impact on the defense industry.

The true returns from the LNS&E investment are just in the beginning stages.

Professor Morris Cohen and his continuing succession of 40 graduate students, funded by ONR from 1947 to date, at a total cost of $1,625,610, have had a substantial impact on the materials posture of the United States through the new knowledge created and the people trained.

The early period of research resulted in a better understanding of the role of martensitic transformation in the hardening of steel. This led to the development of ultra-high-strength steels for aircraft landing gear. Research on metal structure/property relations resulted in the toughening of ship steels through grain refinement. The research also led to important findings in steel strengthening through drastic quenching, design of engineering structures, and a new approach to alloy design utilizing finely dispersed second-phase precipitates.

Further work on the structure/property/processing/overall performance relation concept being applied by Cohen to metals research led him to extend this concept to include ceramics, polymers and electronic materials. This had a profound impact as Departments of Metallurgy switched to becoming Departments of Materials Science worldwide. Also, new professional groups were formed, such as the Federation of Materials Societies and the Materials Research Society.

The importance of materials to the nation became emphasized through the establishment by Congress of a National Commission on Materials Policy in 1970, and a 1973 National Academy of Sciences study, "Materials and Man's Needs," headed by Professor Cohen. This report introduced the concept of the total materials cycle and dealt with materials availability, materials in national security, materials in the economy, and materials in world trade and in international relations. Now an Inter-Agency Committee on Materials has been formed within the Federal Government and Congress is considering legislation related to national materials policy.

As a result of his achievements, Professor Cohen received, in 1977, the first National Medal of Science for metallurgy. And the 98 professional papers resulting from the ONR program at M.I.T. have won 15 other medals and awards from seven nations, and resulted in 15 honorary lectures.

Once again, this is just the "tip" of the iceberg. To illustrate, a survey of the work of only 19 of the 36 Cohen ONR students who have graduated indicates they credit much of their success to M.I.T. training. They have already published 891 professional papers on a wide variety of materials subjects, and have contributed substantially in many areas such as superalloys, integrated circuit materials, high temperature ceramics, fracture mechanics, vacuum induction processing, theory of phase transformations, etc. And now the students have their own set of new students in academia and industry.

The chain reaction continues.

Among the lessons which are apparent from the three basic research projects studied are the following:

- Government officials can indeed select promising young scientists, engineers and research programs which, with proper government investment, will produce advances in knowledge and offer substantial, although unpredictable, benefits to the nation.

- The original postulate behind the formation of ONR was that funding of basic research in universities by the Department of Defense, and the consequent establishment of communications with top scientists and engineers, would ultimately strengthen our national defense. This postulate has been verified overwhelmingly.

- The training of people is an inevitable "fallout" from basic research programs. These people migrate extensively throughout academia, industry and government. They not only make valuable application of their knowledge in predictable and in totally unforeseen fields, but also train others in ever expanding numbers as in a giant chain reaction.

- Sometimes it is possible to trace directly vast economic returns from government investment in basic research, as shown in this report. More often, one is faced with the difficult task of estimating the worth to society of a professionally trained person and his career contributions. It became abundantly clear from interviews made during this study that few scientists and engineers had studied the significance of their work in affecting socioeconomic growth. There is obvious room for research here.

- The payback from government investment[1] in basic research usually begins long after the administration which had the foresight to make the original investment has vacated office. But, the payback is for the benefit of the citizens, not for reward to any single administration. We must have both citizens and elected officials who understand the long-range role of basic research in fostering social and economic growth and who will carefully consider this small, but exceedingly important portion of the Federal budget. A fertile area for further study to advance public understanding is the record of past returns on government investments in basic research.

If ONR, through its timely investments, had not brought together the brilliant teams of people in the projects described in this report, the flood of knowledge and practical accomplishments attained would very likely have been postponed for many years, or perhaps not have been attained at all.

1. For the past 35 years most Federal Government documents describing basic research budgets and programs, including messages to Congress, speak about the "support" of basic research.

The word "support" is a particularly poor choice as it connotes carrying, or promoting the interest of, or propping up such as to keep the sick from fainting. All of these meanings understandably frighten the Congressmen who appropriate the funds.

We hope this report helps to point out that the proper word is not "support" but *investment*. We *invest* in basic research because we expect returns in the future from the knowledge developed and the people trained. The vast returns demonstrated in this report from just a few examples should serve to notify our citizenry that some past Congresses and defense officials have indeed acted with great wisdom.

BACKGROUND

A. THE EVOLUTION OF THE OFFICE OF NAVAL RESEARCH

Establishment of the Office of Naval Research (ONR) in 1946 represented the first major breakthrough in the substantive funding of basic research by the Federal Government. All other Federal offices or agencies now funding basic research, including the National Science Foundation, followed along a trail already competently blazed by ONR.

To start anything new in Washington is difficult. To succeed in getting one part of the Department of Defense to be the first agency of the Federal Government to have the authority to invest large sums in basic research, while also utilizing novel and quite liberal contractual terms, required miraculous luck. It also required perseverance.

As with most good concepts, the ONR idea was based on simple observations. These derived largely from a very few young Naval Reserve officers[1] serving in a part of the Office of Secretary of Navy which gave them access, beginning in 1941, to essentially all of the vast World War II military R&D programs of the United States and allied nations.

By late 1942, three things had become apparent to them. First, the mountingly successful come-from-behind efforts of the Allied Forces seemed to be based on the introduction of new technological advances into warfare. Second, many of these technological advances were apparently originated by scientists and engineers ordinarily associated with basic research activities in universities or with basic and applied research in industrial laboratories.

Finally, the Navy Department, as organized in late 1942, had *no mechanism for liaison with such research experts*, except through the then existing Office of Scientific Research and Development (OSRD), Executive Office of the President. But, Dr. Vannevar Bush, Director, had already indicated that he planned to terminate OSRD at the end of World War II. How, then, could the Navy reorganize to maintain relationships after the War with the elite of the United States scientific and engineering community? Failing this, might not the Navy enter any future war with outdated weapons systems and operational capabilities?

Believing such a potential national disaster could not be risked, the aforementioned small group of Naval Reserve officers, which had begun plotting for change, invented the ONR concept in December 1942. What was the ONR concept? In retrospect, it may sound like routine wisdom. The logic went something like this:

- For the Navy to maintain proper liaison after the War with the nation's leading scientists and engineers, it must establish a special

1. The present author was one of those.

Office with its own budget and the authority to invest in and contract for basic and applied research. Creation of this Office would require an Act of Congress.

- Any such Office would have to be positioned within the Office of the Secretary of Navy rather than under the Chief of Naval Operations, because the latter would always be inclined to take too short-range a position regarding investment in R&D.

- While the Chief of Naval Research heading the proposed Office of Naval Research could be a Naval Officer, he would require two safety valves in order to maintain the objectivity and forward thrust of the Office. First, he must report to a civilian Assistant Secretary of Navy who would be a recognized civilian scientist or engineer capable of influencing proper R&D program formulation. And, second, a Naval Research Advisory Committee (NRAC) made up of nationally recognized leaders would have to be formed. This committee would advise the Secretary of Navy on research matters. Should ONR be confronted with top policy problems beyond its capabilities, NRAC would be expected to help settle these with the Secretary of the Navy.

The concept was fairly clear by late 1943, and the time for perseverance had arrived. The young Reserve officers stuck their necks out a mile and started selling the concept not only inside the Navy Department but also within the Executive Office of the President.

After three long years, success was finally attained with the passage of Public Law 580 by Congress on August 1, 1946. That story has been told elsewhere.[1,2,3]

The aspect of miraculous luck? Well, that had at least three facets. First, the Reserve officers were able to obtain early backing for the concept from such national science leaders as Dr. Jerome C. Hunsaker and Dr. V. Bush. Second, political leaders within the Navy Department, such as Assistant Secretary Struve Hensel, Vice Admiral H.G. Bowen, and Commodore Lewis L. Strauss, swung around to the concept and obtained the interest of powerful Congressman Fred Vinson, veteran Chairman of the Naval Affairs Committee, in sponsoring a bill to establish ONR. And, third, the end of the war found the Navy Department with excess funds, some $40 million of which Secretary James Forrestal was persuaded (somewhat reluctantly) to earmark for ONR.

B. RATIONALE FOR THIS PARTICULAR STUDY

An obvious question after the passage of over 35 years is whether all the effort involved in establishing ONR, and the many millions that the Navy Department

1. The Evolution of the Office of Naval Research, Bruce S. Old, *Physics Today*, Vol. 14, No. 8, August 1961.

2. *Men and Decisions*, Lewis L. Strauss, Doubleday & Company, Inc., 1962.

3 *Ships, Machinery and Mossbacks*, Vice Adm. Harold G. Bowen, Princeton University Press.

has since invested in basic and applied research, have resulted in a positive return to the United States.

Any attempt to try to answer that question broadly would, of course, entail a major, lengthy, and costly study.

Therefore, the unsolicited proposal which initiated this study suggested a much more modest approach aimed at evolving a method which, if promising, could be utilized and expanded into a more comprehensive study. The earliest basic research work funded by ONR began in 1946. It was hypothesized that sufficient time has elapsed so that any new knowledge gained might by now have had some impact on socioeconomic growth and on the national defense posture. Furthermore, people trained during this early work should also have been able to utilize such training in making their own contributions to our society and its growth. Finally, it was pointed out that the timing for initiating the study was urgent, since many of those who should be interviewed were post-retirement age and the ranks were thinning rapidly. (See Appendix B for list of deceased principals.)

STUDY OUTLINE

The proposed study was aimed at examining a method for determining the returns gained from a sample of early ONR investments in basic research. The Massachusetts Institute of Technology (M.I.T.) was chosen as the locale because, beginning in 1946, it was one of the first universities to contract with the Navy. The idea was to select about three types of ONR projects at M.I.T. and to try to uncover:

- What new knowledge and understanding were gained as a result of the basic research performed, and how the information has been utilized to the benefit of the nation.

- What people were trained during the work, and what contributions they have made to society, at least partly attributable to this training.

The study activities began with a visit to the Office of Sponsored Programs at M.I.T. to inspect their records of early projects first funded by ONR in the period of 1946-47. From among about 30 such projects identified and considered, three widely different types of M.I.T. projects were arbitrarily selected for study:

1. *Project Whirlwind* — This project began with the purpose of developing a new high-speed, computerized training system which would allow a pilot to obtain a feel for flying a particular airplane before it was ever constructed. The objectives changed during the project to the building of a general-purpose computer. Nevertheless, the drive for the creation of the new basic knowledge required to perform reliable, high-speed computation persisted throughout.

2. *The Laboratory for Nuclear Science and Engineering* — This was a large multidisciplinary laboratory aimed at expanding knowledge in many areas of nuclear science and engineering.

3. *Work of Professor Morris Cohen and Students* — Professor Cohen, a metallurgist, has had since 1947 a succession of 40 graduate students who performed thesis work under his guidance with ONR funding. A study of the influence of a single professor over a 35-year period thus became possible.

The method of developing information was largely dependent upon interviewing or corresponding with key professors, students, and administrators involved in the programs (see listing in Appendix A). Also numerous M.I.T. progress reports were read. Obviously, the sample was too small for a quantitative or statistical approach. Early on, it was decided rather to choose an anecdotal course, and enthusiastic ONR concurrence for this method was obtained.

PROJECT WHIRLWIND

A. INTRODUCTION

The genesis of Project Whirlwind was an idea for a universal flight trainer-aircraft simulator which was nurtured for some years by the internationally recognized engineer, Luis de Florez, who, during World War II, headed the Special Devices Division of the Bureau of Aeronautics[1] of the Navy Department. During 1943, Captain de Florez discussed his ideas for an advanced trainer-aircraft simulator with members of his own technical staff and scientists at the Bell Laboratories and the Massachusetts Institute of Technology (M.I.T.).

The idea intrigued some of the staff at M.I.T., and by April 1944, Professors John R. Markham, Joseph Bicknell and Otto C. Koppen had completed a brief study and report on the feasibility of using a flight trainer and calculating machine for determining flight characteristics. A copy was sent to de Florez by Professor Jerome C. Hunsaker, then Chairman of the National Advisory Committee for Aeronautics, with the comment that the proposed simulator offered a tool of very great research significance if the handling characteristics of an airplane could indeed be estimated prior to construction.

This task was recognized to be extremely complex. The trainer-simulator would have to be capable of solving and displaying on an instrument panel in real-time some 90 equations involving (1) basic equations of motion, (2) equations relating to wind, body and earth axes, (3) auxiliary equations of motion, (4) control surface hinge moment equations, (5) aerodynamic coefficient equations, (6) instrument equations, and (7) miscellaneous other equations. Such capability required developments going far beyond the state of the art.

The Navy responded by negotiating a contract with M.I.T. on December 14, 1944, for $75,000 (NOa(s)-5216) to make a feasibility study of an Airplane Stability and Control Analyzer (ASCA). Placed in charge of the project was Jay W. Forrester, then age 26, who had been an Assistant Director to Professor Gordon Brown, Director of the highly innovative Servomechanisms Laboratory. Forrester chose Robert R. Everett, 23, as his top assistant since they had already been working together on conceptualizing the problem in anticipation of receiving the contract. A few additional engineers from the Servomechanisms Laboratory were added to the project staff.

The rate of progress during the first five months was such that M.I.T. submitted, on May 22, 1945, a proposal for extension and modification of the contract to build an ASCA for approximately $875,000 to be spent over an 18-month period. The Navy authorized the extension under a Letter of Intent dated June 30, 1945 (Contract Noa(s)-7082).

1. The Special Devices Division was transferred to the Office of Research and Inventions (ORI) of the Office of the Secretary of the Navy upon its formation on May 19, 1945. ORI was then transferred to the Office of Naval Research which was formed by an Act of Congress, August 1, 1946. Soon thereafter, de Florez was promoted to Rear Admiral.

Thus, the ASCA project was off and running and the momentum attained made it difficult to change course even though one influential Navy captain characterized it as "a physicist's dream and an engineer's nightmare." Indeed, the project kept going full steam even after the objective of the work was changed from an analog computer aimed at an ASCA to a digital general-purpose computer renamed Whirlwind in 1947.

The history of Whirlwind, with its many surprises, administrative crises and technical developments, has been well recorded by other authors.[1,2,3,4,5] These references have all provided important inputs to this study.

To summarize the history of Whirlwind for the reader we have constructed a chronological chart (Figure 1) recording the major technical and administrative events of the project from 1944 to 1959.

This paper takes a different course from previous histories in that it attempts to assess the returns to the nation which resulted from the investment of approximately $3.6 million by the Navy and $13.8 million by the Air Force in basic engineering research at M.I.T. aimed at evolving the first real-time computer. The returns, which are astounding, occurred in the following categories:

- New knowledge created;
- Training of people;
- Revolution in teaching;
- National defense posture; and
- Stimulus to the computer industry and the formation of new companies.

Whenever possible, tables or figures will be utilized to illustrate returns in order to maximize brevity.

