IDA

INSTITUTE FOR DEFENSE ANALYSES

Science and Technology in Development Environments

Findings and Observations for the Missile Defense Agency from Commercial Industry and Defense Programs

Richard Van Atta, Project Director
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Andrew Hull
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Michael Lippitz

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PREFACE

The Missile Defense Agency (MDA) tasked IDA to study and assess management methods and organizational structures that have proved successful in the development of technologies, with an emphasis on the roles of longer term science and technology (S&T) work and radical innovation in support of ongoing systems development. To do so, this report reviews and analyzes the experiences of several (1) public organizations that undertook large-scale systems developments and (2) large private companies that have been consistently technically innovative. This provides the groundwork for consideration of specific management and organizational options for MDA.

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I. INTRODUCTION

A. TASK

On 2 January 2002 the Secretary of Defense signed a memorandum creating the Missile Defense Agency (MDA) to meet four top priorities:

- To defend the United States, deployed forces, allies, and friends from ballistic missile attack.
- To employ a Ballistic Missile Defense System (BMDS) that layers defenses to intercept missiles in all phases of their flight (i.e., boost, midcourse, and terminal) against all ranges of threats.
- To enable the services to field elements of the overall BMDS as soon as practicable.
- To develop and test technologies; use prototype and test assets to provide early capability, if necessary; and improve the effectiveness of deployed capability by inserting new technologies as they become available or when the threat warrants an accelerated capability.[1]

The action incorporated projects that had resided in the Ballistic Missile Defense Office, the Air Force, and the Navy into a single agency. It also provided new and untested management freedom; for example, the memorandum stated, “The current Service missile defense Operational Requirements Documents are not consistent with the proposed [BMDS] development program objectives and are hereby canceled.”[2]

The top management of MDA focused on creating a new management and oversight structure for these missile-defense endeavors. This included establishing two industry panels—one focused on system engineering and integration, the other on battle-management issues—to advise MDA on a new development road map, particularly one

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[1] SECDEF memorandum to DEPSECDEF, CJCS, and others; Subject: Missile Defense Program Direction; 2 January 2002.

[2] Ibid.

unconstrained by the Anti-Ballistic Missile Treaty, which would no longer be in force in June 2002. The teams were given 6 months to start delivering results.[3]

MDA established a new process based on capability-based requirements[4] to implement an evolutionary acquisition strategy in which the overall system moves toward its objective capability by deploying an initial system based on achievable technologies, then a series of improved follow-on capabilities in blocks based on subsequent spiral development.[5] In this system, MDA, in consultation with users, defines a desired operational capability that is not tied to a specific threat or a particular technical solution. Then it defines and develops an initial "block" of militarily useful and supportable operational capability that can be effectively developed. As technology improves, subsequent blocks of capability will be developed through spiral development, an iterative process for developing the defined set of capabilities within a block. This differs from traditional "requirements"-driven development, which specifies a required capability, then conducts the research and development to meet it, with anything below that requirement deemed unresponsive.

The maintenance of world-leading capability in missile-defense systems requires continuing advancements in a number of critical technologies. For the near term, these technologies are readily identifiable and included in the system-development programs. For the long term, technology advances that can increase capability (especially those offering revolutionary advances) must be identified and the development risks, payoffs, and transition opportunities assessed. Because of the number of immediate challenges they faced, senior MDA executives initially emphasized development of near-term capability rather than science and technology (S&T) research for the long term.

To address S&T research, MDA tasked the Institute for Defense Analyses (IDA) to conduct a study of the practices of public- and private-sector organizations in the management, programming, organization, support, and review of S&T that had proved successful in the development of technologies, particularly those that included a long-term vision to maintain positions of capability dominance. This study focused on the

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[3] Robert Wall, "Missile Defense's New Look To Emerge This Summer: Airborne Laser, Other Projects Get Makeover as Anti-Ballistic Missile Treaty Restrictions Fall by the Wayside," *Aviation Week & Space Technology (*25 March 2002), p. 28.

[4] SECDEF memorandum, 2 January 2002.

[5] USD(AT&L) memorandum to Secretaries of the Military Departments and others, Subject: Evolutionary Acquisition and Spiral Development, 12 April 2002.

research conducted by organizations, rather than on their product development. The resulting assessment was provided to senior MDA executives in January 2003.

B. APPROACH

IDA carried out the study with a team of analysts who were experienced in a diverse range of technologies and technology-management approaches. Several case studies were conducted. The case study results were collectively reviewed in workshops involving several team members to distill and integrate their findings. A Senior Advisory Committee, each member of which had experience as a senior federal government or corporate technology executive, periodically reviewed the work product of the study team and provided guidance.

The information-gathering activities of the team fell into four broad categories:

- The team studied organizations in industry and government that are credited with being successful at technology development/utilization. The team generally sought out public-sector programs made up of multiple smaller projects. In industry, the team sought out "serial innovators," corporations with lengthy track records, rather than those with one spectacular success. In both the public- and private-sector organizations studied, the team sought to identify their key characteristics for success and assess the extent to which these characteristics could be applied to other organizations and areas of product responsibility.
- Within the organizations studied, the team sought opportunities to conduct retrospective studies of successful product or system developments that had large technology content.
- The team also reviewed outcome studies of technology programs and investments made in the past.
- Finally, the team actively sought out the perspectives on successful and unsuccessful organizations and processes for technology selection and development from senior technology executives in industry and government, including but not limited to those who participated on the study team and its Senior Advisory Committee.

Our focus has been to look at how leading firms in commercial industry have pursued innovation and to depict how they have developed management approaches to link this innovation to their product-development activities. We also looked at several large-scale defense development efforts—similar in scale and scope to aspects of MDA—to see how these employed and managed S&T. An important distinction should be made about these different sets of cases. We considered the commercial firms as corporate entities over time, looking at overall corporate practice. Specific projects identified as being important to the firm's strategic objectives (such as DuPont's Kevlar, Corning's optical fiber, and IBM's photolithography) were examined in the context of this overall corporate perspective. For the defense cases, we explored specific, large-scale programs. Generally, these programs were major development efforts that took place over several years, but they were focused on specific products or mission areas, such as ballistic missiles, jet engines, or nuclear reactors. Thus, in contrast to the private firms, these programs were narrower than a corporation's overall research and development (R&D) activities, but they also tended to be much larger in size and receive more funding than any single program in private industry. The focus of the cases, both industry and government, is on employing S&T to achieve larger organizational goals—outcomes of larger importance to the enterprise. Thus, we believe that the cases, while different, are useful bases for insight about the pursuit and management of S&T.

The purpose and value of this study is not to tell MDA how it should manage and conduct its S&T. That is something that only MDA's corporate management can do. However, through this study we can inform MDA how these programs and corporations found answers to key questions on why and how to conduct strategically focused S&T that may provide insights useful to MDA. For the agency's consideration, we provide some options for the organization and management of S&T based on our findings (see Section III).

1. Factors to Be Considered

The study sponsor asked us to consider the following:

- **Industry Lessons Learned**
  - Executive attitudes towards central R&D centers,
  - Decision process for new products,
  - Near-term vs. far-term investment balance,
  - Transition planning,
  - Business unit involvement in S&T management,
  - Need for S&T champion for individual S&T projects, and
  - Role of Corporate Chief Scientist.

- **Department of Defense (DoD) Programs[6] Lessons Learned**
  - Perceptions regarding the need for S&T;
  - Where support was obtained—Industry, DoD Lab, or internal project staff;
  - How the funding level was established;
  - Process to evaluate technical risk and maturity levels in project components; and
  - Balance between risk reduction, block upgrades, and investment in new concepts.

This study did not examine (nor was it asked to examine) the existing S&T management or projects conducted by MDA. In performing its assessment, the team recognized that (1) MDA is an organization utilizing capabilities-based requirements to conduct spiral development involving development blocks, and (2) MDA is a defense agency that works largely through contractors. In developing options, the study did not limit itself to MDA's current organizational structure and processes, however.

This report reviews S&T organization and management practices for the MDA by

- Documenting the S&T management practices of several successful technology-intensive U.S. defense programs and large corporations;
- Identifying in these cases a set of S&T management methods determined as most important to the success of the corporation or program; and
- Assessing these methods in terms of their pertinence to MDA.

2. Importance of Addressing Approaches to Science and Technology

Addressing the management of S&T at this time is important because the role of S&T and its applications in achieving organizational goals has been fluctuating. Some of this has been provoked by changing external factors—globalization of industrial competitiveness, the greater concern for return on investment over shorter time horizons, the need to reduce costs of production and operations, the rapid obsolescence of technological advances, and the unpredictability of who will benefit most from its introduction—but the role of government in fostering and supporting technology advancement

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[6] When discussing the public sector, this report uses the terms "program" and "project" somewhat differently than is common DoD practice. "Program" refers to the overarching organization and activity; program headquarters will be treated as comparable to corporate headquarters, to a limited degree. "Project" refers to an organization and activity, *within a program,* focused on some part of the program. Project officers will be treated as comparable to the managers of corporate subordinate (strategic) business units (SBUs), again recognizing that the comparison is not exact.

relative to the private sector has also changed dramatically. Investments in new technologies, spurred by scientific discoveries, occurred with increasing rapidity over the last several decades. A notable dynamic of the 20th century has been the concentrated efforts by governments to harness this new knowledge for political and economic advantage and the drive by competing private firms to capitalize on these ideas. Both governments and private firms have had to appreciate the implications of these new ideas and determine how to respond to them. For national governments, the harnessing of new technologies derived from scientific advances was seen as having fundamental implications for economic competitiveness and for security. For firms in what became known as high-tech industries, it was seen as being the fundamental basis of a firm's ability to compete and to survive.

The demands of World War II spurred the developmental implementation of new technologies by American companies funded by the Federal Government. These firms joined in unprecedented relationships with government laboratories and universities to bring fundamental new capabilities into being for meeting defense needs. This interlinking of private companies, academia, and government to foster and deliver new capabilities for America's defense created a profound shift in the concerted pursuit of S&T to achieve advantage. This linkage was sustained after World War II because of the rise of the Soviet threat, and its effects became ingrained in the corporate practices of much of U.S. industry—from materials to electronics to aviation.

An outgrowth of this massive investment was the rise and rapid expansion of a defense-specific industry largely made up of new companies whose primary business was to develop and produce military capabilities contracted by the U.S. Government. Although some commercial products firms maintained vestiges of their defense businesses from World War II, most have almost entirely withdrawn from providing defense-specific products. Thus there were two parallel, but related post-war dynamics—industrial S&T with a primarily commercial focus and government-funded, defense-focused S&T.[7] These two dynamics were enormously successful. The United States grew to be an unprecedented economic power based on the growth of new industries that rested on a foundation of earlier scientific advances and technological developments. The United States became a military superpower, developing and fielding weapons and

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[7] Note that these two dynamics did interact and they were intertwined. There also was the funding of basic science by NSF that provided a base for both of them.

related capabilities that provided technology that overmatched that of its determined, but eventually overwhelmed, adversary.

S&T is clearly a hallmark of America's position of world leadership—economically as well as militarily—yet, over the last two decades much has changed to cause those in government and industry to reconsider the approaches to S&T that were so patently successful before. In the 1980s, as worldwide competitive pressures undermined once dominant market positions, the question of whether and how much to invest in S&T loomed large for industry. Many firms jettisoned or substantially scaled back their corporate laboratories and focused increasingly on the near-term. During the same period, the government began to see reduced payoffs for government-sponsored S&T, as commercial enterprises worldwide demonstrated shorter and shorter product turnaround, outstripping the ability of government to develop and employ technological advances. In government and industry science was viewed by many as unproductive. A major issue was the apparent inability of their scientific establishments to produce useful results, especially results that directly and particularly benefited their organizations. Although considerable attention was given to "technology transfer," the process was seen as highly inefficient, giving rise to considerable doubt about the value of investing in scientific endeavors, especially those that entailed large-scale facilities and would take some time to bear fruit.

3. Definition of Terms

We have adopted several key terms in this study. They are explained in the paragraphs that follow.

a. Science and Research (Scientific Research)

The terms "science and research" refer to intellectual activities characterized by application of a set of practices—the scientific method—in pursuit of "new knowledge of the underlying foundations of phenomena and observable facts"[8] through the formulation and testing of hypotheses, theories, and laws. It is common to distinguish basic research from applied research. Basic research (or pure research or fundamental research) refers to the codification, classification, and modeling of nature. Applied research is scientific

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[8] OECD, *The Measurement of Scientific and Technical Activities*, 1993.

work aimed at a specific objective and informed by the constraints of an intended application. In some circumstances, research can be simultaneously basic and applied.[9]

b. Technology, Engineering, and Development

Technology is the "practical application of knowledge in a particular area." Engineering and development are problem-solving activities (1) aimed at using knowledge to realize new or improved technologies (products or processes) and (2) characterized by exploration of tradeoffs among technical properties, including performance and quality; manufacturing limitations and costs; and customer values.

It is common to consider engineering to be applied science, but it is more than that. Engineers commonly make use of scientific principles and understandings to achieve a particular end, but the primary focus is solving problems and creating products in a particular field using both science and technology. For instance, chemical engineering is not just applied chemistry; rather, it is a combination of chemistry and mechanical engineering aimed at developing equipment, processes, and process controls for large-scale production of chemicals.[10] Likewise, electrical engineering is a combination of physics, materials science, mechanical engineering, and network analysis, among others, aimed at building systems for electrical transmission, microelectronics, and other fields.

c. Interactions between Science and Technology

Science emerged from natural philosophy. Engineering traces its roots to craftsmanship.[11] The two perspectives interact in several ways to generate improved technologies and innovative products. The problem of establishing a positive feedback relationship between science and engineering in today's S&T environment is one of the central challenges addressed by this study. At one level, technology developers leverage science to create and refine products. The problem of conceiving new applications for new scientific discoveries is a creative exercise that is difficult to characterize or control;

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[9] In other words, the notions of "basic" and "applied" are not opposites in the context of research. A scientist at a university and a scientist at a pharmaceutical company may both undertake exactly the same research program in cell biology. Whether they are trying to solve a particular problem is not necessarily helpful in distinguishing their activities.

[10] Example from Nathan Rosenberg and Richard R. Nelson, "The Roles of Universities in the Advance of Industrial Technology," in Richard S. Rosenbloom and William J. Spencer, eds., *Engines of Innovation: U.S. Industrial Research at the End of an Era* (Harvard Business School Press, Boston, Mass., 1996), p. 90.

[11] Newton Copp and Andrew Zanella, *Discovery, Innovation, and Risk: Case Studies in Science and Technology* (MIT Press, Cambridge, Mass., 1992), p. 5.

it has been described as "grabbing lightning."[12] For better understood application areas, science plays the less dramatic role of allowing developers to better predict performance and hence arrive at good designs with fewer iterations. A contemporary example of this is in the pharmaceutical industry, where models and tools for characterizing and manufacturing specific molecules based on scientific understanding of underlying principles have replaced much of the trial-and-error methods of days past, wherein tens of thousands of compounds would be tested and characterized in an attempt to discover novel biological properties that could be exploited in drugs.

Science is also a resource that engineers can call on when development is stalled by a fundamental gap or limitation in knowledge. For example, the process used to make one product may no longer work for another product that seeks to realize the same functionality in a smaller package. In trying to solve the problem, it might be determined that the material being employed took on different properties when scaled down. To achieve the desired product, a scientific study of the properties of the material may be required.

The relationship between science and technology is dynamic, with positive feedback. Scientists and engineers learn from each other:

> In addition to contributing useful tools for scientific research, engineering helps shape basic questions in scientific research. Careful investigation of steam engines revealed the laws of thermodynamics, which in turn led to improvements in engine design. Smallpox vaccine eventually helped spark scientific interest in the immune system and eventually promoted further development of vaccines.[13]

The methods and tools developed by technologists are often encapsulated into science. Although thermodynamics is not regarded as a "pure" science, many thermodynamic principles flowed back into physics departments and became part of the science. Similarly, electrical engineers developed solid-state quantum physics in the 1950s and 1960s to understand semiconductors; this understanding flowed back into physics departments as condensed-matter physics. By the same token, many scientists do significant engineering work when designing experimental apparatus to study basic phenomena. For

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[12] Richard Leifer, Christopher M. McDermott, Gina C. O'Connor, Lois S. Peters, Mark Rice, and Robert W. Veryzer, *Radical Innovation: How Mature Companies Can Outsmart Upstarts* (Harvard Business School Press, Boston, Mass., 2000), p. 25.