Figure 2 provides an overall view of the contributions of Whirlwind. The categories of return are described in more detail in the text which follows.

---

1. An Introduction to the Early Technical History of the M.I.T. Whirlwind Computer, 1944-1951, Richard R. Mertz.

2. *Project Whirlwind — The History of a Pioneer Computer*, Kent C. Redmond and Thomas M. Smith, Digital Press, June 1980.

3. *The Digital Computer Whirlwind*, Karl L. Wildes, M.I.T., September 1976.

4. *A History of Computing in the Twentieth Century*, chapter on Whirlwind, Robert R. Everett, Academic Press, Inc., 1980.

5. Lecture by Jay W. Forrester at Digital Equipment Corporation on June 2, 1980.

M.I.T. initiates small feasibility study of Aircraft Simulator and Control Analyzer (ASCA) for Navy.	Dec. 1944 $75K	
M.I.T. proposal for a major extension of the ASCA is approved by Navy.	June 1945 $875K	Japan Surrenders
New proposal to Navy switching from slow analog to promising digital techniques, and broadening scope to include a general purpose machine as well as an aircraft analyzer. Name of machine changes to Whirlwind.	March 1946	
Reliable, fast internal storage identified as a major problem. Program on electrostatic storage tube improvement initiated (S.H. Dodd and P. Youtz).	$1194K	
Five-digit multiplier developed (Taylor). Can multiply two binary five-digit numbers in five microseconds with great reliability. Fast enough for "real-time" computation. Use of high-speed video circuitry.	1947	
Marginal checking to spot about-to-fail tubes (Forrester). Used on Taylor multiplier. Forrester initiated lectures at M.I.T. on digital computers.		
Crystal matrix switch developed to control very high-speed computer (D. Brown).		Whirlwind staff studying its application to anti-submarine problems. Sylvania selected as subcontractor to fabricate hardware.
Block diagrams for high-speed synchronous parallel logic evolved stipulating the coordinated operation of basic components of Whirlwind (Everett).		
Five bit multiplier performs 5×10^9 multiplications over 45 days without error.		
Vacuum Tube life extended to 10,000 hours in some cases.	1948	ONR questions project continuation because of size of budget. R&D Board of Defense Dept. studies status of all computer projects. An Ad Hoc Committee recommends Whirlwind be terminated unless a suitable application found.
Approximately 15 engineers on the project along with about 55 additional graduate students and others.		
Von Neumann visited in February and was ecstatic over technical progress.		An M.I.T. Committee concludes Whirlwind is promising (Booth).
First comprehensive conversion routine for translating machine language (C.W. Adams). Worked closely with other computer groups on software.	$900K	ASCA Project indefinitely postponed.
	1949	Whirlwind objective becomes general purpose computer. Completion date postponed to end 1950.
Cathode ray tube used to display calculations and to detect malfunctions. Permanent storage for tests.		Air Force Air Material Command requests study of application of high-speed computers to air traffic control.
Forrester not satisfied with electrostatic tube storage progress so initiates work on magnetic core storage. W.N. Papian began work on cores.	$300K	M.I.T. reviews its entire computer situation.
		Intelligence points out USSR atomic bomb threat via North Pole flight (August).
		Prof. G.E. Valley, member Science Advisory Board of Air Force suggests new air defense study (November).
		Air Defense System Engineering Committee (ADSEC) established (December).

FIGURE 1 CHRONOLOGY OF WHIRLWIND

Chance meeting of Valley and Wiesner followed by meeting of Valley with Forrester results in Air Force selection of Whirlwind (January).	1950	ONR wishes to limit Whirlwind budget to $250,000.
ADSEC suggests using Whirlwind for trial interceptions of aircraft using Bedford radars.		
Estimated cost of electrostatic tubes for storage too high, but work to get Whirlwind I operational continues.		
Patent applied for on magnetic core digital storage device by Forrester (May).	1951	Project Charles undertaken with leadership of F.W. Loomis, J.R. Zacharias and other ONR-funded scientists to study the technical problems of air defense (February to August).
Successful tracking and guiding of aircraft on collision-course interceptions computed by Whirlwind (April).	Air Force Contract	Project Lincoln, later Lincoln Laboratory, established by M.I.T. July 26. M.I.T. Digital Computer Lab becomes Division of Lincoln.
Work of Bell Laboratories on transistors developed in 1948 point to transistorized computers. Work on this begun at Whirlwind.		
Programmers began working with students on plotting information with WWI computer on cathode ray tubes. The beginning of computer graphics (C.W. Adams).		
Air defense needs are critical so design concepts for Whirlwind II are started (Taylor).	1952	
Serious shortage of manpower is attacked to try to keep WWI and WWII on schedule.		
Papian made 16 x 16 array of ferritic material with 20x faster switching speeds (May). It took 2 years and many people to make first usable memory (D. Brown).		IBM brought in as subcontractor to M.I.T. to develop and construct Semi-Automatic Ground Environment (SAGE) air defense system (October). 85 IBM engineers.
WWI achieves seven consecutive hours of error-free operation despite use of tubes. Vacuum tube reliability in pulsed circuits increased from a few hundred to thousands of hours — but troubles persist.		
The Cape Cod System suggested by Project Charles to test multiple-radar network linked to WWI, though incomplete, was vectoring instructions for guidance of manned interceptors in real time.	1953	
The Memory Test Computer demonstrated reliable operation with a 32 x 32 x 16 magnetic ferrite storage (Olsen) (May).		
Electrostatic tube work halted as first bank of magnetic core storage wired into WWI. Maintenance problems and high tube cost overcome (August).		
Whirlwind I able to track as many as 48 aircraft.		
Multiple consoles used to control multiple aircraft represented first timeshared computer. Use of very sophisticated software.	Air Force Total $13.8 million	
Manufacture of components for WWII, or AN/FSQ-7, started by IBM.	1954	
	1955	The M.I.T. Computation Center was established.
Cross Telling or transfer of information from WWI to XD-1 and back achieved without error (Dodd).	1956	
Reliability over two week period reached 99.3%.		Forrester moves to Sloan School as Prof. of Industrial Management.

FIGURE 1 CHRONOLOGY OF WHIRLWIND (Continued)

The TX-O Transistorized Experimental Computer became operational. This represented the beginning of the second generation of electronic computers (Sept.).		R. Everett becomes head of Division VI of Lincoln Lab. (July).
TX-2 was developed as a very flexible transistorized device of "Control-memory" nature general purpose computer.	1957	
First full sector of SAGE in place for protection of New York and Philadelphia area. Can sift out potential enemy aircraft from tens of thousands of routine flights (June).	1958	Sputnik I (May). The Mitre Corp. is formed by M.I.T. at request of Air Force to take over from Lincoln and integrate the SAGE Air Defense System (July).
The transistor-driven core memory CG-24 computer and radar system first tracked Sputnik I (May).		
Whirlwind I is leased to Wolf R&D Corp. Ultimately placed in Smithsonian.	1959	
	1960	

FIGURE 1 CHRONOLOGY OF WHIRLWIND (Continued)

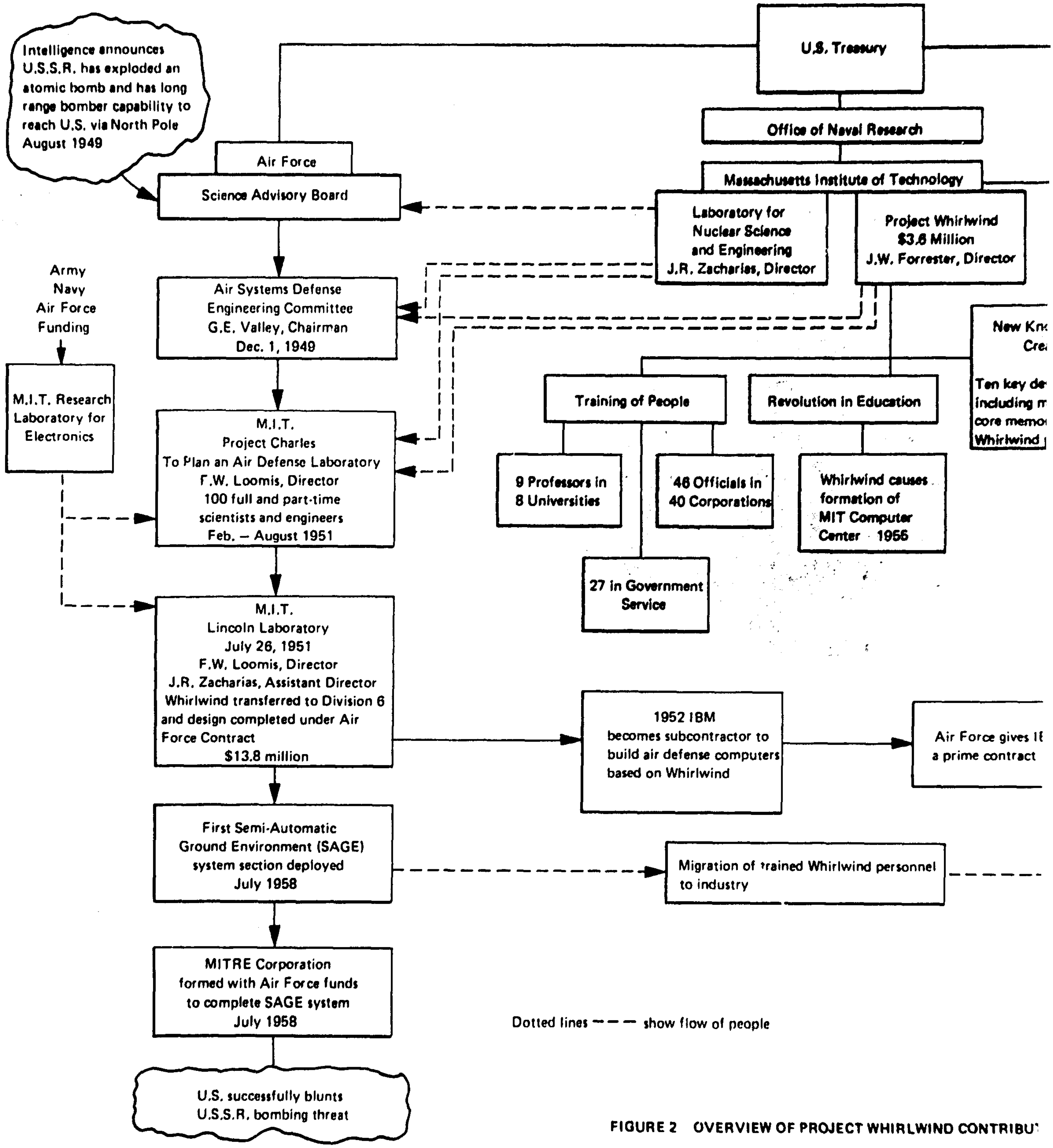
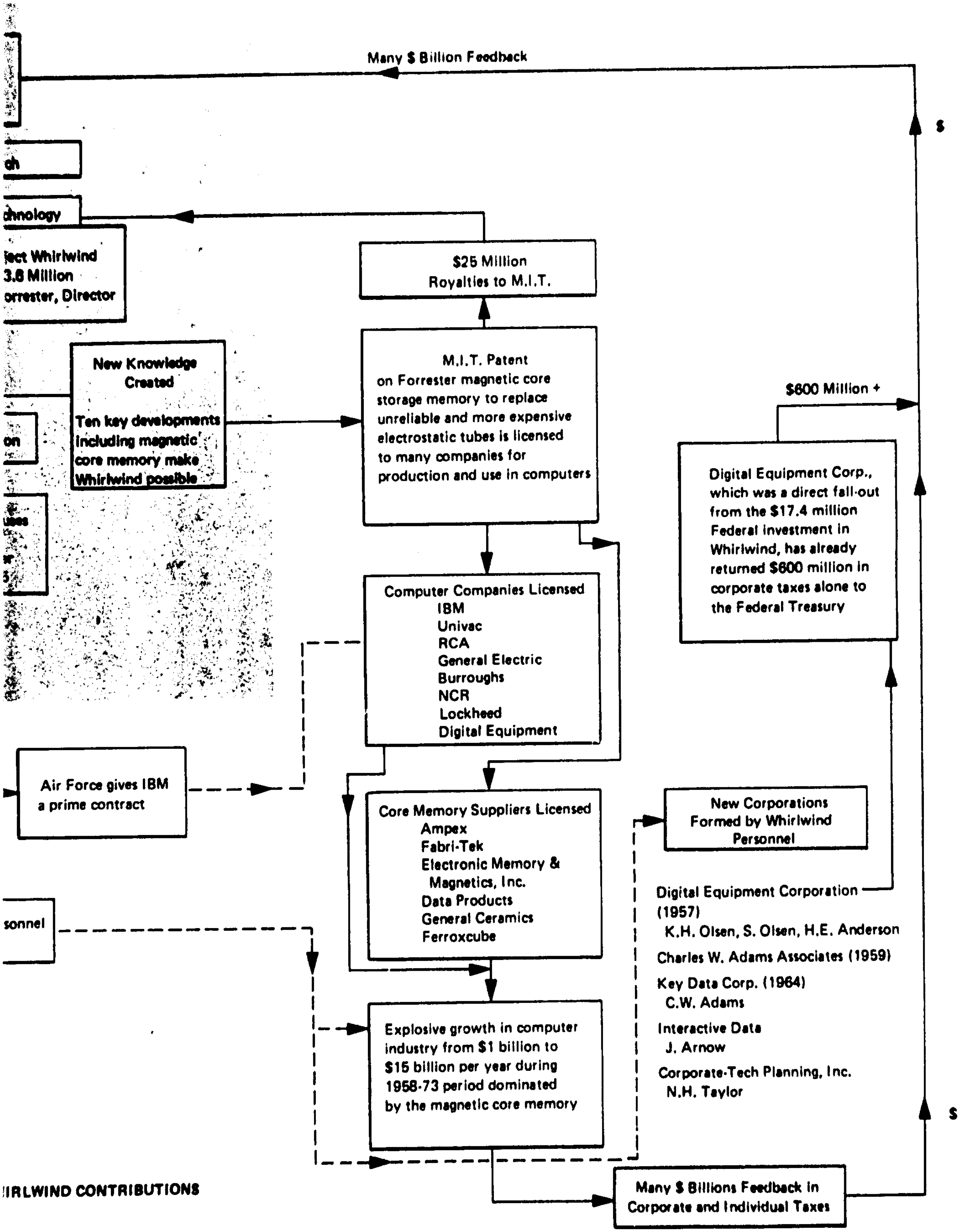


FIGURE 2 OVERVIEW OF PROJECT WHIRLWIND CONTRIBU



IRLWIND CONTRIBUTIONS

12

B. NEW KNOWLEDGE CREATED

In order for Whirlwind to meet its ultimate goals of real-time, or ultra-high-speed, and reliable operation, a number of new developments had to take place. The most important of these are listed in Table 1. Some commentary may be helpful.