[13] Copp and Zanella, p. 8.

example, some particle physicists devote their careers to designing detectors for high-energy collision experiments.

d. Incremental Innovations, Radical Innovations, and Breakthroughs

Incremental innovations are improvements in existing products based on extensions of known applications, approaches, and understandings. These improvements are sometimes referred to as "continuous" improvements. Radical innovations are changes that displace current products, transform existing relationships with customers and suppliers, and often change the entire market. They are based on new approaches and understandings. These improvements are sometimes referred to as "discontinuous" or "disruptive" improvements/innovations, in that they reorder existing relationships.[14] Radical innovations are often based on scientific breakthroughs, which typically consist of the articulation of a new model with significantly greater predictive power concerning a set of phenomena.

4. Modern History of S&T Organization and Management[15]

Around 1900 the leading firms in science-based industries, including GE, AT&T, DuPont, Corning, and Kodak, created R&D programs. The reasons they did so were generally the same:

- *Competition*—These companies perceived threats to their core technical advantages. Urged on by scientifically oriented managers, the firms set up laboratories as a form of life insurance.

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[14] The concept of a disruptive technology itself can be traced back to Joseph Schumpeter's *Capitalism, Socialism and Democracy* (1942). Schumpeter describes capitalist economies as engines of "creative destruction" in which new firms adopt disruptive innovations that challenge existing firms' dominance. His concept was based on recognition that long-term profitability in a competitive environment depended on creating market inefficiencies that could then be exploited. Successful firms make above-average profits over time by constantly innovating, that is, by constantly disrupting the market. More recently, the term "disruptive technology" was popularized in Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Harvard Business School Press, 1997). He defines disruptive technologies as those that "bring to the market a very different value proposition than had been available previously." Geoffrey Moore uses the term "discontinuous innovation" in *Crossing the Chasm* (Harper Business, 1991) to refer to "products that require us to change our current mode of behavior or to modify other products and services."

[15] The material in this subsection is drawn primarily from Rosenblum & Spencer, eds., *Engines of Innovation* (Harvard Business School Press, Boston, Mass., 1996), Chapter 1: "Evolution of US Industrial R&D," pp. 13–85.

- *Federal antitrust action*—Executives believed they could overcome federal suspicion of large-scale industry by rationalizing their businesses and striving to compete based on innovation.
- *Internalization*—Investments in R&D were part of a general movement toward internalizing functions such as manufacturing and marketing within corporate management hierarchies rather than relying on external suppliers in the market. This was also the time during which corporations began organizing themselves into product divisions, raising the issue of whether to centralize R&D or leave it attached to dispersed product groups.
- *Diversification*—The outbreak of World War I enhanced U.S. corporate R&D in several ways. Cut off from German dye and pharmaceutical industries (and aided by the confiscation of German patents as "alien property"), U.S. chemical and pharmaceutical companies established R&D labs. Scientific elites seized on the opportunity to promote the development of domestic R&D establishments, buoyed in part by the successful application of science to wartime problems such as chemical warfare and submarine detection. (The Naval Research Laboratory can trace its origins to World War I.)

Between 1919 and 1936, U.S. manufacturing firms established 1,150 industrial research laboratories. The number of industrial research professionals (scientists and research engineers) employed by these firms grew from 2,775 in 1921 to 27,777 by 1940. By the end of the interwar period, a formula for industrial R&D seemed to have emerged: Do world-class fundamental research, and you will find important new products that you can commercialize and profit from enormously because they are completely proprietary.

World War II fostered the "Age of Big Science." Spurred by the needs of World War II, American commercial industry played a vital role in developing and implementing fundamentally new capabilities and new areas of technology. Firms such as General Motors, Ford, and Chrysler; General Electric and Westinghouse; AT&T; and IBM were mobilized to support the war effort both with their industrial production and their technological capabilities. Such firms joined with government labs and universities to bring fundamental new capabilities into being for meeting defense needs. This interlinking of private companies, academia, and government to foster and deliver new capabilities for America's defense caused a new and profound shift in the concerted pursuit of science and technology to achieve advantage.

Vannevar Bush's *Science: The Endless Frontier*[16] helped them along by promoting the so-called "linear model" of development: The idea that investment in the "best science" would yield a cornucopia of new technologies and products. The linear model was reinforced by the creation of high-profile corporate laboratories at such firms as IBM and Ford and the large-scale expansion of basic research at existing corporate laboratories, such as those at DuPont and AT&T. It was also reinforced in 1950s by widening appreciation of the commercial implications of Bell Labs' invention of the transistor. Frederick Terman, one of Bush's MIT students, built on the idea of science-technology interaction by fostering academic-industrial partnerships with companies near Stanford University, which eventually begot Silicon Valley. This time period also saw the creation of the National Science Foundation, based in part on Bush's formulation, and the emergence of the U.S. Navy, through the Office of Naval Research, as the major government funder of basic research in the United States.

The demobilization following World War II was cut short by the Cold War. Government facilities originally conceived as temporary were transformed into national labs. The Air Force created TRW, a systems-driven high-tech firm, headed by Woolridge (from Hughes and earlier Bell Labs) and Ramo (from Hughes and earlier GE labs). Federal spending for research was almost entirely in the direction of the military. There were massive efforts in nuclear capabilities and delivery systems; air and missile defense; development and application of electronics for surveillance, reconnaissance, and command and control; new platforms for sea and air employing new propulsion technologies; and the incorporation of a wide range of technical advances into older weapons (e.g., tanks employing turbine power and composite armor). The interlinking of private companies, academia, and government from World War II became ingrained in the corporate practices of much of U.S. industry. From materials to electronics to aviation, old firms were challenged to adopt and adapt as new firms arose to take advantage of new opportunities. Many industries—notably electronics—came to depend on military R&D funding. By 1960, the U.S. government was paying for 70 percent of electronics R&D. After the Soviet Union launched Sputnik in 1957, first the Advanced Research Projects Agency (ARPA) and then the National Aeronautics and Space Administration (NASA) were created in recognition of the need to harness science to help pursue the Cold War.

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[16] Bush, Vannevar, *Science: The Endless Frontier, A Report to the President by Vannevar Bush, Director of the Office of Scientific Research and Development, July 1945* (United States Government Printing Office, Washington, D.C.: 1945).

By the late 1970s, the linear S&T model began increasingly to be questioned as corporations noticed that few blockbuster products had come out of the fundamental research of their corporate laboratories. At the same time, the government began to see a decreasing return on its investment in S&T, as worldwide commercial investment with shorter and shorter product turnaround outstripped the ability of government to absorb technological advances. In short, a major issue in both industry and defense was the apparent lack of performance of their scientific establishments in producing useful results.

General economic problems such as the inflation of 1970s compounded the problems for corporate R&D investment. In the 1980s, worldwide competitive pressures undermined once dominant market positions, and a crisis in confidence grew in U.S. industry—beginning with heavy industry and moving to high tech over the decade as first Japan and then other Asian economies captured increasing market shares. Firms began to focus increasingly on near-term manufacturing and rapid product development and, in the funding pinch caused by this relentless new competition, began to cut future-oriented R&D to address the crisis of lost market position and mounting financial losses. A major outcome of these pressures was the shutting down of many corporate research laboratories in the 1980s and 1990s. These pressures also led to collaborative efforts, including consortia, such as SEMATECH and MCC, and partnering in research through corporate joint ventures and similar arrangements.

The growth in the diversity of research organizations and their globalization was one of the major developments of the 1980s and 1990s, with firms looking externally for new ideas and new partners to help bring the ideas into fruition. (With the end of the Cold War, one could even contract R&D in Russia at a fraction of the cost of research in the United States.) Industrial research moved away from hierarchical, linear models to more flexible technology outsourcing arrangements. The advent of the Internet fostered this trend by facilitating distributed work.

There continues to be considerable doubt as to the value of investing in scientific endeavors, especially those that entail large-scale facilities and take some time to bear fruit. At the same time, one of the persistent anxieties today is that the outsourcing model of R&D will not generate truly breakthrough technologies such as transistors and lasers. These technologies emerged out of the outstanding dynamic of the mid-20th century wherein

- Government and private-sector investments in science and new technologies accumulated with increasing rapidity and complexity over several decades;

- The U.S. Government made concentrated efforts to harness this new knowledge for military, political, and economic advantage; and
- Competing private firms strove to capitalize on these advances.

Recently, the corporate management literature has begun to address the important elements underlying radical innovations, and many of the technology-dependent corporations that had shifted heavily toward business unit support have begun to reinvest in core technologies that are deemed essential to their strategies to maintain leadership in their markets.

II. FINDINGS

A. WHY DO S&T?

Many commercial firms that had made major investments in S&T over the past several decades have gone through fundamental examination of the need and value of science to their enterprise. Many firms closed major research facilities, while others, such as Rockwell and Xerox, have spun theirs off as independent businesses. Others have concluded that if they were to continue with corporate S&T investments, they would have to organize and manage them in a substantially different manner. Underlying these determinations is a major reexamination of the basic question: Why do S&T? This goes to the heart of the enterprise's strategy.

The firms' common answer to this question is substantially the same as in the defense programs we reviewed—*to achieve, or to maintain and enhance, superiority in their market, field of expertise, or area of responsibility*. S&T was seen as supporting this goal in several ways, depending on the particular situation of the organization. Among the most common:

- Creating a portfolio of core technologies, expertise, and intellectual property to then provide a proprietary base of capabilities for meeting future needs of the enterprise;
- Solving problems associated with identifying, developing, bringing to market, or deploying new products, systems, and capabilities; and
- Identifying and articulating new technological directions in response to technical, political, economic, and social changes.

B. MOST IMPORTANT MANAGEMENT METHODS

The study found that a number of organizational and management methods were being employed by forward-looking organizations to address (1) determining the strategic balance and focus of the S&T portfolio, (2) effectively managing the operation of the S&T enterprise in terms of balancing between innovation and implementation, and (3) providing mechanisms to align S&T activities and results to the organization's strategic direction.

The following are the most important of these management methods:

- Top-level, long-term support for research in selected “core technologies” that contribute to meeting the key challenges—or more broadly, underlie the missions, strategies, and goals—of the organization.
- Intense attention paid to guiding and managing the work of the organization’s scientists and technologists toward achieving organizational goals.
- Cross-disciplinary, cross-functional teams at various levels of the organization that enhance the ability to understand the changing environment, link research with development, and promote communication across organizational boundaries. Especially notable was the use of
    - High-level organizational teams (such as Core Technology Steering Groups) to monitor critical S&T programs and maintain alignment with top-level organizational goals, and
    - S&T assessment bodies (internal organization, external advisory, or consultative groups) that maintain awareness of global technology developments and their potential implications for the organization’s mission.
- External and internal networks to gather ideas and information on changes in the environment and conscious efforts to maintain corporate memory of the results of research.
- Metrics, analytical methods, and monitoring processes to oversee and manage individual research projects.
- An independent organization for supporting long-term S&T that promotes innovation while seeking to coordinate its efforts within business units or project offices to the extent possible. (The radical innovation hub is a particularly promising proposed model of such an organization that will be discussed in Chapter III, Assessment.)

C. DoD CASE STUDIES—OVERVIEW

We looked at prominent past examples of public-sector[17] programs that sought to develop defense or defense-related products. Our choice of public-sector cases was driven by five principal criteria:

- the program was a publicly acknowledged success,

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[17] All public-sector programs studied were in the DoD. Programs in other government departments were considered, but for purposes of this assessment, the DoD programs were deemed to be the most useful.

- sufficient data were available to draw useful lessons,
- the program was expected to have a large S&T content,
- the program's main focus was on fielding or building something, and
- the program was new in the sense of being created especially to deal with a specific product/problem.

Based on these criteria, we examined the following public-sector programs:

- Jet turbine engine development,
- Night vision program,
- Polaris submarine-launched ballistic missile,
- Atlas intercontinental ballistic missile,
- The Navy's nuclear reactor program, and
- Project Defender and related early programs to develop ballistic missile defenses.

From the outset, we realized that it would be difficult to focus the study on the management of S&T rather than on the larger engineering-development process. Consequently, the study team developed a set of questions to guide its research process:

- Was any S&T done as part of the project? Why?
- In what area(s) was the S&T done? How cutting edge was that S&T?
- Where was the S&T done? In-house? Using existing government or private sources?
- How much or what percentage of the overall budget went for S&T? How was this decided and by whom?
- What management and organizational approaches were used to execute S&T? What issues were raised by these approaches? Was there any tension between S&T and more product-oriented engineering elements?
- What was the return on investment in S&T as gauged by outcomes or impacts?

Key Findings

- Programs were generally high-profile, high-risk undertakings, the success of which generally depended upon exploiting multiple interdependent and immature, cutting-edge technologies.

- Program managers generally emphasized the importance of getting the “best and brightest” people to staff these new organizations, with best and brightest usually being defined (in part) as people with solid technical credentials.
- Programs were generally driven by tight (and sometimes accelerating) schedules. Consequently, there was a tendency to adopt strategies that emphasized getting an initial system into the field quickly, even if that meant accepting reduced performance in the initial model, similar to the spiral development concept. However, in several cases, managers also invested in the future by beginning more capable follow-on systems even before the initial system was finished.
- Senior managers perceived their programs as engineering development programs, but were forced by circumstances to do S&T research nonetheless. The reasons for doing so included (1) the inability to solve problems that surfaced during development without doing research, (2) an insufficient knowledge of basic phenomenology, and (3) a desire to invest in the perfection of immature technologies that held promise for significantly enhanced performance in future models of the system.
- Program managers emphasized that all S&T research had to have a direct product focus and address mission needs, even if that research was rather fundamental in character.
- Even though much of S&T research was outsourced, program offices maintained tight control over what was being done and who was doing the work. Program offices also served as a focusing mechanism to ensure that the research was product and mission oriented.
- Several programs emphasized the importance of having dedicated support from outside R&D providers. The Naval Reactors program did this by establishing two dedicated Atomic Power Laboratories. In the Polaris case, the program director insisted that R&D contractors assign people full-time to Polaris projects and house them together in physically separate space whenever possible.
- Some programs benefited from earlier investments by others in technologies that they knew would someday be of importance. An example of this is Polaris benefiting from earlier Office of Naval Research work on high-strength, high-temperature materials.
- Many programs used a dual-track approach to solving key S&T problems. At least two of the programs made a conscious decision to make the dual-track approach competitive as well. These managers believed that competition between companies or research teams was an important managerial tool for getting results more quickly and spurring innovative solutions.

- Several programs regularly solicited advice on S&T issues from outside the organization. In some cases, a continuing S&T advisory panel made up of nationally recognized technical experts from industry and universities provided advice. Outside S&T advice was used as a source of new ideas, as well as a way to validate or critique existing approaches being considered within the program. In several cases, the initial scope and direction of the program was strongly influenced from the outside by an ad hoc national S&T panel charged with addressing national requirements and means of addressing those requirements.
- In addition to creating S&T advisory panels, program managers tried a number of other approaches for tapping into outside sources of S&T ideas. The Defender program, for example, sponsored an annual missile-defense conference where the focus was on getting technical people to talk to technical people. Defender also sponsored a classified journal to offer a venue for technical papers. The Polaris program conducted "idea safaris" where program managers made visits to industry and universities to solicit new ideas.
- Programs conducted regular technology reviews wherein the program leadership would meet with technical people and designers to review progress and to scrutinize recommended technological approaches. Scientists provided the program manager with an alternative voice and technical expertise to counterbalance the information advantage enjoyed by subsystem managers.