When Whirlwind began, it was conceived as an analog computer, but it soon became evident that this machine would be too slow. With suggestions and encouragement from Perry Crawford of the M.I.T. Center of Analysis and later the Navy Special Devices Center, Forrester and Everett moved into synchronous parallel (rather than sequential as used in many other machines of the day) digital computation because this offered the promise of reaching real-time speeds.

The five digit multiplier was a giant step forward as it demonstrated real-time speed, accuracy and reliability. The famous Princeton mathematician, John von Neumann, who was also developing a computer for ONR, visited M.I.T. in 1948 shortly after the multiplier completed 5 billion multiplications without error. Upon seeing the machine operate, he became so excited he kissed Norm Taylor on both cheeks!

Some experts believe the software contributions made during the Whirlwind development were as important as the many hardware advances.[1]

The invention of the magnetic core storage memory revolutionized computer design, cost and reliability and stimulated the rapid growth of the computer industry. This will be covered in more detail under another category of Whirlwind returns.

Telephone lines are now routinely used for data transmission and computer links. Most major computers now use synchronous parallel logic and feedback of improved instructions. And, computer-aided design and manufacturing and time sharing are now big businesses.

C. TRAINING OF PEOPLE

While training of people is usually not an objective of ONR or Air Force research contracts, it is an inevitable "fallout." And Whirlwind-trained personnel have made rich contributions to our society.

In the early days of Whirlwind, about eight engineers carried the brunt of the research work, augmented by a staff of about 25, many of whom were part-time graduate students. These eight — Forrester, Everett, Taylor, Dodd, Youtz, Wieser, O'Brien, and Brown -- were particularly talented and inventive and all have had brilliant careers.

By September, 1948, the organization chart showed about 50 professionals and an administrative staff of some 12 people. When Whirlwind was transferred to

1. "History of Programming Languages" June 1-3, 1978, Association for Computing Machinery, Inc.

TABLE 1

NEW KNOWLEDGE FROM WHIRLWIND

1946 Adoption of synchronous, parallel digital computation because of the high-speed logic potential (Perry Crawford, J.W. Forrester, R.R. Everett). The logic was developed through block diagrams by Everett.

1947 To test the speed which computer circuitry could attain, N.H. Taylor built a five digit multiplier. The computing time realized of 5 microseconds (5 millionths of a second) was fast enough for real-time computing. For control, a 1 microsecond crystal or diode switch was developed (D.R. Brown). For more reliability from electrostatic tubes, a system of marginal checking was conceived to discover latent tube failures (J.W. Forrester). Also, more reliable tubes were developed (S.H. Dodd and P. Ycutz). As a result of these several developments, the five digit multiplier operated 45 days without error in late 1947.

1948 Developed software for the first comprehensive routine for translating coded orders into machine language, and many other software advances, such as the first compiler, assembler and interpreter (C.W. Adams, J. Arnow, H. Bennington, Sheldon Best, H.H. Laning, A.J. Perlis, A. Siegel, C.R. Wieser, N. Zierler, C. Zraket).

1949 First use of a cathode ray tube to display calculations and information.

1950 This led to the development of a light gun photocell to permit the first communication between the operator and the computer in aircraft intercept exercises (R.R. Everett). Thus, computer graphics was spawned, leading years later to computer aided design, engineering and manufacturing.

Invention of the magnetic core storage memory to replace the more expensive and less reliable electrostatic tubes (J.W. Forrester). Laboratory development by D.R. Brown, W.N. Papian, et al.

While earlier demonstrated at the Bell Laboratories (G. Stibitz), Whirlwind first used telephone lines for massive transmission of radar data for practical real-time input to a computer for air defense control.

1952 While the concept of redirecting calculations by feeding back improved instructions in real time is attributed to John von Neumann, Whirlwind was the first high-speed computer to reduce this significant advance to practice (R.R. Everett).

1953 Multiple consoles were used to control multiple aircraft intercepts so that Whirlwind became the first dedicated purpose time shared computer.

Division 6 of Lincoln Laboratory late in 1951, the organization chart[1] showed approximately 100 professionals. About 20 of these had been connected with the project for some years, and they provided the necessary continuity.

In checking the careers of people, we were successful in tracing about 80, but were unable to get data on about 50 others. (See Appendix C.) Table 2 contains summary information on the positions in society attained by those located. It is particularly interesting that Whirlwind engineers transferred their knowledge to so many universities and industrial companies by migrating all over the United States.

TABLE 2

CAREERS OF PEOPLE TRAINED IN WHIRLWIND

Four have been elected to the National Academy of Engineering — J.W. Forrester, W.K. Linvill, R.R. Everett, and A.J. Perlis.

One has been elected to Inventors Hall of Fame — J.W. Forrester.

Nine have become professors of computer sciences, mathematics and business in eight universities.

Twenty-seven have continued to contribute to national defense through executive positions at M.I.T. Lincoln Laboratory, MITRE Corporation (the current President is R.R. Everett), and in government agencies.

Some 46 engineers entered industry, transferred vital Whirlwind know-how, and attained key executive positions in 41 different companies in the computer, aerospace, consulting, etc., segments of industry. About 50 persons were unaccounted for and 6 are deceased.

Several assisted in establishing professional society activity in the computer field. N.H. Taylor was Program Chairman of the first National Joint Computer Conference in 1951.

A number of Whirlwind personnel established new companies. More about this in a later category of Whirlwind returns.

There is an amusing story about the initiation of professional society activities. In organizing the first Computer Conference in 1951, Norm Taylor scoured the United States and U.K. and finally acquired 19 qualified speakers (3 from Whirlwind) for an attendance of 877. Now, of course, there are hundreds of speakers each year, and attendance at the 20th anniversary in 1971 was 20,000!

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1. The Digital Computer, Karl L. Wildes, M.I.T. Electrical Engineering and Computer Science, September 1976, pages 5-143 and 5-160.

D. REVOLUTION IN TEACHING

A quite unexpected, but highly significant, return from Whirlwind was the revolution it initiated in teaching.

This all began when Whirlwind became operational about 1951. M.I.T. faculty and students wanted to learn how to use the machine for calculations in connection with their research. C.W. Adams began working with a number of them during hours when the machine was available. Soon, Professor Philip M. Morse, who headed an Institute Committee on Machine Methods of Computation, became his faculty contact. As activity increased, ONR funded a project with Morse called Machine Methods of Computation and Numerical Analysis. A number of Departments at the Institute had ONR Assistants who wrote reports and theses on their work with Whirlwind. Many became so intrigued they altered their specialties to become computer scientists.

Soon it became apparent that M.I.T. should consider establishing a computation center. Professor Morse and his committee so recommended to President Killian in July 1955. IBM offered to supply a large computer, and M.I.T. and IBM announced, on September 23, 1955, the establishment of the M.I.T. Computation Center. IBM also provided funds for research assistants, so ONR was relieved of this funding.

The growth and extension of the Center led Gordon S. Brown, Dean of Engineering, to write in 1967:

> "The digital computer promises to alter the way of life of human beings within the next decade as much, if not more than, Gutenberg's invention of printing from movable type ... The frame of reference is so changed that the student may ask questions that heretofore would not have made sense. Herein lies the potential for revolution in the teaching-learning process that today can be only dimly perceived. It promises not only to change the content of what we teach to students, but also to revolutionize the methodology whereby we do it."

E. NATIONAL DEFENSE POSTURE

At this point, it would be appropriate for members of Congress and the Executive Office of the President to observe that all of these returns from basic engineering research are nice, but then ask, "What did the work contribute to national defense? After all, the funds were provided by the Department of Defense, so what more direct returns did Defense obtain?"

As we shall see, the answer to this line of questioning is very direct and positive.

First, let us return to one of the basic concepts upon which ONR was founded. It was postulated that the Navy could best maintain its posture as a world leader in the development and utilization of the most advanced defense systems if it continued the access to outstanding basic and applied research scientists and engineers it had established in World War II. That postulate turned out to be entirely correct in the cases studied.

The mechanism by which the successful continental air defense system of the United States came into being is depicted schematically in Figure 2.

The activity all began with Professor George E. Valley, who was doing basic research work in cosmic rays in the Laboratory for Nuclear Science and Engineering under ONR funding. As did many other professors, Valley served in an advisory capacity to the Department of Defense — in particular as a member of the Science Advisory Board of the Air Force. Intelligence announced to that Board in August, 1949, that the U.S.S.R. had exploded a nuclear weapon and also had long-range bomber capability for delivering such weapons to the United States via the North Pole. On November 8, 1949, Valley wrote the Science Advisory Board suggesting forming an Air Systems Defense Engineering Committee (ASDEC) to study means of meeting this threat. ASDEC was established in December, 1949, with Valley as Chairman.[1]

In considering a model for an air defense system, the Committee soon conceived of a high-speed centralized computer system to correlate data fed to it from many radars. Through a chance meeting with Professor Jerome B. Wiesner,[2] Valley became aware of the great potential offered by Whirlwind. He promptly extended a permanent invitation to J. W. Forrester in March, 1950, to sit with ASDEC. Almost immediately, the Air Force decided to fund tests involving feeding Bedford, Mass., radar information into Whirlwind for trial aircraft interceptions.

The urgency for a U.S. air defense system was heightened by the outbreak of the Korean War in June, 1950. As a result, and because of the progress being made by ASDEC, the Chief of Staff of the Air Force requested President J.R. Killian of M.I.T. to establish and administer a laboratory to study air defense. In February, 1951, M.I.T. decided to organize Project Charles to formulate sound plans for establishing such an air defense laboratory. Professor F. Wheeler Loomis of the University of Illinois was made Director and he was joined by about 30 essentially full-time participants with distinguished scientific and engineering backgrounds, and about 70 others who were part-time contributors. Among the former were Professors Jerrold R. Zacharias, Jay W. Forrester and George E. Valley. By July, 1951, their planning was completed and the final report was dated August. The charter for Project Lincoln, later named M.I.T. Lincoln Laboratory, was dated July 26, 1951. Prof. F. Wheeler Loomis was named Director of Lincoln and Prof. Jerrold R. Zacharias, Director of the Laboratory for Nuclear Science and Engineering, became Associate Director.

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1. Other members were M.I.T. Professors C.S. Draper, W.R. Hawthorne, H.G. Houghton, and H.G. Stever; J. Marchetti, Air Force Cambridge Research Laboratory; G.C. Comstock, Airborne Instruments Laboratory; and A.F. Donovan, Continental Air Command.

2. Wiesner at that time was working in the Research Laboratory for Electronics which was jointly funded by the Army, Navy and Air Force. Later he became Science Advisor to President John F. Kennedy and then President of M.I.T.

Whirlwind was transferred to the Lincoln Laboratory for the completion of its development under Air Force funding. (This was fortuitous, as ONR funding was being curtailed.) The machine development was essentially completed and running with magnetic core memories in 1954 at a total cost of $17.4 million, of which $3.6 million was earlier Navy funding. Also transferred to Lincoln were many key people from the Research Laboratory for Electronics, which was jointly funded by the Army, Navy and Air Force. (NOTE: ONR played an important role in this highly productive laboratory — but that story will have to be told in a subsequent report.)

In October of 1952 the International Business Machines Corporation was brought in as a subcontractor to M.I.T. to build the production models of Whirlwind II, now designated by the Air Force as AN/FSQ-7. Some 85 IBM engineers were assigned to the project and they, along with Lincoln engineers, completed the design. Soon IBM was given a prime contract by the Air Force, and the manufacture of components started in early 1954.

Meanwhile, the development of a prototype for the Semi-Automatic Ground Environment (SAGE) air defense system was progressing well. Known as the Cape Cod system, it consisted of a network of radars and telephones. With Whirlwind processing some 20,000 instructions, successful intercepts of "enemy" aircraft were being made by December 1953.

The SAGE air defense system was first deployed on July 1, 1958 at McGuire Air Force Base in New Jersey for protection of the New York-Philadelphia area. Since it was deemed inappropriate for a university to take responsibility for the continuing task of systems engineering for the nationwide air defense system, the Air Force asked M.I.T. to assist in the establishment of an independent, non-profit, public interest corporation to address this requirement. The result was the organization in July 1958 of the MITRE Corporation. With the Air Force funding, MITRE took over the systems engineering for the installation and integration of the SAGE air defense system.[1]

The USSR air threat was successfully blunted.

F. STIMULUS TO INDUSTRY

Whirlwind was a stimulus to industry in three ways — it sparked the rapid growth of the computer industry; some of its people formed new companies, and it initially demonstrated some techniques which have led to entirely new industries. The result has been an incalculable but vast dollar feedback to the U.S. Treasury, as depicted in Figure 2.

The stimulus to growth of the computer industry was a direct consequence of the invention of the magnetic core storage memory which was more reliable and less expensive than electrostatic tubes. Mean time to failure on the memory rose from 2 hours to 2 weeks. IBM first obtained know-how by working on SAGE with M.I.T.,

1. MITRE, The First Twenty Years, MITRE Corporation, Bedford, Mass., 1979

and other computer companies and core memory suppliers learned through visits to M.I.T. and the influx of former Whirlwind people into industry. M.I.T. received about $25 million in royalties from licensing the industry for non-government sales.

During the 1958-73 period in which the magnetic core memory dominated computer design, the industry's sales grew exponentially from $1 billion to $15 billion per year.[1] IBM got the jump by using 2.5 billion cores in 1963 compared with about 0.5 billion by all competitors. By 1970, IBM was producing or buying almost ten times as many core memories as the combined competition, with total cores exceeding 90 billion per year by 1973.

Also, the formation of the new companies listed in Figure 2 was as a direct result of Whirlwind training. Kenneth H. Olsen, who worked on Whirlwind before founding the Digital Equipment Corporation, has called Whirlwind the first mini-computer and states his company was based entirely upon Whirlwind technology. That company alone has already returned to the U.S. Treasury approximately $600 million in corporate Federal income taxes (aside from many individual income taxes of employees)! Were that portion of the earnings of many other companies and thousands of individuals in the computer industry attributable to Whirlwind calculable, the return to the Federal Government in taxes for its estimated $17.4 million investment in basic engineering research would certainly reach many billions of dollars!

And more is to come. The early work at Whirlwind demonstrated the possibility of numerically controlled tools, computer aided design, computer aided engineering, computer aided manufacturing, and time sharing (dedicated purpose), all of which are now emerging industries.

In summary, the returns to the nation from the Navy and Air Force investment in Whirlwind have far exceeded the fondest dreams of its original backers. It survived early difficulties and changed objectives, and ultimately contributed significantly to national defense, to education, to industry and to our balance of trade. And the contributions continue as the people trained go forward to pioneer in the application of computers in many new areas of our economy. Truly a remarkable story.

1. *Data Processing Technology and Economics*, Second Edition, Montgomery Phister, Jr., Santa Monica Publishing Company, 1979.

LABORATORY FOR NUCLEAR SCIENCE AND ENGINEERING

A. INTRODUCTION

Shortly after the surrender of Japan on September 2, 1945, the personnel in the Office of Research and Inventions (ORI) (the immediate predecessor to the Office of Naval Research) were so convinced that the Navy should and soon would be authorized to contract with universities for research that they initiated conversations with M.I.T. (and others).