Appendix A contains summaries of the public-sector case studies.

D. INDUSTRY CASE STUDIES—OVERVIEW

The industry aspect of this study drew upon detailed discussions with industry executives who had first-hand knowledge of the company, the public record, and the R&D management literature. In all of our corporate case studies, we were able to hold informal discussions with one or more serving or retired senior research executives. The public record included corporate annual reports and Securities and Exchange Commission filings. Secondary sources included books and journals. Because the companies we studied were generally recognized as successful exploiters of technology, worthy of study, it was common to find one or more books devoted to them. The journal of the Industrial Research Institute, *Research-Technology Management*, proved to be a particularly rich source of written statements by senior corporate research executives over the years.

In our reading and discussions, we employed a guide for gaining insight into four areass:

- Why the corporation performs S&T research;
- How the corporation manages its research, both strategically and tactically:
  - How it decides the allocation of resources to S&T, overall and by area;
  - How it manages project selection, accountability, and termination;
- How the corporation organizes its S&T research function:
  - What research is managed centrally and what is decentralized;
  - What research is done centrally and distributed in-house, and what is outsourced;
- How the S&T research function relates to the rest of the corporation:
  - Role of executives from outside the research function in S&T management;
  - Communicating and using research results, notably project transitioning.

To put these four areas into context, we first sought to understand each corporation's business, including its vision of itself, its strategy for applying its vision to its marketplace(s), and its position in its market(s). Second, we developed a preliminary answer to the question, "Why do S&T?" to help us address the other three areas. The research then addressed S&T research organization, management, and relations with the larger business.

We selected the following companies:

- DuPont
- IBM
- GE
- Corning
- Sun
- Daimler-Chrysler
- Rockwell

These companies were selected because they all had been identified in the literature or through discussions with industry experts as firms that were (1) commercially oriented with concerted S&T research programs that had entailed "serial innovation," that is, bringing to market new technologies on multiple occasions, or (2) noted in some regard as having effective and useful processes or mechanisms for managing the S&T enterprise. We identified some additional firms of interest for the study, but because neither extensive available literature based on first-hand assessment of the firms' S&T strategies and management nor access to key corporate officials was available, we did not include them.

After collecting sufficient information and confirming that a particular corporation offered significant lessons, a written case study was prepared and reviewed by the IDA study team and by one of the senior research executives with whom we had discussed the corporation. For some corporations less extensive reports were prepared.

Key Findings

The mission of a for-profit publicly held corporation is to build stockholder value—to make money and grow the company—and its R&D functions must support this mission. Many companies that have engaged in large-scale S&T over the years have gone through throes of reevaluation, and many have made major changes in their strategies and approaches. At the strategic level, many companies have either closed or substantially cut back their corporate research activities, especially large central laboratories. Today, some of what were the most prominent corporate research laboratories are now independent entities, essentially separate companies in business to do S&T for others or to produce products and profits from their S&T divorced from the firms that they were once part of. This list includes Xerox PARC; Rockwell Science Center; Hughes Research Lab; Sarnoff Lab from RCA (which was spun-off by Thomson when it bought RCA); and Lucent, which comprises the former AT&T's heralded Bell Labs.

Thus, many firms have had to grapple with whether they should do S&T in central or corporate research organizations or seek to achieve their corporate objectives through some combination of (1) R&D within their product divisions, (2) outsourcing of S&T to others (including their spun-off laboratories, other independent laboratories, universities, and National Labs), and (3) licensing intellectual property or its outright acquisition by buying other firms. Firms that have chosen to retain their own central research operations have gone through major redefinitions of how those operations should be related to the overall objectives of the firm and how the research should be focused and managed. As a result, the leading firms that are conducting large-scale and ongoing S&T are managing it and conducting it in ways vastly different than they were in the recent past.

Our case studies, and the recent literature on S&T management, have captured what might be called an experiment in adaptation by a set of firms that have determined that S&T is intrinsic to their competitive position. The experiment is to find ways of making the results of their investments in science benefit the objectives of the firm, so that the firm can succeed in its technology-based strategy, without actually trammelling the innovation process. Complicating this, the overall outcomes for the firm in terms of growth and profit may rest more with other factors than with successfully developing new products based on S&T. On the other hand, failure in the S&T aspect of the enterprise may well spell failure for the firm overall.

With some exceptions, effective S&T management processes and principles appear highly transferable, as firms have actively sought out lessons from one another, adopting processes and approaches judged effective in other organizations. However, in applying the practices of others an organization should be prepared to adapt them—sometimes considerably.[18] It is likely that some of the findings for this study may be highly appropriate and applicable to MDA use, although the different focus of MDA's mission and context of MDA as an organization will have to be carefully considered in applying the lessons from industry. For example, DuPont's Guiding Principles for Technology are market relevance, technology uniqueness, and commercialization plan. For MDA, this could be translated to mission relevance, technology innovation, and implementation plan.

The following are some of the key findings from the commercial case studies:

- For a technology organization, S&T is not optional: consistent, long-term support at the highest level is needed if it is to achieve results.
- S&T must be represented at the executive committee level to adequately link S&T to technical capabilities, programs, and needs throughout the organization.
- Firms have sought S&T management processes that are both structured and flexible to manage resources and ensure relevance, while not stifling innovation and creativity. The intent is to manage, support and accelerate the innovation process, not to attempt to schedule breakthroughs.

From the cases we examined, this balance of the tension between fostering creativity and achieving productive results is the greatest challenge of S&T management. Corporations' efforts to rationalize, focus, and harness S&T through the use of an array of methods and tools must be carefully monitored to prevent the process from taking over the purpose, thereby inundating its participants with time-consuming meetings,

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[18] Arthur N. Chester, "Aligning Technology with Business Strategy," *Research-Technology Management*, Vol. 37, No.1, January–February 1994, pp. 23–32.

paperwork, and activities that are ancillary to achieving the desired results. Other considerations include the following:

- An adequate level of relatively stable S&T resources is important to keep the work flowing through the stages, retain sufficient technical capacity in the organization to be able to respond to unanticipated needs, and to “keep the pipeline full.”
- Portfolio approaches are often effective, both for management tools (to customize solutions for different needs) and for innovative programs. These include mechanisms to identify, collect and rapidly screen new concepts for feasibility and to end unproductive or stalled projects quickly.
- Care needs to be taken when applying analytical assessment approaches so as to not eliminate potentially uniquely valuable contributions, which may appear to have low potential value or poor performance. For example, for Dupont, Kevlar might not meet current financial targets based on historic development costs, yet the product has unique benefits for civilian and military users, and it is currently profitable.
- Creating the climate to innovate and providing the incentives and the linkages to foster the movement of innovation into application require careful management attention. Firms have devoted considerable effort to developing approaches, methods, and tools for improving both these aspects of technology management. Managing technical staffs toward the objectives of the organization entails the use of a range of incentives and metrics for individuals and groups.
- Teamwork, stability, and organizational memory must be balanced with the need to reassign individuals—especially between the research and the development parts of the organization—to overcome organizational resistance to change and to align skills with needs. Longevity and long-term commitment to the organization and mission success are valuable; the willingness to make moves—often as an actual formal position change—is perhaps the greatest indicator of that commitment.
- Key assumptions regarding technology thrusts and the mix of projects (including the balance of near and far term as well as the types of technologies) must be assessed periodically and at decision points. This evaluation should be made by experts within the organization and possibly outside the organization.
- Firms have placed great emphasis on participation and “ownership” of S&T activities by those who must implement and operate the innovation with early and frequent involvement of business units and lead customers. Co-location or close interaction of those who develop the innovation with those who must implement or operate it enhances communications and transfer of ownership.

Appendix B contains summaries of the industry case studies.