Captain Robert D. Conrad, U.S.N., of ORI approached Professor Robley D. Evans on the subject of research in nuclear physics, since long-range Navy interest in this field was of predictable importance. Evans discussed the matter with Professor George R. Harrison, Dean of Science and John C. Slater, Professor of Physics. The concept was quickly broadened into one of organizing a multi-disciplinary laboratory for the study of nuclear science and engineering. Events moved rapidly and on December 19, 1945, President Karl T. Compton announced to the M.I.T. staff the formation of the Laboratory for Nuclear Science and Engineering (LNS&E). Professor Jerrold R. Zacharias, who had joined M.I.T. from Los Alamos in October, was appointed Director. Negotiations on how the Navy and M.I.T. were to handle the funding proceeded into the summer of 1946, as the birth of ONR became imminent.

The objectives of the Laboratory for Nuclear Science and Engineering (LNS&E) were stated as follows:

(a) Obtain, through design, construction, and purchase, the necessary facilities for modern nuclear research not formerly available to the departments of Chemistry, Physics, Metallurgy, Biology, Chemical Engineering, Electrical Engineering and Mechanical Engineering;

(b) Cooperate with these departments on all research bearing on all applications of nuclear science and engineering, providing facilities for research in these fields;

(c) Undertake in its own interest such researches as are not being carried out by the various academic departments and yet needed for an orderly development of the nuclear field; and

(d) Train personnel in nuclear science and engineering for the design, operation, and use of nuclear devices

A number of promising young and middle aged scientists followed Zacharias (aged 40) to M.I.T., attracted in part by the promise of the new LNS&E with its potentially solid funding and broad scientific scope. Among these were Victor

Weisskopf (38) and Herman Feshbach (29) heading the Theoretical Group; Bruno B. Rossi (41) heading Cosmic Ray Group along with Herbert S. Bridge (27), Matthew Sands (27), R.W. Williams (26), R.W. Thompson (27), and George E. Valley (33); I.A. Getting (33) heading the Synchrotron Group; and Charles D. Coryell (34), John W. Irvine (33) and David N. Hume (28) heading the three Chemistry Groups. The organization of the laboratory as of January 1949 is shown in Figure 3. In addition, an Advisory Committee was established consisting of Professor John Chipman, Metallurgy; Professor A.C. Cope, Chemistry; Professor R.D. Evans, Physics; Professor I.A. Getting, Electrical Engineering; Professor E.R. Gilliland, Chemical Engineering; and Professor J.C. Slater, Physics.

As is the case with any new laboratory, it took LNS&E a while to get organized in an administrative sense in order to arrange the proper funding of new personnel, equipment and space. This was followed by the construction of special equipment, checkout experiments and the ultimate collection of data, all of which consumed considerable time before new experimental results could be analyzed and reported. The budget of the laboratory started at about $300,000 in 1946, then climbed and remained rather steady from 1948 to 1958 at $1.2 million per year. The total ONR funds invested in the LNS&E amounted to about $14 million. After 1958 the Atomic Energy Commission (and its successor agencies) became the prime contractor for the laboratory, and the budget was expanded.

The returns from the ONR investment in LNS&E fall into the following main categories:

- New knowledge created
- Training and education of people
- National defense posture
- Stimulus to industry

We will now attempt to summarize the contributions made in these areas. In this connection, Figure 3 presents an overall view of LNS&E.

B. NEW KNOWLEDGE CREATED

It is extremely difficult to try to summarize the knowledge created by the approximately 400 persons who worked at one time or another in the 10 groups in LNS&E over the 12 years from 1946 to 1958 under ONR prime contract. Only a few key items can be mentioned in an article of this type. Fortunately, any reader interested in technical details can find these in the quarterly progress reports filed in the laboratory headquarters, and in the more than 600 articles which appeared in physics[1] journals, and the more than 100 in chemical, professional journals.

The people who worked in the various groups are listed in Appendix D. The topical highlights of their research programs are listed in Table 3.

1. The physics articles are listed in the LNS&E Final Report under Contracts NS 011-07806 and NONR-1841 (16) May 15, 1958.

OFFICE OF NAVAL RESEARCH
PRIME CONTRACT 1946-1958 $14 MILLION TOTAL

Laboratory for Nuclear Science and Engineering
Organization as of Jan. 1949
Director: Jerrold R. Zacharias

Cosmic Ray
B.B. Rossi

High Voltage Res.
J.G. Trump

Theoretical
V.F. Weisskopf

Neutron and Gamma
Ray Shielding
C. Goodman

Nuclear Chemistry
Inorganic
C.D. Coryell

Synchrotron
I.A. Getting

Nuclear Chemistry
Organic
J.D. Roberts

Radioactivity and
Cyclotron
R.D. Evans

National Defense Studies

Nuclear Propulsion of Submarines

April 1948 — Prof. C. Goodman assists Navy and Atomic Energy Commission in initiating high priority program led by Capt. H.G. Rickover, and training of officers.

Blunting the U.S.S.R. Nuclear Bombing Threat

August 1949 — See Figure 2 for answer to Soviet threat provided by Project Charles, Lincoln Laboratory and MITRE Corporation, with inputs from Laboratory for Nuclear Science and Engineering, Whirlwind and Research Laboratory for Electronics.

Meeting the U.S.S.R. Submarine Threat

Project Hartwell
Director: J.R. Zacharias
Administration provided by LNS&E

June 1954 — About 60 scientists and engineers participate in summer study of protection of overseas transportation. Many important suggestions made including low frequency directional listening (Lofar), helicopters for anti-submarine warfare, Marriner high-speed freighters, etc.

Anti-Submarine Review

Project Lamplight
Director: J.R. Killian
Technical Director:
J.R. Zacharias

June 1954 — Administration provided by Lincoln Lab. Review of status of submarine detection systems.

People Trained

3 Nobel Laureates
21 elected to National Academy of Sciences
9 elected to National Academy of Engineering
4 who participated in National Defense Studies later served as Science Advisors to U.S. Presidents
113 professors in 56 universities
105 officials in 74 industrial corporations
78 Ph.D. degrees granted
1000 Senior thesis students

New Knowledge Creat

Over 700 articles were publis
professional journals and thir
classic text books were writte
The knowledge has contribu
stantially to our understandi
the origin of the universe; nu
reactions, sub-atomic structu
matter; elementary particles;
reactor design, organic and in
chemistry; nuclear medicine;
tronium and the study of "ex
oil and gas reservoir discover
of hyperthyroidism, location
tumors, metabolism of vario
cancer cell screening, etc.

FIGURE 3 OVERVIEW OF LABORATORY FOR NUCLEAR SCIENCE AND ENGINEERING CONTRIBUTIONS

OTAL

ring

Nuclear Chemistry
Organic
J.D. Roberts

Radioactivity and
Cyclotron
R.D. Evans

Chemistry of
Fission Elements
D.N. Hume

Nuclear Cross
Sections
R.J. VandeGraff

Feedback of Taxes
to the Federal Treasury

New Companies Founded

High Voltage Engineering Corp.
Tracerlab, Inc.
American Science and Engineering, Inc.
Education Development Center, Inc.

New Knowledge Created

Over 700 articles were published in professional journals and thirteen classic text books were written. The knowledge has contributed substantially to our understanding of the origin of the universe; nuclear reactions, sub-atomic structure of matter; elementary particles; nuclear reactor design; organic and inorganic chemistry; *nuclear medicine*; positronium and the study of "exotic atoms," oil and gas reservoir discovery; treatment of hyperthyroidism; location of brain tumors, metabolism of various elements, cancer cell screening, etc.

Y FOR
INEERING CONTRIBUTIONS

TABLE 3

RESEARCH PROGRAM HIGHLIGHTS LNS&E 1946-58

Cosmic Ray Group	Investigate the nature of cosmic rays and physical aspects and astrophysical implications.
	Instrumentation development — fast ionization chambers, scintillation counters, etc.
	Study of cosmic ray bursts in ionization chambers.
	Identify the nuclear-active component of cosmic rays of various altitudes using observatories, balloons and B-29 flights.
	Study of magnetic latitude effect.
	Study of high-energy interactions and the properties of elementary particles produced using multiple cloud chambers.
	Meson decay studies, discovery of positive K-meson.
	Giant air showers and their astrophysical implications.
	Work with synchrotron in π-meson decay.
	International Bolivian air shower experiments.
Theoretical Group	Quantum electrodynamics, calculation of the Lamb shift and proof of TCP theorem.
	Analyses of nucleon-nucleon scattering.
	Development of optical model for nucleon-nucleon interaction.
	Statistical theory of nuclear reactions.
	Electromagnetic production of pions, the Primakoff effect.

Nuclear structure, healing distance, deformed nuclei, shell structure.

Theory of cosmic ray phenomena.

Nuclear Inorganic Chemistry Group

Separation of Zr and Hf.

Production and separation of isotopes from irradiated targets.

Solvent extraction.

Ion exchange equilibria and membranes.

Formulation of scintillation counter materials (for Radioactivity Group) and understanding of scintillation process.

Distribution coefficients.

Separation of rare earths.

Radioactive decay energies.

Nuclear Organic Chemistry Group

Use of tracers to study the mechanisms of organic reactions and structures.

Decarbonylation reactions of polycarbonyl compounds.

HCl exchange of camphane chloride.

Structure of Ketene dimer with C^{14}.

Effects of isotopes on reaction rates.

Analytical research at submicrogram levels.

Effects of deuterated solvents on rates of various solvolytic reactions.

Correlation rates of solvolysis.

Chemistry of Fission Elements Groups

Dissociation constant of Cb in aqueous solutions.

Thiocyanate complexes of fission elements.

Ce, Zr radiometric analysis.

	Photometric titration.
	Ion exchange with Hf and Zr.
	Principles of polargraphy.
	Analytical applications of radioactivity.
	Thermometric titrations.
	Flame photometry.
	Electrodepositions behavior of metals.
High Voltage Research	Design and construction of very large Van de Graff generator
	Two to three million volt x-rays for cancer therapy.
	Bactericidal effects of x-rays on foods and drugs.
Neutron and Gamma Ray Shielding Group	Investigation of numerous materials for shielding properties.
Synchrotron Group	Design and build a 300-MeV Synchrotron.
	After completion in July 1950, the machine was used to study photon scattering from complex nuclei, the photoproduction of mesons, etc.
	Design, construction and experimentation with cloud chambers.
Radioactivity and Cyclotron Group	Radiation effects in humans exposed to radium.
	Synthesis of radioactive compounds for research.
	Metabolism of various elements in animals and humans.
	Development of controlled background facility.
	Instrument development — ionization chambers, scintillation counters, etc., and their associated electronics.

Decay modes and nuclear energy levels involved in radioactivity.

Electron-positron annihilation process — discovery of positronium.

Mechanism of beta decay, the helicity of positrons.

Production of isotopes using the redesigned Markle Foundation cyclotron, and undertaking elastic scattering experiments.

Nuclear Cross Sections Group Conversion of generator to positive ion acceleration and construction of 180° magnetic spectrograph permitted higher-resolution and accuracy in nuclear and mass spectroscopy.

Using the new ONR generator along with a unique broad-range magnetic spectrograph allowed extension of studies to nuclei throughout the periodic table. Energies and angular distributions of the charged particles from many nuclear reactions were studied.

Analysis of cosmic rays and other charged particles in emulsions.

*Photonuclear Research Group** Follow-through design and construction of 17-MeV microwave linear accelerator, first started in the Research Laboratory for Electronics.

Application of the accelerator to nuclear structure studies employing photon induced reactions, including studies of photo fission and photoneutron processes.

Development and application of time-of-flight techniques for the measurement of MeV-energy range neutrons emitted by photo-excited nuclei.

Initiation of the concepts, technological requirements, and physics justification for higher energy work. This led later to the design and construction of the MIT/BATES 400-MeV Linear Accelerator Laboratory.

*Some new Groups were formed after the 1949 organization shown in Figure 3.

At the outset it is important that the reader recognize that a long time may have to pass before the significance to mankind of certain new knowledge created through basic research becomes apparent. Some of the knowledge developed in LNS&E has yet to find application, aside from the important aspect of training people. Some of the knowledge has been applied in expected, and also in totally unpredictable, fields and uses. And some of the knowledge has found important utility in furthering our understanding of nature. We will explore briefly these latter two contributions.

Some of the practical uses of knowledge developed in LNS&E are:

- The members of various groups within LNS&E initiated work with teams of medical specialists and made pioneering and important contributions to the new field of nuclear medicine. For example, they established acceptable levels, or effective thresholds, for radiation in humans through studies of radium and mesothorium in exposed humans; learned the metabolism of Fe, Ra, I, Ca and Zn in humans; treated hyperthyroidism with I^{131}; and synthesized many radioactive compounds for use in medical diagnosis and treatment. Furthermore, they developed new instruments for medical research and clinical use such as positron scanning to locate brain tumors, a whole-body radiation counter, counting rate meters, scalers, etc.; x-ray therapy for cancer; etc. Today, nuclear medicine is an indispensible activity, and medical research and treatment are major users of radioactive materials.

- The Theoretical Group produced a number of papers of permanent value which had a large impact on physics in such areas as quantum electrodynamics, the nuclear two- and three-body problem, nuclear reactions, meson physics and nuclear structure. The group of papers on nuclear reactions found important practical application in the design of nuclear power reactors for naval ship propulsion and central power stations.

- The three chemical groups contributed to our understanding of chemistry in many ways. The Inorganic Chemistry Group's work on solvent extraction and ion exchange equilibria and on developing and understanding scintillation counter materials was important. The Organic Chemistry Group's studies of the mechanisms of organic reactions and structures using tracers led to the publication of textbooks which have been, and still are, widely used. And the Chemistry of Fission Element Group added importantly to our knowledge of photometric titration, thermometric titration, flame photometry, and analytical procedures at the submicrogram level.

- The work of the Radioactivity Group led to the construction of powerful new measurement tools which permitted the development of our comprehensive knowledge of nuclear decay mechanisms which, in turn, made decisive contributions to the theory of nuclear structure and weak interactions, so indispensible in all fields of applied radioactivity. Also, the discovery of positronium (the atom without a nucleus, consisting of an electron and a positron) opened up a new field of positronium chemistry and the study of other "exotic atoms," and also has led to the application of positronium tomography in medicine.

- From work in the Neutron and Gamma Ray Shielding Group evolved the development of a practical neutron log by Clark Goodman, Charles W. Tittle and Henry Faul.[1] The device was commercialized by Schlumberger Limited. Almost all oil and gas produced today comes from accumulations in the pore spaces of reservoir rocks. Well logging is used to evaluate a potential reservoir for its porosity and hydrocarbon saturation. Neutron logs and other logs are used principally to delineate gas and oil formations and to measure the extent of depletion over time. This instrument occupied, and continues to play, a significant role in U.S. gas and oil discovery.