E. CONCLUDING REMARKS ON CASE STUDY FINDINGS

In sum, looking at industry and large DoD programs, we found that:

- For the organizations we studied, S&T research was an essential contributor to achieving, maintaining, or enhancing superiority in their market or mission area.
- Public-sector programs that focused on the engineering development of large, complex systems generally have taken on more, broader, and deeper S&T activities than initially anticipated as necessary to achieve their intended objectives.
- Technology-intensive corporations sponsored research because it brought attractive returns on the funds invested or allowed them to maintain mastery of certain technologies at the core of their businesses.
- Many elements of successful S&T research management are common across most of the cases, both commercial and DoD. In particular, current industrial research management is so much like S&T management in a large, long-lived DoD development program that lessons from the former can be applied to the latter. That corporations get feedback much more quickly on their management approaches than does DoD suggests that their lessons will be especially useful to MDA.

Section III brings together what we learned in our case studies, literature reviews, and discussions with students and practitioners of industrial research and DoD S&T.

III. ASSESSMENT

A. THE FUNDAMENTAL ISSUES

The findings of this study suggest a series of fundamental questions that organizations answer when assessing S&T research strategy and management. These questions range across strategic and operational levels. Within that range are several areas in which a large-scale technology organization (with multiple projects or units) must decide where to position itself with respect to S&T. From our examination of several government programs and corporations, we conclude that the model described below is a fair representation of how top executives can proceed from the broadest strategic decisions to a few necessary operational decisions in an orderly way.[19]

Over the past two decades, firms in high-technology industries have become increasingly attentive to the strategic implications of their technology innovation and development activities. As one technology executive put it, there is a need to "align technology strategy with business strategy."[20] We look at business strategy at the strategic level and at the operational level. At the *strategic* level, we distinguish issues associated with *strategy determination* from those associated with *strategy implementation* (see Table III-1). At the *operational* level, we identify several methods for managing S&T that have been employed successfully by organizations we studied. Because these methods overlap, we consider them in three groups: *innovation promotion, focusing research,* and *technical personnel management* (see Table III-2). The remaining sections of this chapter address the issues and methods shown in the tables.

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[19] This is not to suggest that any organization studied actually followed such a logical path. Some arrived at their current configurations through demonstrably painful fits and starts, with wrong turns along the way. Moreover, the organizations we studied were not static, and their decisions were not made once and for all; making these decisions was (and will be) an ongoing activity. The flow described here is an attempt to sketch out a reasonable approach to making the decisions that are necessary to achieving a balanced S&T program, avoiding a number of detours and dead ends, and recognizing that future adjustments are inevitable.

[20] Arthur N. Chester, "Aligning Technology with Business Strategy," *Research-Technology Management*, Vol. 37, No. 1, January–February 1994, pp. 25–32.

Table III-1. Strategic-Level Issues

Strategy Determination	Strategy Implementation
Should the organization support substantial S&T research? Identifying key challenges and core technologies. Balancing the focus of S&T research: near-term vs. long-term, offensive vs. defensive.	Centralized/decentralized control of the types of research. Where to perform centrally controlled research. Funding adequate to sustain consistent efforts. Strategic staffing and training.

Table III-2. Operational Methods

Innovation Promotion	Focusing Research	Technical Personnel Management
Balance research management independence and unit involvement Innovation hubs Internal and external networks and analyzing their outputs	Strategic level: Steering groups Operations level: Cross-functional teams Oversight and accountability	Incentive systems Selection, education, and training Personnel assignments

Note that organizations, whether corporate or government, have origins and histories—cultures—that profoundly affect which methods and approaches they may choose and can implement successfully. This is nontrivial: it implies that tools, methods, structures, and processes that have been found to be successful cannot simply be imported and expected to work. The proper "choice of technology management tools and strategies depends upon those distinctive characteristics of the company that affect technology and technologists."[21] This will also be the case for MDA.

B. STRATEGIC-LEVEL ISSUES

1. Strategy Determination

In this subsection we discuss strategy from three angles: (1) deciding whether to do S&T research, (2) key challenges that face the organization in executing its strategy and selecting core technologies that underlie its missions and goals, and (3) establishing

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[21] Arthur N. Chester, "Business Culture and the Practice of Technology Management," *International Journal of Technology Management*, Vol. 13, No. 2, 1997.

the balance of the S&T research to be done near term and long term and between offensive and defensive (in terms of business opportunities).

a. Should the organization support substantial S&T research?

In the early history of American industrial research, organizations pursued science within central research labs, believing that good science resulted in world-beating products, without questioning this view. More recently, firms such as GE and IBM found it necessary to learn when this view is true and what makes it so. That is, what kind of science done in what way makes world-beating products? An organization may determine that it has need for little if any research, especially that which probes the fundamentals of science. For the vast majority of corporations and many government development programs, this is an acceptable and appropriate decision. For example, it is unlikely that professional services firms or retailers would see a need to pursue scientific research. Consider computer maker Dell. Dell integrates, assembles, and markets technology produced by others, yet has risen to be the fourth largest firm in the computer-information industry. But other firms in the computer industry have strategies that support corporate S&T operations (although nearly all these companies have gone through major re-thinking of their fundamental approach to their research activities).

If an organization determines that it must depend on itself to create the technology it needs, in effect, it defines itself as a technology organization. The public-sector programs we examined all found that they had to conduct or support advanced research, rather than just near-term engineering development, to carry out their systems-development missions. For example, in the naval reactors program, research was necessary in a number of fields, biological radiation shielding among others, to operate the first nuclear power plants. Other research, including a great deal in nuclear physics, was needed to eventually create long-lived reactor cores that dramatically enhanced the operational value of the nuclear-powered submarine and reduced its maintenance costs.

In our case studies of leading innovators in industry, we found two themes regarding long-term S&T research. Both represented pragmatic conclusions that resulted from agonizing corporate self-searching:[22]

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[22] This self-searching was particularly intense from the mid-1980s through the mid-1990s, when financial specialists dominated corporate America. The self-searching of some other corporations led to the cessation of S&T research. For example, Xerox PARC, Rockwell Science Center, Hughes Research Laboratory, and RCA's Sarnoff Laboratory became independent contract research entities. Regardless of the outcomes, the changes were almost always traumatic.

- Research had paid off, but it had to be linked to business strategies much more closely.
- Intellectual leadership in core technologies was crucial to maintaining the market leadership position that allowed them to earn premium profits.

The result was not only a change in how S&T research was managed, but often a change in the corporation as a whole. For example, in a discussion with project staff, Louis Gertsner said that the most important professional decision he has ever made was to reverse the plan to split up IBM that was being considered when he arrived. He added that the single most important reason for his action was the "crown jewels." He said, "Who's going to support a $6 billion research budget after the company is broken up? No one!"[23]

What is important to MDA is that these two conclusions drove industrial R&D closer to the conditions of the public-sector programs that we studied.[24] It would be difficult to argue that the S&T research-management practices of the pre-1985 industrial laboratories are relevant to a results-oriented, schedule-driven government development program. On the other hand, because of the reorientation that took place in industrial research, the S&T research-management practices of leading technology companies in the 1990s and more recently are clearly relevant.

b. Identifying key challenges and core technologies

To the extent that organizations have decided to conduct S&T research beyond the simplest and most immediately applicable (and sometimes even there), they have needed to deal with building the substantive intellectual framework for this S&T research. They have typically done so by identifying a combination of key technical challenges to be met and core technologies to be mastered. For example, in GE's 2001 annual report, its chairman and vice-chairmen signed a statement that identified some additions to GE's list of key challenges and core technologies, "We will advance in new

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[23] Discussion with Bradley Hartfield, 20 November 2002, Cambridge, Mass.

[24] Two caveats apply. First, in industry, central control of research is almost always tied to conducting research in a central corporate research center. This was definitely not the case in the government projects we studied; there, central *control* was the norm, but the research was conducted at several places. Second, a corporation has more incentive than a government program to capitalize on serendipitous discoveries; the corporation's discovery of something that does not fit into an existing business can start a new business, albeit with some difficulty, while the government program is probably limited to providing the discovery to others to exploit.

areas—such as molecular imaging, distributed energy, advanced composites and sensors—with much of the research led by the GE Global Research Center....”

For a *key challenge,* the orientation and emphasis is on what (business, mission, or operation) the organization wants to do, regardless of the technologies to be employed. For a *core technology,* the orientation is reversed; the emphasis is on the body of technology from which the organization will draw solutions to one or more challenges.