- In 1956, Professor I.A. Pless of LNS&E began his work at M.I.T. on bubble chambers. To cope with the overwhelming amount of data, Pless developed a system called Precision Encoding and Pattern Recognition (PEPR) to automate the scanning of bubble chamber pictures. Every physics laboratory immediately had to have one. Some years later, a doctor from the Children's Hospital Medical Center in Boston spoke to Professor Pless about the possibility of automating the laborious process of scanning autoradiographs. Some thesis work by David J. Zahnizer under Pless, followed by additional work at the University of Nijmegen, has led to the ability to distinguish between normal and abnormal cells. A new device called Bio PEPR can be used, for example, to screen smears for cervical cancer. It can screen in eight hours what would take a technician 10 to 12 days to perform. Other variations of PEPR read rainfall maps and make road maps. Certainly no one could have predicted these possible future uses of what was once a physics laboratory instrument.

LNS&E research also contributed to our better understanding of nature:

- The Cosmic Ray Group, along with groups at Cornell University, the University of Chicago, California Institute of Technology, Columbia University, Harvard University and the National Observatories, completely revolutionized our understanding of the universe. A blending of nuclear, plasma and particle physics has permitted us to formulate a grand concept about the origin and workings of the

1. Goodman became a Vice President of Schlumberger and later Professor of Physics, University of Houston. Tittle and Faul are Chairmen of the Physics Departments at Southern Methodist University and University of Pennsylvania, respectively.

universe. This concept is fundamental to our understanding of the nature of the world in which we live.[1]

- The high energy and particle physics work at LNS&E and elsewhere can be thought of as representing a third stage of atomic research. The first stage consisted of research on atomic structure, which led to our knowledge of electron shells. This knowledge provided us with an understanding of the constitution of all substances which make up our world — metals, solids, gases and fluids. The second stage involved research on the nucleus of the atom and led to our understanding of fission and fusion, and brought about the advent of nuclear medicine and nuclear power. The third stage explores the structure of the nucleus and the nature of elementary particles and interacting forces. This third stage is still unfolding, and it is too early to recognize what significant practical applications will result from the new knowledge being created. On the basis of past experience, however, the chances are that such applications will have a profound impact.

C. TRAINING AND EDUCATION OF PEOPLE

At the close of World War II, both students and facilities for doing graduate work in nuclear science and engineering were very scarce. This was clearly recognized by M.I.T. and, therefore, the administration was receptive to the ONR offer to fund research in this area. An interdisciplinary Laboratory for Nuclear Science and Engineering was rapidly organized, and contract negotiations with ONR were completed in 1946.

While the primary aim of the Navy was to accelerate the discovery of new knowledge and understanding in a field of potential interest to defense, an inevitable "fallout" of this work was to be the training of many people. LNS&E turned out to be quite unique in this respect.

Between 1946 and 1958 about 400 persons participated in research at LNS&E as part of the teaching staff or as graduate students or assistants. The group leaders in the laboratory were carefully selected and recruited by Zacharias and others at M.I.T. In Rossi, Weisskopf, Coryell, Roberts, Hume, Trump, Goodman, Getting, Evans and Van de Graff, the laboratory was blessed with young and talented leaders who were recognized as having great promise by their peers. Therefore, these men attracted excellent co-workers and students to LNS&E.

We have been able to trace the careers or present positions of over two-thirds of the 400 LNS&E participants (see Appendix D). As would be expected, many have remained in academia. At least 117 are professors in 38 U.S. and 10 foreign universities, 106 have key positions in 74 industrial corporations and 57 are in

1. "Cosmic Rays," Bruno B. Rossi, McGraw-Hill Book Co., 1964.

government service. (About 130 were unaccounted for.) They have carried their knowledge to every corner of the United States. Much more interesting than numbers, however, are some of the career attainments by those trained in LNS&E and associated defense activities, as summarized in Table 4.

It is immediately apparent from inspection of Table 4 that the ONR investment in LNS&E helped to produce an unbelievable array of talent. The contributions they have made to our society in services rendered, new knowledge and understanding created and applied, and the continuing education they are providing others in universities, industry and government are mind-boggling, ever-increasing and immeasurable.

In addition to the 78 graduate students awarded doctorates, still another group received valuable training which must not be overlooked. Professors in LNS&E made it a practice to encourage seniors to perform their thesis work in the laboratory. Over 1,000 bright young men responded, and they in turn have advanced into responsible positions in academia, industry and government.

The outstanding caliber of the LNS&E staff and students is indicated by the fact that about 7 percent have been elected to the National Academy of Sciences or the National Academy of Engineering, as against a national average for all science and engineering doctorates of about 0.6 percent.

LNS&E personnel made a special contribution to education by writing the first textbook on nuclear reactors, "Science and Engineering of Nuclear Power" with contributions by M. Deutsch, R.D. Evans, B.T. Feld, F. Friedman, C. Goodman et al. A course was initiated in 1947 and became very popular. This was the first step toward the later establishment of the Nuclear Engineering Department at M.I.T.

Other very important textbooks were also written by various LNS&E staff as listed in Table 5. These have contributed greatly to education in many universities. Also, as previously mentioned, the laboratory produced 700 articles which appeared in professional journals to add to the storehouse of knowledge.

It is apparent that the training and education "fallout" from this ONR investment continues to compound through the years as professors produce more professors, industrialists train more professional staffs, and publications inspire more publications. It is truly a chain reaction.

As might be expected, the people associated with different groups within LNS&E tended to choose different career patterns, as shown in Table 6. Those in the more basic Theoretical and Cosmic Ray Groups remained for the most part in academia, whereas those trained in the three Chemistry Groups were largely attracted to industry.

TABLE 4

SOME CAREER HIGHLIGHTS ON PEOPLE TRAINED IN LNS&E 1946-58 ACTIVITIES

- Three have become Nobel Laureates (M. Gell-Mann, B. Richter, G. Wilkinson);
- Twenty-one have been elected to the National Academy of Sciences (J. Chipman, G.W. Clark, M. Deutsch, S.D. Drell, H. Feshbach, M. Gell-Mann, M.L. Goldberger, W.L. Kraushaar, M.S. Livingston, F.E. Low, H. Primakoff, N. Rasmussen, B. Richter, J.D. Roberts, B.B. Rossi, J.C. Sheehan, H.E. Simmons, V.F. Weisskopf, J.R. Zacharias, J.B. Wiesner, G. Wilkinson);
- Nine have been elected to the National Academy of Engineering (I.A. Getting, E.R. Gilliland, H. Mark, N. Rasmussen, J.E. Snyder, Jr., J.G. Trump, R.H. Wertheim, A.D. Wheelon, J.B. Wiesner);
- Four, who participated in LNS&E studies for the Department of Defense, later served as Science Advisors to U.S. Presidents (J.R. Killian, J.B. Wiesner, E.E. David, Jr., H.G. Stever);
- Three study participants or students have become university presidents (J.R. Killian and J.B. Wiesner of M.I.T. and M.L. Goldberger of the California Institute of Technology);
- Eighty-one are Professors of Physics in forty-one universities;
- Thirty-two are Professors of Chemistry in twenty-four universities;
- Fifty-seven are in Government service in twenty-eight locations;
- One hundred-six are officials in seventy-four industrial corporations;
- One was Secretary of the Air Force (H. Mark);
- One was Chief Scientist of the Air Force (G.E. Valley);
- One was Oceanographer of the Navy (J.E. Snyder);
- Two became President of the American Physical Society (V. Weisskopf, H. Feshbach);
- One was Director General, European Center for Nuclear Research (V. Weisskopf); and
- Many people trained served or now act in important advisory capacities to the Government.

TABLE 5

SOME CLASSIC TEXTBOOKS BY LNS&E STAFF

Science and Engineering of Nuclear Power, R.D. Evans, B.T. Feld, C. Goodman, M. Deutsch, F. Friedman, et al.

Theoretical Nuclear Physics, J.M. Blatt and V.F. Weisskopf.

Atomic Nucleus, R.D. Evans.

Statistical Mechanics, K. Huang.

Methods of Theoretical Physics, P.M. Morse and H. Feshbach.

Organic Chemistry: Methane to Macromolecules, J.D. Roberts, et al.

Basic Principles of Organic Chemistry, J.D. Roberts and M.C. Caserio.

Classical Electrodynamics, J.D. Jackson.

Theoretical Nuclear Physics, H. Feshbach and A. deShalit.

Models of Elementary Particles, B.T. Feld.

Optics, B.B. Rossi.

High Energy Particles, B.B. Rossi.

Ionization Chambers and Counters, B.B. Rossi and H. Staub.

TABLE 6

CAREER CHOICES OF LNS&E GROUPS

Universities	Government	Industry	Unaccounted For
	Theoretical Group		
24 Professors in 19 Universities	3 in 3 Laboratories	7 in 6 Companies	12
	Cosmic Ray Group		
23 Professors in 15 Universities	7 in 6 Laboratories	7 in 7 Companies	8
	Radioactive Group		
14 Professors in 10 Universities	17 in 10 Laboratories	12 in 12 Companies	16
	Synchrotron Group		
6 Professors in 6 Universities	3 in 2 Laboratories	8 in 8 Companies	27
	Elemental Particle Scattering[*]		
[illegible] Professors in 2 Universities	5 in 4 Laboratories	8 in 8 Companies	4
	High Voltage Research		
3 Professors in 3 Universities	4 in 4 Laboratories	13 in 13 Companies	24
	Nuclear Cross Sec[illegible]		
4 Professors in 3 Universities	—	4 in 4 Companies	3
	Neutron and Gamma Ray Shielding		
3 Professors in 3 Universities	2 in 2 Laboratories	3 in 3 Companies	6
	Three Chemistry Groups		
32 Professors in 24 Universities	16 in 11 Laboratories	44 in 34 Companies	26

[*]Some new Groups came into being after the 1949 organization shown in Figure 3.

D. NATIONAL DEFENSE POSTURE

One would normally picture a laboratory performing basic research in nuclear science and engineering to be far removed from the practical problems of national defense. Yet, we have already seen in the previous section on Whirlwind that the successful SAGE national air defense system received its initial push through the initiative of Professor George E. Valley, who was working in the Cosmic Ray Group at LNS&E.

And that is not the only instance of national defense benefiting from the basic ONR postulate that continuing Navy access to outstanding basic research scientists and engineers would inevitably evolve new and improved defense measures. As noted in Figure 3, there were a number of important developments.

First, the LNS&E leadership in knowledge of nuclear power reactors represented by the previously mentioned first textbook and course on reactors was soon to have great impact on the Navy ship propulsion program. Professor Clark Goodman participated in an April 5-6, 1948 meeting of the Underseas Warfare Committee of the National Research Council on nuclear propulsion of submarines and other ships. Attending the same conference were Admirals W.S. Parsons and Earl W. Mills of the Navy Department, Lewis L. Strauss of the Atomic Energy Commission, and many other prominent people. Discussions at this meeting had a major influence, according to Mills, on the establishment of the nuclear powered submarine as a high priority development project. The Navy immediately arranged to send about 20 officers to attend the nuclear reactor course at M.I.T. being taught by C. Goodman, et al. Thus, LNS&E played a key initiating role in the nuclear powered submarine project so successfully implemented by Captain (later Admiral) Hyman G. Rickover. This effort constituted a vital contribution to the U.S. first line of defense.

Second, in late 1949 it became apparent that the increased performance and number of Soviet submarines represented a threat to national security. A visit to M.I.T. by Mervin J. Kelly and James B. Fisk of the Bell Laboratories and E.R. Piore of ONR triggered active discussion of the subject. Professors Jerrold R. Zacharias, Albert G. Hill, Jerome B. Wiesner, Lloyd Berkner, and others formulated a proposal for a broad study of the protection of overseas transportation. An audience was obtained in January 1950 with the Chief of Naval Operations, and he immediately agreed to fund a study, named Project Hartwell. Since LNS&E could provide facilities, it was possible to move rapidly in organizing a classified project with Jerrold Zacharias as Director and Malcolm M. Hubbard of LNS&E as Executive Officer, and ONR as the funding agency. Recruitment of expert personnel from university and industry (particularly the Bell Laboratories) laboratories began for a summer study to be initiated in June 1950 with a series of Navy briefings. Over 30 full-time and many part-time top scientists and engineers worked the entire summer, submitting a final report September 21, 1950. It contained many suggestions of great importance to the security of overseas transport including:

- The use of helicopters in antisubmarine warfare equipped with sonnobuoys and antisubmarine weapons.

- The use of low frequency for directional listening arrays for submarine detection (Lofar).

- Antisubmarine submarines.

- Secure short-range communication.

- Torpedo detection arrays.

- High-speed, over 19 knots, merchant ships (Mariner class).

- Command and control network (Sosus).

And, third, in 1954 a similar study, Project Lamplight, was established under the Lincoln Laboratory to review the status of submarine detection systems. President James R. Killian headed the project and Jerrold R. Zacharias was Technical Director.

Among those who worked on various aspects of these studies for the Defense Department were four men who later became Science Advisors to U.S. Presidents: James R. Killian, Jerome B. Wiesner, Edward E. David, Jr., and H. Guyford Stever.

Another contribution to national defense was the development of a frequency standard based on a cesium atomic clock by Jerrold R. Zacharias and several members of the Molecular Beam Laboratory, including John G. King, J. Hates, R.D. Haun, B. Gittelman, R. Daly, et al. The atomic clock found important uses in establishing worldwide time standards, military communications and navigation, timing radio astronomy observations, and tests of special and general relativity.

E. STIMULUS TO INDUSTRY

Several companies were founded by persons trained in LNS&E, or became viable as a result of development made within LNS&E.

Tracerlab, Inc. was formed in 1946 by William E. Barbour, Jr., based initially upon the automatic scaler developed by Wendell C. Peacock in the Radioactivity Group of LNS&E. Tracerlab also produced other instruments and tagged isotopes and performed important work for defense intelligence. The company grew to an annual sales volume of about $15 million by 1955. At that time, a number of staff members became involved in forming several additional companies, and Tracerlab ended up as part of the Laboratory for Electronics.

High Voltage Engineering Corporation was formed in 1946. The success of the company was highly dependent on an order for a machine from LNS&E, on the knowledge developed by LNS&E in building the largest Van de Graff generator of the day, and on the transfer of key people from LNS&E to High Voltage Engineering. The company's 1980 sales exceeded $85 million.

Martin Annis, who received his doctorate based on work performed in LNS&E, established American Science and Engineering, Inc., in 1958. One of its purposes was to perform basic research, and Annis kept his Cambridge firm in close touch with LNS&E through having various professors on his Board of Directors, including Bruno B. Rossi, Herman Feshbach and George W. Clark. Annis attributes to LNS&E an important role in the entry of the company into x-ray astronomy, x-ray scanners for airport security, computerized tomography and remote readout systems for meter reading. The company has also worked for the Department of Defense on nuclear weapons effects at high altitude. Annual sales now exceed $25 million.