In the public-sector cases we studied, the emphasis tended to be on key challenges where success depended on maturing and exploiting multiple cutting-edge technologies. Government programs facing key challenges tended to pursue, at minimum, two or more alternative technological approaches. This pursuit often evolved into designating some of these as core technologies, which were then pursued long term. In several government programs—among them, jet engines, nuclear reactors, and night vision—the program identified and supported research on core technologies that had been determined to be strategically important for the continued successful development of future capabilities to meet key challenges. Not surprisingly, core-technology research provided not only major innovations, but also incremental, continuous progress for near-term product improvement and performance. The jet-engine case study demonstrates how sustained emphasis on core technologies over the years provided the serial improvements that led to the current generation of power plants with demonstrated superior performance and reliability.

In the last two decades, targeting research on core technologies aimed at meeting corporate strategic objectives has become the norm in industrial R&D. The corporation’s mission and objectives establish the challenges. From them, technology research priorities are derived, often leading to a set of core technologies on which to focus. Research in these core technologies then is monitored, judged, and resourced accordingly. The choice of targeted technology programs, rather than scientific disciplines, has become a characteristic of industrial R&D operations and management strategy in high-technology enterprises. Although many corporations seek to “keep the technology pipeline full,” they do not support science for science’s sake. Some organizations, including Corning, DuPont, GE, IBM, and Sun in the cases examined, have explicitly conducted research to explore and define potential new core areas where there were judged to be prospects for major breakthrough or change-state results, but the outcomes are still highly uncertain.

Technology companies employ a wide range of futures research techniques, such as technology road mapping, gap assessment, and other approaches to understanding the future, to guide strategic decisions on research, in particular to identify key challenges and core technologies. Although we have not traced the antecedents of all these techniques, they appear to be close to and perhaps drawn from military approaches to similar matters. The point is not that one or another technique is superior; it is that the corporations see the need to devote significant talent to this aspect of guiding research. As DuPont's chief technology officer said, "If you do not have a vision of the world 5–10 years out, you should not be doing R&D."[25]

Implicit in capabilities-based requirements and spiral development is a set of key challenges that must be met in future capability "blocks." MDA must identify the technologies, not all of which are likely to be in hand, to be mastered to meet the key challenges. The methods used by public-sector organizations and corporations to determine their key challenges and business strategies, and then derive core technologies from these, may inform MDA's thinking on the role of research in capabilities-based requirements and spiral development. It is likely that industry's experience in deriving core technologies would prove helpful in focusing S&T research to make it a vital part of MDA's development strategy of MDA's development strategy. Steering groups, technology advisory councils, and internal cross-functional teams will be discussed under operational methods for focusing research.

c. Balancing the focus of S&T research: near-term and long-term, offensive and defensive

The balance of the S&T research between near-term and long-term and between offensive and defensive is a critical management issue—perhaps the most critical issue beyond the basic issue of whether to do S&T research. Table III-3 shows this balance in matrix form.[26]

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[25] We found that corporate executives tended to think of the near term as 2–3 years and the long term as 5+ years. In contrast, government officials tended to think of 5–7 years as mid term and 10+ years as long term.

[26] For simplicity, we will address the "near- vs. long-term" balance. However, a balance must be struck between "known-unknowns" and "unknown-unknowns," that is, recognized problems that stand in the way of mission success and potential dangers and opportunities that threaten the mission or offer new ways to achieve it. Known-unknowns tend to be embedded in problems that the organization would like to solve soon; thinking about unknown-unknowns tends to be oriented longer term. Therefore, this is almost the same as determining balance between near term and long term in the focus of the organization's S&T activities. The near- vs. long-term terminology will do, as long as we recall that unknown-unknowns can become immediate crises, as occurred with the Soviet launch of Sputnik on 4 October 1957. Of course, there may be key challenges that do not have to be solved for several years, making the research supporting them a matter of long-term known-unknowns. Either can have an offensive focus (searching for opportunities) or defensive focus (seeking to anticipate dangers).

Table III-3. Balancing the Focus of S&T Research

	Defensive	Offensive
Near term:	Research to conquer technical challenges blocking performance of the current mission	Research to improve performance in the current mission, often dramatic—but still incremental—innovation
Long term:	Research to hedge against changes in technology or the world environment	Research seeking radical innovation that will alter the playing field, including perhaps making obsolete current technology

Naval reactors, Polaris, and Atlas placed (or found) themselves squarely in the upper-left quadrant; the character of their S&T research programs reflected that fact. As they began to see their way clear to achieving acceptable performance with their first "product," they shifted emphasis to the right or sometimes also down, but arguably never into the lower-right quadrant. For example, efforts to increase the range of the Polaris missile were a combination of a desire to improve current mission performance (increase time on "alert" status, broaden the azimuths from which targets might be attacked, etc.) and a hedge against the possibility that Soviet anti-submarine detection technology might improve dramatically.

Top management's perception of where these balances were to be struck influenced decisions on research strategy implementation: where to vest control, where to perform it, etc. For naval reactors, Polaris, and Atlas, the urgency of conquering their immediate challenges drove these organizations to central control of research. We do not know whether this persisted throughout the relatively short lives of the Polaris and Atlas programs. It persisted in naval reactors for decades.

The old IBM Watson Laboratory, AT&T Bell Laboratory, and GE central R&D laboratory were the products of corporate decisions to emphasize the lower-right quadrant, based on the conviction that centrally supported, but largely uncontrolled, top-notch scientists would perform research that would produce breakthrough products and, incidentally, help in the other three quadrants as well. All this changed starting in the mid-1980s, and such corporate laboratories (in which central control and central performance were intertwined) were divested, broken up, or made to emphasize service to the business units and other corporate near-term objectives. On the other hand, Corning and DuPont seem to have addressed the balance earlier in setting overall corporate strategy; their central R&D facilities weathered the storm through the 1980s and 1990s with relatively minor adjustments.

Decisions on what to emphasize in the matrix strongly influence, if not dictate, where to vest control of research—centrally or decentralized among the units/projects. Decisions on the time horizon will certainly influence the organization's perspective on where the locus of control should be—at the corporate (or government program) headquarters level or distributed within the business units of a corporation (or the projects of a government program). We found broad agreement that placing the responsibility for research into long-term matters with project officers or business unit executives is a formula for failure. In tightly run government programs or corporations, these people are too focused on achieving near-term results to pay adequate attention to activities that will not come to fruition for several years. In addition, they head organizations that are devoted to current methods and products; these organizations resist innovations that disrupt their routines and impact on their costs and schedules. *If the organization is to do long-term research, it will have to be centrally controlled.* Subsidiary units can be made responsible for near-term (2–3 year time horizon) research successfully; this research can also be centrally controlled.[27] Further, central control of even near-term research into matters that are of concern to two or more subsidiary units appears to have merit—to ensure that the researchers attend to the needs of all units.[28]

2. Strategy Implementation

Setting of strategy is not static; in today's rapidly changing technological, business, and geopolitical worlds, S&T strategy must be constantly appraised and accordingly modified. Here, we address implementation of strategy. Implementation refers to processes, mechanisms, and approaches for bringing the strategy into fruition—realizing it within the organization—with concrete actions. Specifically, we will address centralized/ decentralized control of the various types of research, where to perform centrally controlled research, and two overarching resource issues. In principle, these resource issues are how to give long-term S&T research enough basic support to succeed. In practice, they boil down to providing enough funds to sustain consistent efforts and attracting and retaining top-quality people to guide and perform research.

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[27] We do not reject the possibility that the incentives for business unit managers and project officers could be changed to allow them to attend to long-term research within the purview of their own units or projects. The lesson would still remain for research that spans several units or projects or lies outside the boundaries of any of them, however.