As an outgrowth of his earlier work on upgrading high school science curricula, Jerrold R. Zacharias formed Educational Services, Inc., in 1958. The company became the Educational Development Center, Inc., in 1967. It has performed extensive services in planning and implementing the formation of colleges and institutions of higher learning in many nations. Work is also carried out on health education and family studies. The annual services amount to approximately $12 million, a major portion of which is funded by agencies of the Federal Government.

There is still another form of industrial stimulus for which basic research in physics, such as carried out in laboratories such as LNS&E, is responsible — the insatiable appetite of the physicist for something bigger or smaller or better. An example of this is the particle accelerator. Professor M.S. Livingston co-invented the strong-focusing principle which allowed larger and larger accelerator construction because the magnets required much less iron. But now electrical energy is becoming so expensive the next forward step demands the use of low-temperature superconducting magnet windings. This thrust places new demands upon industrial suppliers which will, no doubt, lead to practical applications totally unforeseen at this time. A study by the European Center for Nuclear Research (CERN)[1] of 127 companies which supplied special equipment to CERN confirms the beneficial effects of such contracts on individual corporate economic and quality performance.

Finally, there have been contributions to the defense industry through the many suggestions emanating from LNS&E studies for new detection, weapons, communication and transportation systems. The full impact of LNS&E 1946-58 research results on U.S. industry will not be known for some years.

1. "A Study of Economic Utility Resulting From CERN Contracts," H. Schmied, CERN 75-5, June 1975

THE WORK OF PROFESSOR MORRIS COHEN AND STUDENTS

A. INTRODUCTION

The metallurgy of steel was of obvious interest to ONR in 1947 because of the lack of basic understanding of the structure and resulting properties of this complex material upon which the Navy was and is so dependent.

Therefore, when Professor Morris Cohen submitted a proposal in 1947 aimed at beginning to unravel some of the mysteries in the hardening of steel, it provoked immediate interest. Cohen was known to ONR materials scientists as a man of great promise. While then only 34 years old, he already had been awarded the Howe Medal of the American Society for Metals in 1945 and was promoted to the rank of full professor in the Metallurgy Department of M.I.T. in 1946. His proposal was accepted with great enthusiasm as Cohen and his fellow scientists made M.I.T. a leading candidate to become a world center of excellence in metallurgical research. Thus began a program which has fulfilled expectations and produced so many interesting findings that it still continues to be funded today — in fact, it is the longest continuous ONR individual contract.

The titles of the first and succeeding ONR programs under the supervision of Cohen are:

1947-1948: "Effect of Strain on the Hardening of Steel"

1948-1949: "Effect of Strain on the Hardening of Steel" and "Quantitative Measurement of Retained Austenite"

1949-1952: "Effect of Strain on the Hardening of Steel" and "Relation Between Retained Austenite and Mechanical Properties of Steel"

1952-1955: "Effect of Strain on the Martensitic Transformation" and "Relation Between Retained Austenite and Mechanical Properties of Steel"

1955-1982: "Relationships Between Metallurgical Structure and Properties"

Over this span of time, the total investment by ONR amounted to $1,625,610. A continuing succession of 36 students have submitted theses, and four additional students are still at work.

The returns from the ONR investment in Professor Cohen and associates and student fall into the following main categories:

- New knowledge created
- Training of people
- National materials posture

These are outlined in Figure 4 and described in more detail in the text.

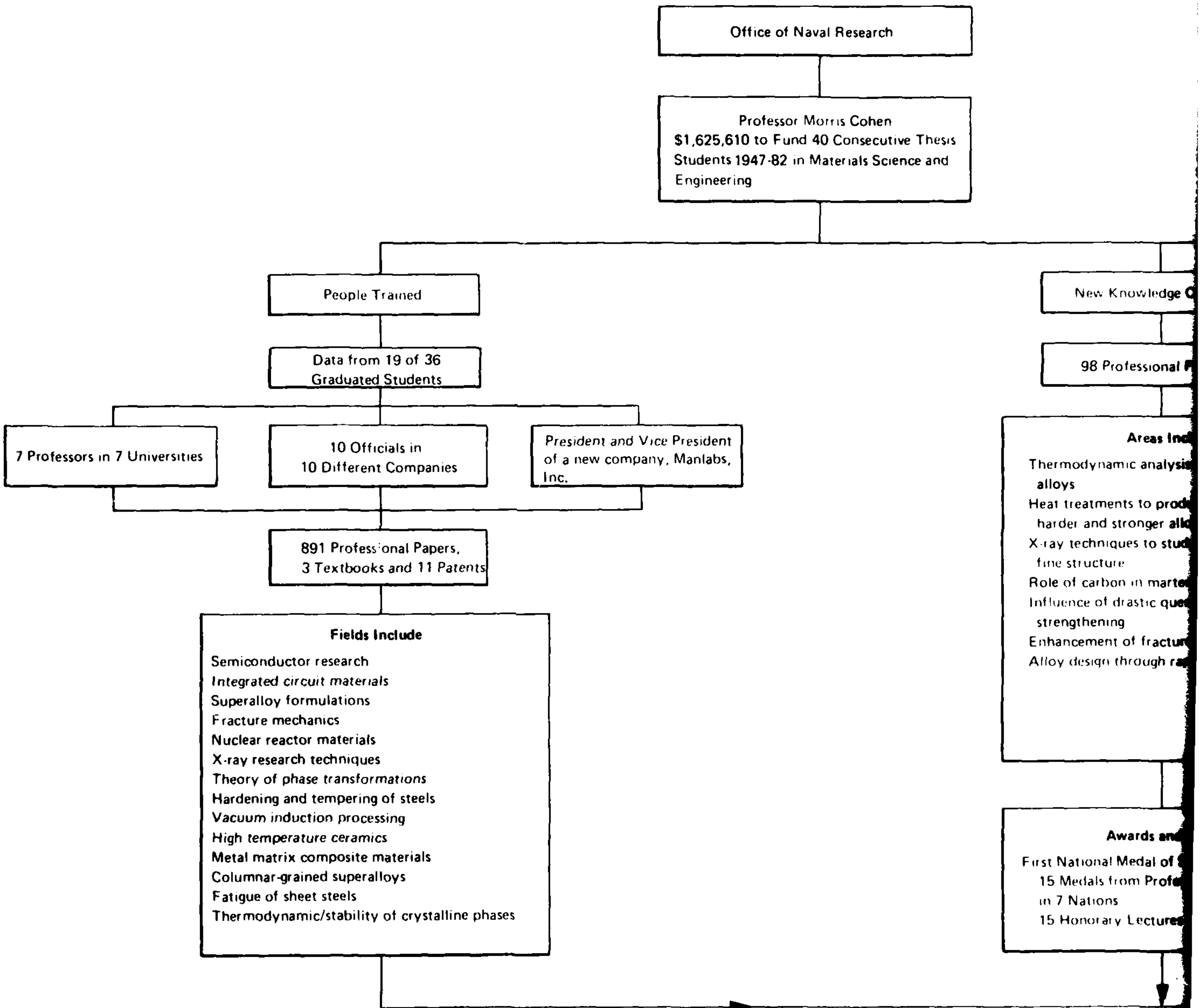
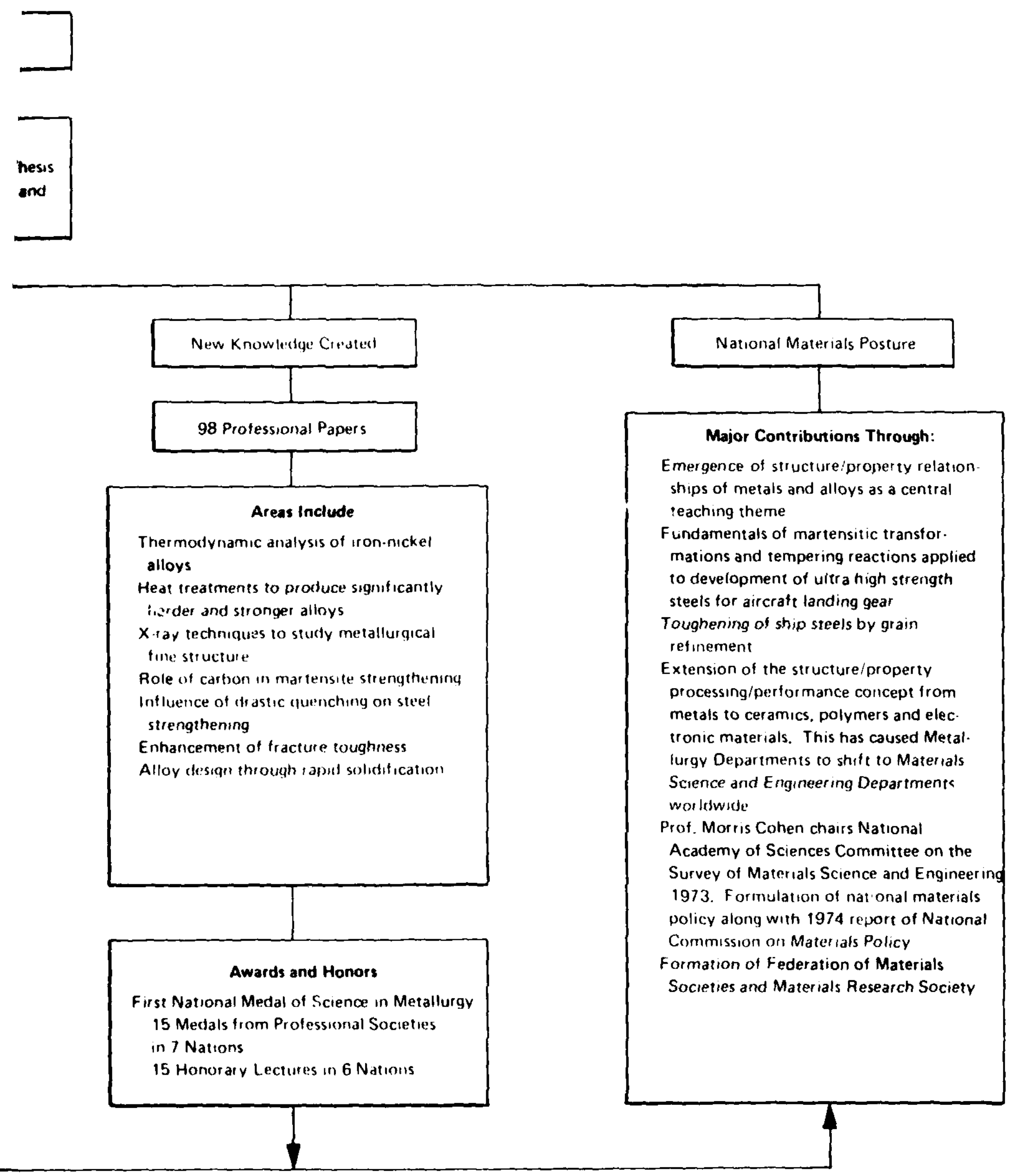


FIGURE 4 OVERVIEW OF CONTRIBUTIONS OF PROFESSOR MORRIS COHEN AND ONR FUNDED STUDENTS



F PROFESSOR MORRIS COHEN

B. NEW KNOWLEDGE CREATED

As a direct consequence of the ONR program of research, Cohen and associates (Professors B.L. Averbach, R. Kaplow and S.B. Vander Sande) and students have published 98 papers in various professional journals.

During the 35 years of research work, Cohen and associates prepared end-of-year letter reports of the highlights. A few key quotes from these reports (Table 7) summarize the new knowledge created.

The fact that the materials community, worldwide, valued these contributions highly is amply demonstrated by the honors emanating from the work (Table 8). In addition, Professor Cohen has become one of the few persons elected to both the National Academy of Sciences and the National Academy of Engineering.

Of course, this represents only the beginning of the generation of new knowledge, as the students trained here have, themselves, already published over 800 additional papers in professional journals.

C. TRAINING OF PEOPLE

Letters were sent to the 36 graduate students of Cohen who have completed their thesis work funded by ONR and who have graduated from M.I.T. The following information was requested:

Current bibliographical data

List of publications

Statement of the impact, if any, of M.I.T. study on your career

Statement of the impact of your work on your technical field or on society in general

An analysis of the replies received from 19 of the 36 students (some addresses proved incorrect) reveals some fascinating information.

The bibliographical data show that approximately two-thirds of the respondents have joined a variety of industrial companies in the ferrous, nonferrous, automotive, and manufacturing industry segments in research and executive positions. One has established, with his brother, a new company, Manlabs, Inc., which performs materials research at the level of about $1.5 million per year. One-third have established academic careers as professors in seven universities. This information confirms previously presented Whirlwind and LNS&E data which show that ONR-trained personnel have indeed migrated to many companies and universities in diverse geographical locations and thus succeeded importantly in spreading the methods and knowledge generated at M.I.T.

TABLE 7

NEW METALLURGICAL KNOWLEDGE CREATED BY COHEN AND ONR STUDENTS

Based on the martensitic reaction and its reversal in the iron-nickel system, a general thermodynamic analysis of iron-nickel alloys in the solid state has been evolved.

Considerable progress has been made toward understanding the thermodynamic driving force and mechanism of martensitic transformations.

Data on iron-nickel-carbon alloys indicate that a significantly harder and stronger alloy results if austenite is stabilized against further martensitic transformation by repeating cooling and heating cycles.

X-ray techniques have been developed to study the influence of metallurgical fine structure, such as grain boundaries, subboundaries, dislocation arrays and interstitial solute atoms on mechanical properties.

The reverse martensitic transformation regenerates the parent phase, austenite, in a highly distorted form, leading to a type of internal work hardening, and increasing the austenite yield strength by 2.5 times.

The high strength of freshly quenched iron-carbon martensites is due primarily to solid-solution hardening by the interstitial carbon atoms. Internal twinning and high dislocation densities are only second-order strengthening mechanisms in high-strength martensites.

Mössbauer studies indicate iron-carbon martensites are stronger than iron-nitrogen martensites because of a strong covalent-type bond between carbon and nearest-neighbor iron atoms.

It has been established that the remarkable strengthening of iron by carbon is attributable mainly to the distortion of the iron lattice by the carbon atoms rather than to any electronic or chemical interactions.

By means of drastic quenching (splat cooling), the highest-carbon martensite to date has been attained, thus extending the potential level of strengthening in steel. New experimental evidence indicates that nucleation sites generated by the martensitic transformation itself are more important in governing the overall reaction rate than nucleation sites in the austenitic parent phase.

The strength-differential effect between compressive and tensile yield strengths of martensite is now sufficiently well established to try to take advantage of the extra compressive strength for engineering structures.

Fracture studies indicate that strain-induced nucleation in the plastic zone at the top of an advancing crack tends to arrest the crack and thereby enhances the fracture toughness.

A new approach to alloy design is evolving in this program based on the pinning of grain boundaries by finely dispersed second-phase precipitates which are dissolved in the liquid state and precipitated in the solid state by virtue of rapid solidification.

TABLE 8

HONORS EMANATING FROM ONR PROGRAMS OF METALLURGICAL RESEARCH AT M.I.T. UNDER M. COHEN SUPERVISION 1947-1981

Awards Related to Research Programs

Henry Marion Howe Medal of ASM	1949
Institute of Metals Award of AIME	1950
Mathewson Gold Medal of AIME	1954
Clamer Medal of the Franklin Institute	1959
Gold Medal of ASM	1968
Gold Medal of Japan Institute of Metals	1970
La Medaille Pierre Chevenard of the Societe Francaise	1971
Proctor Prize of the Research Society of North America	1976
Albert Sauveur Achievement Award of ASM	1977
National Medal of Science	1977
Honorary Degree, Doctor of Technology, Royal Institute of Technology, Sweden	1977
Joseph R. Villela Award of ASTM	1979
Honorary Degree, D.Sc. in Tech., Israel Institute of Technology	1979
Honorary Professorship, Beijing University of Iron and Steel Technology, China	1980
Honorary Professorship, Beijing Institute of Aeronautics and Astronautics, China	1980
Hobart M. Kraner Award, American Ceramic Society	1981

Honorary Lectures on Research Programs

Edward DeMille Campbell Lecture of ASM	1948
Institute of Metals Lecture of AIME	1957
Coleman Lecture of the Franklin Institute	1960
Houdremont Lecture of the Intl. Inst. of Welding	1961
Howe Memorial Lecture of AIME	1962
Hatfield Memorial Lecture of the British Iron and Steel Institute	1962
Opening Lecture, Intl. Conf. on the Strength of Metals and Alloys	1967
Japan Inst. of Metals Lecture	1970
Opening Lecture, Intl. Conf. on the Science and Technology of Iron and Steel	1970
T. A. Read Memorial Lecture, University of Illinois	1976
Honorary Member's Lecture, Japan Inst. of Metals	1978
Honorary Guest Lecture, Korean Inst. of Metals	1979
Indian National Science Academy, New Delhi	1980
Nelson W. Taylor Lecture, Pennsylvania State University	1980
Keynote Lecture, International Conference on Solid-Solid Phase Transformations, Carnegie-Mellon University	1981

It was rather straightforward for the respondents to list their publications and patents. As mentioned earlier, the ONR work under Cohen resulted in 98 publications. It is most revealing to discover that with only 19 of the 36 Cohen students reporting, some 891 professional papers have been published, over 11 patents have been issued, and three textbooks written by them. These large numbers do not, of course, include numerous company confidential reports prepared by the majority of students who have chosen industrial careers. This is still another powerful example of the chain reaction which occurs in the generation of knowledge from professor to students. Furthermore, we have not, in this particular study, included the next generation contributions made by the persons trained in turn by the first generation of students.

Answers regarding the impact of M.I.T. graduate education on future individual careers are naturally somewhat subjective. They generally gave M.I.T major credit along three lines. First, almost everyone stated that the training received in research methods had formed a solid basis for subsequent careers in performing and managing research, including attitude, approach, self-confidence and perseverance. Second, while some of the respondents continued to work in lines closely related to their theses, many migrated importantly into diverse new fields, as indicated in Table 9, based on their confidence to perform. And, third, several replied that a substantial benefit was the interaction with bright fellow graduate students and the reputation gained from having attended M.I.T. To keep things in perspective, one respondent said he thought a doctorate from any other good university would have stood him in equal stead.

TABLE 9

SOME INDIVIDUAL CONTRIBUTIONS OF COHEN STUDENTS

Development of fundamental information on deformation processes in crystals through experiments on bulk perfect crystals of germanium and silicon.

Development of information on the control of oxygen and its precipitation behavior in silicon which is crucial to the fabrication of integrated circuits.

Produced through X-ray topography some of the first images of section patterns of stacking faults in crystals.

Development of a basic model for the vacuum induction refining process.

Invention of Udimet 700 and contributions to the development of many other superalloys.

Developments in the field of fracture mechanics, particularly unstable failure of structural steels.

Improved metal forming equipment design to increase the productivity of capital.

The role of molybdenum in superalloys.

Breeder reactor materials development leading to extending core life.

Significant contributions to the principles of heat transfer of steel.

Responsible for analysis of properties, performance, and post-irradiation examination of nuclear fuels and materials to improve availability of nuclear power plants.

Application of computer techniques for phase diagram calculations to real systems has been utilized to provide practical information concerning the processing and performance of diverse materials.

Theory and mechanisms of phase transformations; hardening and tempering of steels. Development of high-precision X-ray diffraction techniques. Strengthening mechanisms.

The application of the metallurgical view to the microstructural design of ceramic materials for high temperature gas turbine engines and the development of metal matrix composite materials.

Writing to bridge the gap of misunderstanding between technology and the layman.

Attempting to show the status of metallurgy as a discipline and as a profession and to show that metallurgists have an important role to play in the development of industry in Australia.

Successful contribution to use of columnar-grained alloys in aircraft gas turbine engines.

Significant contributions to the characterization and utilization of the fatigue properties of sheet steels.

The request for information on the technical impact of the work of Cohen students after graduation produced a large variety of answers which are summarized in Table 9. A glance at this very incomplete list of technical contributions shows work ranging from very fundamental solid state research to the very practical, such as improved superalloys for commercial and military jet engines. The wide range of interests which have emerged is certainly unpredictable.

D. NATIONAL MATERIALS POSTURE

It is now important to try to analyze what has been the effect of all this work. The short answer is that there has been a complete revolution over the past 35 years in the science of materials, and this work has been central to that revolution.

Before we trace briefly some of the events of the revolution, it is important to understand that Professor Cohen had over these 35 years, in addition to the 40 ONR-funded students, some 115 other thesis students now spread around the nation, many of whom are world famous in their chosen careers. (Note: That story will be told later by Cohen.) While no one person could be said to be responsible for the explosive growth in materials science, it is apparent that the early work on the martensitic transformation in the hardening of steel had great influence on initiating the revolution. And the continued ONR funding of Cohen and his associates and students fanned the flames, as was recognized in the citation for the first National Medal of Science in metallurgy to Cohen in 1977. Now back to the history.

The emergence of the structure/property relationships of metals and alloys as a central theme in physical metallurgy occurred during the early 1950's. This carried over into the teaching core of physical metallurgy nationwide. Emphasis was placed on thermodynamics, kinetics and mechanics.

At this point, Cohen — and probably others — began to see this fundamental physical metallurgy had to be tied intimately into processing and service performance to obtain an effective model for the overall field of metallurgy. This helped establish a countercurrent flow of information between the scientists and users of metals. Practical outcomes began to appear in the late 1950's. For example, the fundamentals of martensitic and tempering reactions in ferrous alloys were the basis for the development of ultra-high-strength steel for aircraft landing gear. And research on ship steel failures, funded by the Navy, resulted in tougher steels through grain refinement.

Next, the structure/property/processing/performance concept for metals was extended to ceramics, polymers and electronic materials. This led to the emergence of materials science and engineering as a multidiscipline, and the renaming of metallurgy departments around the world to departments of materials science and engineering. They began awarding degrees in materials science and materials engineering, as well as in metallurgy, ceramics and polymerics. Proof of the logic of this interplay is the recent advance in toughening of brittle ceramics by deformation-induced martensitic transformations.

Paralleling the revolution in materials science, was the recognition that materials, along with energy, food and the environment, are basic resources of mankind. In 1970, Congress formed a National Commission on Materials Policy to develop a national materials policy. In June 1973, the Commission issued a report making recommendations on the supply, use, recovery and disposal of materials. Also in 1970, the National Academy of Sciences appointed a Committee on the Survey of Materials Science and Engineering (COSMAT). Professor Cohen was made chairman of that committee and some of his students were among those contributing to the Committee's 1974 report, "Materials and Man's Needs." That report introduced the concept of the total materials cycle and dealt with materials availability, materials in national security, materials in the economy, and materials in world trade and in international relations.

Out of these reports grew a new emphasis on materials processing for enhancing productivity and extending structure/property relationships. Once again, ONR-funded work under Cohen on rapid solidification processing is leading to higher strength alloys and new methods of alloy design.

The recent emphasis on materials has led to the formation of several new organizations. Within the Federal Government, an Inter-Agency Committee on Materials (COMAT) has been formed. Also newly created are two professional organizations — the Federation of Materials Societies and the Materials Research Society. Finally, there is legislation in Congress related to national materials policy.

Thus, it is abundantly clear that our national materials posture has strengthened markedly over the past 35 years and that ONR funding at M.I.T. has played a key role in accelerating this achievement. Such strengthening has, of course, contributed importantly to the defense as well as the civilian portion of our national materials position.

APPENDIX A
PERSONS INTERVIEWED OR CONTACTED

Project Whirlwind

Jay W. Forrester, Professor, M.I.T. (253-1571)
Robert R. Everett, President, MITRE Corporation (271-2000)
Kenneth E. McVicar, Vice President, MITRE Corporation
Jack Jacobs, Vice President, MITRE Corporation
John A. O'Brien, Executive, MITRE Corporation
Hugh W. Boyd, Executive, Raytheon Corporation (Ret.) (438-0162)
Norman H. Taylor, President, Corporate-Tech Planning, Inc. (890-2600)
Charles W. Adams, President, Key Data (Ret.) (862-4994)
Norman S. Zimbel, Senior Staff, Arthur D. Little, Inc. (864-5770)
Jack Arnow, President, Interactive Data (Ret.) (862-6294)
Kenneth H. Olsen, President, Digital Equipment Corporation (897-5111)
Douglas T. Ross, President, Sof Tech, Inc. (890-6900)
Fernando J. Corbato, Professor, M.I.T. (253-6001)
Philip M. Morse, Professor, M.I.T., Emeritus (253-3602)
Nathaniel Rochester, Executive, IBM
Emmanuel R. Piore, Vice President, IBM (Ret.)
Robert J. Horn, Jr., Patent Lawyer (227-6300)
Henry W. Fitzpatrick, Assistant Director, Lincoln Laboratory (862-5500)
Karl L. Wildes, Professor, M.I.T., Emeritus (253-4616)
Gwen Bell, Director, Digital Equipment Corporation Museum (467-4036)
Lewis M. Branscomb, Vice President, IBM (914-765-6466)
Jerrier A. Haddad, Vice President, IBM (914-686-4460)
Frederic G. Withington, Vice President, Arthur D. Little, Inc. (864-5770)
Beth Parkhurst, Digital Equipment Corporation Museum (467-4036)

Laboratory for Nuclear Science and Engineering

Jerrold R. Zacharias, Professor, M.I.T., Emeritus (253-7772)
Victor F. Weisskopf, Professor, M.I.T. (253-4887)
Herman Feshbach, Professor, M.I.T. (253-4801)
Robley D. Evans, Professor, M.I.T., Emeritus (602-948-3060)
Bruno B. Rossi, Professor, M.I.T., Emeritus (253-4283)
Peter T. Demos, Professor, M.I.T. (253-7592)
Frederic J. Eppling, Staff, LNS&E, M.I.T. (253-2395)
Martin Deutsch, Professor, M.I.T. (253-4289)
Jerome Friedman, Director, LNS&E, M.I.T. (253-2361)
George E. Valley, Professor, M.I.T., Emeritus (369-5692)
Charles Weiner, Professor, Archivist, M.I.T.

Note: All telephone numbers are Area Code 617 unless otherwise recorded.

APPENDIX A (Continued)

LNS&E (cont.)

Helen W. Slotkin, Institute Archivist, M.I.T.
Deborah A. Cozort, Archives, M.I.T.
Spencer Weart, American Institute of Physics, New York
Martin Annis, President, American Science & Engineering (868-1600)
Bernard T. Feld, Professor, M.I.T. (253-5090)
Denis M. Robinson, President, High Voltage Corporation (Ret.) (272-1313)
Malcolm M. Hubbard, Former Executive Officer, LNS&E (527-6883)
Costa Maletskos, Consultant (283-2339)
Eric T. Clarke, Vice President, Tech Ops, Inc. (272-2000)
David H. Frisch, Professor, M.I.T. (253-2396)
Louis S. Osborne, Professor, M.I.T. (253-2396)
William W. Buechner, Professor, M.I.T., Emeritus (253-4151)
Norman C. Rasmussen, Professor, M.I.T. (253-3802)
C. Gardner Swain, Professor, M.I.T. (253-1830)
Frederick D. Greene, Professor, M.I.T. (253-1840)
A. Larry Powell, Former Director of Science, ONR, Boston (358-2156)
Irwin A. Pless, Professor, M.I.T. (253-2367)
William E. Barbour, President, Tracerlabs, Consultant (369-9488)
David N. Hume, Professor, M.I.T., Emeritus (253-4507)
John G. King, Professor, M.I.T. (253-4180)
Max Fuchs, National Radio Company (662-7700)
Herbert S. Bridge, Professor, M.I.T. (253-7501)
George W. Clark, Professor, M.I.T. (253-5842)
Ivan A. Getting, President, Aerospace Corporation (Ret.) (213-451-4149)
George Dummer, Vice President, M.I.T. (253-2492)
Patricia S. Moulton, Office of Sponsored Projects, M.I.T. (253-3907)
Catherine E. Distefano, Secretary, LNS&E (253-2362)
Jay Stein, Vice President, American Science & Engineering (868-1600)
Gordon Brownell, Professor, M.I.T. (253-5730)
Lee M. Hunt, Naval Studies Board, NRC (202-334-2000)
Clark Goodman, Professor, University of Houston (Ret.) (714-429-0320)
Albert G. Hill, Chairman, Draper Laboratory, Inc. (258-1000)

Professor Morris Cohen and Students

Morris Cohen, Professor, M.I.T. (253-3324)
Marguerite A. Meyer, Administrative Assistant to Professor Cohen (253-3324)
Laurie Monahan, Secretary, Materials Science & Energy, M.I.T. (253-3324)
Letters and biographies from 19 ex-students
Julius J. Harwood, Ford Motor Company (313-323-0943)
Edward Salkovitz, Office of Naval Research (202-696-4407)

APPENDIX B
LIST OF DECEASED PRINCIPALS

Laboratory for Nuclear Science and Engineering

George R. Harrison, Dean of Science, M.I.T.
Capt. Robert D. Conrad, U.S.N., ORI-ONR
Karl T. Compton, President, M.I.T.
Nathaniel M. Sage, Contract Officer, M.I.T.
John C. Slater, Prof. Physics, M.I.T.
Charles D. Coryell, Prof. Chemistry, M.I.T.
Robert J. Van de Graff, Prof. Physics, M.I.T.
Edwin R. Gilliland, Prof. Chemical Engineering, M.I.T.
Arthur C. Cope, Prof. Chemistry, M.I.T.
Shirley Silverman, Physics, ONR.

Whirlwind

R. Adm. Luis de Florez, Navy Department
William K. Linvill, Prof. Engineering, Stanford University
Patrick Youtz, Lincoln Laboratory, M.I.T.
Harris Fahnestock, Administration, M.I.T.
P. Franklin, Prof. Mathematics, M.I.T.

APPENDIX C
WHIRLWIND PERSONNEL

Later Career Positions Indicated

UNIVERSITY

Jay W. Forrester, Germeshausen Prof., M.I.T.
Edgar Reich, Prof. Mathematics, University of Minnesota
C.H.I. Campling, Prof. Queens University of Canada
J.W. Carr, Prof. Computer and Information Science, University of Pennsylvania
Alex Orden, Prof. Mathematics, University of Chicago
Alan J. Perlis, Prof. Computer Science, Yale
J.S. Rochefort, Prof. Electrical Engineering, Northeastern University
J.J. Gano, Research Staff, M.I.T.
Alfred K. Susskind, Prof. Electrical Engineering, Lehigh University

GOVERNMENT SERVICE

Robert R. Everett, President, the MITRE Corp.
Stephen H. Dodd, Jr., Division Head, Lincoln Laboratory
Alan J. Simmons, Assoc. Leader, Lincoln Laboratory
E.S. Rich, Executive, MITRE (Retired)
D.R. Israel, Executive, Department of Energy, then DOD
Charles A. Zraket, Executive Vice President, MITRE
Kenneth E. McVicar, Vice President, MITRE
John A. O'Brien, Executive, MITRE
W.S. Attridge, Jr., Assoc. Tech. Director, MITRE
R.J. Callahan, MITRE
J.W. Forgie, Staff, Lincoln Laboratory
F.E. Irish, Dpartment Head, MITRE
H.R.J. Grosh, Executive, Bureau of Standards
Nolan T. Jones, Executive, MITRE
H.J. Kirshner, Technical Director, MITRE
A.A. Mathiasen, Staff, Lincoln Laboratory
W.I. Wells, Group Leader, Lincoln Laboratory
Patrick Youtz, Lincoln Laboratory (Deceased)
Jack Jacobs, Vice President, MITRE (Retired)
A.L. Roberts, Vice President, MITRE
R.P. Mayer, MITRE
S.B. Ginsburg, MITRE
J. Ishihara, MITRE
B.E. Morris, Defense Comm. Agency
L.H. Norcott, MITRE
W. Ogden, MITRE
A.M. Werlin, MITRE

APPENDIX C (Continued)

Later Career Positions Indicated

INDUSTRY

Hugh W. Boyd, Executive, Raytheon Corp. (Retired)
David R. Brown, Vice President, Stanford Research Institute
Hubert I. Flomenhoft, Technical Staff, Raytheon, Bedford
William J. Nolan, Designer, Lockheed
C. Robert Wieser, Executive, McDonnell Douglas
Charles A. Prohaska, Senior Chemist, DuPont
Eugene W. Sard, Cutler-Hammer Corp., Melville, New York
Norman H. Taylor, President, Corporate-Tech Planning, Inc.
Gordon M. Lee, Executive, Central Research Labs, Inc.
.L. Best, Digital Equipment Corp.
Norman L. Daggett, Engineer, Interactive Data
G. Hoberg, President, Telecommunications Co., Philadelphia, Pennsylvania
Harry Kenosian, Res. Sel. Hospital, Philadelphia, Pennsylvania
J.T. Gilmore, Jr., Executive, Digital Equipment Corp.
Robert L. Massard, Partner Finntech Corp., Waltham, Massachusetts
Summer, General Dynamics
Charles W. Adams, President, Key Data (Retired)
John M. Salzer, Vice President, Thompson Ramo Woolridge, Consultant
James B. Pickel, Manager, Proc. Instr., Gillette
Norman S. Zimbel, Senior Staff, Arthur D. Little, Inc.
C.L. Corderman, Executive, Medidata Services
Roger L. Sisson, Consultant Math, Inc., Princeton
Jack Arnow, President, Interactive Data (Retired)
William N. Papian, Vice President, consulting company
Kenneth H. Olsen, President, Digital Equipment Corp.
P.R. Bagely, President, Info Tech Inc.
G.R. Briggs, Scientist, RCA Labs
A.J. Cann, Sanders Assoc.
J.W. Craig, Jr., R&D Lab, Sperry
George Economos, Executive, Allen Bradley Company
E.P. Farnsworth, Engineer, New York Telephone Company
C.H. Gaudette, Senior Engineer, IBM
Frank E. Heart, Executive, Bolt, Beranek & Newman
T.S. Greenwood, Design, Bell Laboratories
A. Katz, Systems Director, IBM
J.L. Mitchell, Manager, Westinghouse Electric
N.S. Potter, Executive, Capitol Radio Engineering Institute
B.R. Remis, Staff Engineer, IBM
H.K. Rising, Department Head, Bolt, Beranek & Newman
C.J. Schultz, President, Corp Finen Assoc.

APPENDIX C (continued)

Later Career Positions Indicated

INDUSTRY (continued)

A.V. Shortell, Vice President, Info Dynamic Corp.
F.E. Vinal, Executive, RCA, consultant
R.L. Walquist, Vice President, TRW Systems
M. Florencourt, married Prof. Robert W. Mann, M.I.T.
Herbert D. Benington, Burroughs
E. Blumenthal, Burroughs (Retired)
W.A. Hosier, Sylvania GTE

APPENDIX D
LNS&E PARTICIPANTS 1946-58

Later Career Positions Indicated

Nuclear Inorganic Chemistry Group

UNIVERSITY

C.D. Coryell, M.I.T.
J.W. Irvine, M.I.T.
J.A. Marinsky, St. Un. N.Y.
A.W. Fairhall, U. Wash.
G. Wilkinson, U. Kingdom
C.H. Brubeker, Mich. St.
D.R. Wiles, Carleton U.
R.H. Herber, Rutgers
T.T. Sugihara, Texas A&M
J.M. Alexander, St. U. N.Y.
C.E. Gleit, N.C. State
M. Kaplan, Car. Mellon
R.H. Holm, M.I.T.
J.T. Watson, UCLA

GOVERNMENT

L.E. Glendenin, Argonne
W.B. Lewis, LASL
H.G. Richter, EPA
P. Kafalas, Lincoln
R.C. Sangster, Bureau Standards
D.J. Dietz, LASL
D.H. Freeman, Bureau Standards
A.M. Poskanzer, Lawrence Berkeley

INDUSTRY

R.R. Edwards, Tech. Assoc. Cal.
L.S. Goldring, AMF Inc.
R.A. Brightsen, Westinghouse
R.A. Pike, Norton
D.R. Bentz, Curtis, et al.
R.C. Fix, Interex Corp.
D.G. Harvey, Hittman Assoc.
L. Scala, Westinghouse
E. Rudzitis, St. Illinois

UNACCOUNTED FOR

H.F. Plank
J.H. Baldridge
W.J. Berthel
H.S. Corey
L.L. Altman
R.J.M. Henry
E. Yellin
P. Del Marmol
R.L. Yoest

APPENDIX D (Continued)

Nuclear Organic Chemistry Group

UNIVERSITY

J.D. Roberts, Caltech
W.B. Cornica, U. Cal.
J. Hine, Ohio St.
C.C. Lee, Saskatchewan
E.R. Trumbull, Colgate
C.G. Swain, M.I.T.
J.C. Sheehan, M.I.T.
J.W. McFarland, De Pauw
W.H. Saunders, Rochester
R.F.W. Bader, McMaster
J.L. Schaad, Vanderbilt

GOVERNMENT

J.S. Perkins, Army R.C.

INDUSTRY

M. Burg, DuPont
D.R. Smith, U. Carbide
E.W. Holroyd, E. Kodak
J.A. Yancey, Cabot
R.H. Mazur, G.D. Searle
W.T. Moreheal, Pfizer
W. Sheppard, DuPont
H.E. Simmons, DuPont
V.P. Kreiter, Roswell Park
G.R. Coraor, DuPont
R.N. Griffin, G.E.
A. MacLachlan, DuPont
R.A. Wiles, Allied Chemical

UNACCOUNTED FOR

K.D. Bair
A. Carlsmith
E.F. Cox
A.W. Ford
E.C. Stivers
J.F. Renner
P.M. Zanet
M. Alan
B.E. Pegues

APPENDIX D (Continued)

Chemistry Fission Products Group

UNIVERSITY

D.N. Hume, M.I.T.
L.B. Rogers, Georgia
J.T. Benedict, F. Dickinson
C. Schumb, M.I.T.
S.G. Simpson, M.I.T.
W.C. Purdy, U. Md.
D.M. Hercules, Georgia
W.E. Ohnesorge, Lehigh
W.H. Reinmuth, Columbia

GOVERNMENT

G.W. Leonard, N. Weapons C.
C. Merritt, Army, Natick
M.E. Smith, LASL
J.F. Forstner, SRL
L. Newman, Brookhaven
H.J. Keily, Merrell

INDUSTRY

N.F. LeBlanc, Hercules
J.T. Byrne, Monsanto
R.F. Goddu, Hercules
S.S. Lord, DuPont
H. Fay, U. Carbide
K.W. Gardiner, SRI
H.M. Hershenson, P&W
C.C. Peatie, T.I.
M.A. De Sesa, NL Ind.
J.T. Funkhouser, ADL
E.P. Przybylowicz, E. Kodak
R.U. Robinson, Abbot
R.C. De Geiso, DuPont
J.W. Collat, ACS
T.L. Maple, Contractor
R.F. Breese, R.R. Res. Ctr.
E.A. Burns, TRW Sys.
E.J. Forman, Polaroid
E.A. Heintz, Airco Speer
C.F. Morrison, Valley Lab.
D.L. Maricle, Zito

UNACCOUNTED FOR

G.B.C. Cave
A.B.H. Lauzeche
S.T. Shiang
P.W. Comstock
R. Frank
A.L. Hanson
A.L. Underwood
J.K. Lee

APPENDIX D (Continued)

Cosmic Ray Group

UNIVERSITY

B.B. Rossi, M.I.T.
G.E. Valley, M.I.T.
W.A. Bowers, N. Carolina
H.S. Bridge, M.I.T.
R.T. Hulsizer, M.I.T.
M.L. Sands, U. Calif.
R.W. Thompson, Chicago
R.W. Williams, U. Wash.
W.E. Hazen, U. Mich.
O. Piccioni, U. Calif.
W.L. Kraushaar, U. Wisc.
G. Ascoli, U. Ill.
H.W.J. Courant, U. Minn.
C.P. Leavitt, U. N. Mex.
G.W. Clark, M.I.T.
H.E. De Staebler, Stanford
E.B. Harris, M.I.T.
S. Olbert, M.I.T.
A. Persner, JHU
F. Scherb, U. Wisc.
J.S. Strickland, M.I.T.
G. Valley, M.I.T.
H.V.D. Bradt, M.I.T.
J.A. Earl, Maryland

GOVERNMENT

L.M. Spetner, APL
G. De Saussure, ORNL
D. Willard, Army
R.H. Rediker, Lincoln
R.W. Safford, MITRE
E.A. Boldt, NASA
A. Brenner, Nat. Acc. L.
T. Cline, NASA

INDUSTRY

R.D. Sard, Cutler-Hammer
A.S. Jerrens, Hughes
L. Altman, Bell
M.A. Clark, Aerospace
D.A. Hill, TRW
G. Sandri, Aero Res. Assoc.
J.S. Strickland, Educ. Dev. Ctr.

UNACCOUNTED FOR

C.Y. Chao
R.J. Davisson
B.P. Gregory
J.H. Tinlot
J.H. Vilain
R. D'Arcy
Y. Pal
R. Stora

APPENDIX D (Continued)

Elementary Particle Scattering Group

UNIVERSITY

B.T. Feld, M.I.T.
D.H. Frisch, M.I.T.
L.S. Osborne, M.I.T.
P.T. Demos, M.I.T.
E.J. Winhold, Rensselaer
C.P. Sargent, M.I.T.

GOVERNMENT

R.J. Debs, NASA
J.K. Beling, DDRE
I.L. Lebow, Lincoln
M. Labitt, Lincoln
J.E. Snyder, Navy

INDUSTRY

D.I. Cooper, Cooper, Inc.
M. Annis, AS&E
C.L. Storrs, Comb. Eng.
A. Vash, Damon Inc.
G. Pugh, Gen. Res.
J.L. Burkhardt, A. Sci. Assoc.
F.R. Paolini, Philips Elec.
W. Rankin, Westinghouse

UNACCOUNTED FOR

C.J. Strumski
R.L. Zimmerman
H. Gelernter
P. Rose

APPENDIX D (Continued)

High Voltage Research

UNIVERSITY

J.G. Trump, M.I.T.
C.C. Reynolds, Worcester
H.C. Bourne, Rice

GOVERNMENT

R.B. Marston, NASA
R.A. Jalbert, LASL
C.L. Mc Clelland, State
H. Mark, Secretary, U.S. Air Force

INDUSTRY

C.H. Goldie, H.V. Engrg.
L. Hershoff, IBM
Ge Y. Chao, Wang
R. Scott, Canada Inst.
A. Kusko, A. Kusko, Inc.
J.G. Mann, Duke Power
J.E. Taft, Honeywell
R.M. Morris, NRC Canada
E.W. Webster, MGH
J.H. Anson, Hospital Data
E.F. Buckley, Em & Cum Ind.
G.T. Paulissen, Shell Dev.
L.R. McIntosh, High Voltage

UNACCOUNTED FOR

R.W. Cloud
R. Lamphere
F.J. Rink
J. Danfort
W.C. Schumb
K.A. Wright
C.B. Sharp
B.P. Gregory
J.W. Lathrop
A.M. Clarke
E.E. Gardner
J.E. Nelson
W.W. Evans
E.P. Hanson
J.C. Nygard
R.G. Crook
E.E. Hand
W.S. Moos
S.F. Philip
R.C. Granke
H.P. Weiss
J.C. Overley

APPENDIX D (Continued)

Nuclear Cross Sections Group

UNIVERSITY

R.J. Van de Graff, M.I.T.
W.W. Buechner, M.I.T.
I. Halpern, U. Wash.
E.F. Turner, Wash. & Lee

INDUSTRY

W.J. Ozeroff, McD. Douglas
H.A. Watson, Bell
W.J. Fader, U. Aircraft
S.F. Zimmerman, IBM

UNACCOUNTED FOR

A. Sperduto
J.W. Haffner
R. Sharp

Neutron and Gamma Ray Shielding Group

UNIVERSITY

C. Goodman, Houston
C.B. Sharpe, Michigan
C.W. Tittle, So. Methodist
E.L. Secrest, TCU

GOVERNMENT

P.L. Sagalyn, Army, Wtn.
V.V. Verbinski, ORNL

INDUSTRY

H.B. Moore, Williams Res. C.
C.H. Brumley, Bausch & L.
G.T. Parish, ADL

UNACCOUNTED FOR

A.C. Rand, Jr.
R.S. Misner
I.E. Slawson
J. Sterling
E.C. Farmer
W.M. Preston

APPENDIX D (Continued)

Radioactivity Group

UNIVERSITY

R.D. Evans, M.I.T.
M. Deutsch, M.I.T.
A.E. Miller, Princeton
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APPENDIX D (Continued)

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