[28] As used in this report, control of research does not extend to supervision of how research scientists carry out their explorations. It does cover the range of management controls from selecting core technologies, through resource allocation, to specific go/no-go decisions in the course of reviewing research progress.

a. The center of gravity of S&T research control: centralized vs. decentralized

Figure III-1 is an idealized depiction of where the "center of gravity"[29] of the control of research may lie in an enterprise. In our investigation of public- and private-sector S&T management, strategic-management decisions about where research is controlled fall on a continuum from centralized to decentralized. The top half of the figure is a simplified representation of the many options available with respect to what we term the center of gravity. The bottom half of the figure indicates what kinds of research can be centrally controlled under each of the illustrative options. Both are shown on the chart because decisions on the balance between near- and far-term research and between defensively and offensively oriented research are intertwined with those on the center of gravity of S&T research management in the organization.[30] The matters are closely linked because top management's time and attention span are limited; central control of research employs both. Therefore, senior executives often elect to focus on the lower (long-term) quadrants of Table III-3 because these are the areas in which research may provide great opportunity or prevent disaster. These quadrants are covered by model ④. The decisions made on the distribution of control of S&T research, in turn, influence the options that will be preferred for a number of other aspects of research management.

Central control of all research, ①, is exemplified by three large public-sector programs: nuclear reactors, Polaris, and Atlas. In the private sector we found a counterpart in Corning. The Corning R&D center employs about 1,000 people and has a budget that is 20–30 percent of total Corning R&D expenditures, that is, $130–190 million out of about $650 million. The rest of the R&D budget supports development, pilot operations, advanced manufacturing, etc., in various parts of the corporation. We also saw a wide range of other options in the private sector for positioning the center of gravity of R&D research management.[31]

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[29] The notion of "center of gravity" has been adopted from discussions with Dr. Charles Hertzfeld, former Director of Defense Research and Engineering and former VP for Research of ITT.

[30] For simplicity, we speak of the center of gravity as being the same for all technologies. In fact, the centers of gravity may differ. For example, the GE Global Research Center contains the central *control* function for research in many fields of interest to GE. As is common in industry, much of the research is also performed in the laboratories of the Global Research Center. However, the center of gravity for the control of hydraulics research is within the hydroelectric power business unit, GE Hydro, and much of the research (apparently near-term focused) is performed in the GE Hydro Engineering Laboratory.

[31] We do not show the option of total decentralization on the chart. As discussed earlier, we found consensus that assigning control to business units and project offices is very likely to lead to the

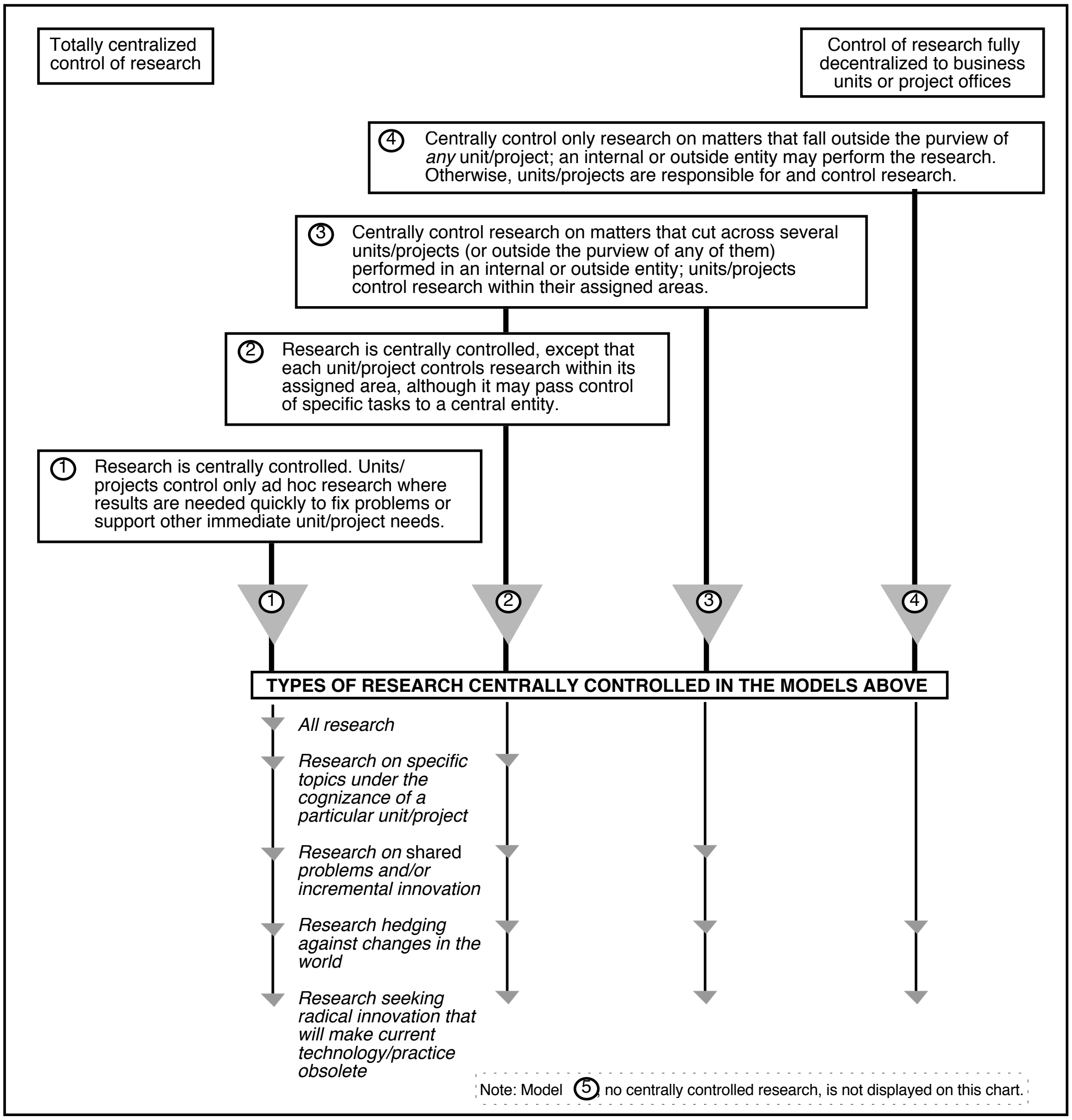

Figure III-1. Management Control of Research—A Range of Options

DuPont, GE, and IBM fall along the continuum from ② to ③, with DuPont and IBM tending toward centralized control of research, with exceptions. In DuPont, control of S&T is highly decentralized into the business units for short-term and intermediate-term programs. The Central R&D (CR&D) is primarily responsible for programs in the 5+-year time horizon, many of which do not support existing business units. Funding for CR&D is a nonoptional component of corporate overhead (by means of allocations from business units), which pays for CR&D facilities, some centralized services, and

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neglect of long-term research, especially that which spans several units or projects or lies outside the boundaries of any of them.

nonbusiness-unit-related long-term programs. DuPont is moving more toward ③ as the corporation allocates more research tasks to business-unit facilities where previously only development work was conducted.

GE exemplifies where business units control most research. Still, a significant fraction is performed centrally (a substantial fraction of which is also centrally controlled) in the GE Global Research Center by mutual agreement of the business units and the center. At the turn of this century GE was spending about $2.3 billion on R&D, 90 percent self-funded. How much of this was research and how much development is unclear. At any rate, the Global Research Center was funded at about 10 percent of the total. Of its approximately $200 million research budget, one-fourth of the center budget was centrally controlled corporate funding, and three-fourths was from GE business units or external sources, the latter overwhelmingly U.S. Government sources for research being done in partnership with a GE business unit.[32] As discussed elsewhere in this report, both GE and IBM passed through a traumatic realignment of their industrial research in the late 1980s and early 1990s, which in effect shifted them to the right on this matrix.

We did not encounter a corporation where a substantial long-term S&T activity was divorced from service to operating business units, so model ④ is somewhat artificial.[33] Central control of only that research which spans several projects or business units or is in areas outside any project or business unit, model ③, is not far from the practice of GE and, increasingly, DuPont. What is artificial in model ④ is the depiction of this as isolated from research being done for business units; in all corporate cases of which we are aware, the two types of research overlap.

In sum, we saw a wide range of other options in the private sector for positioning the center of gravity of S&T research management. Although the public-sector programs we examined fit model ①, we have not identified a reason why the other models could not work in the public sector, including model ④.

In a complex that is a multiple-product enterprise, we have seen that there is always a visible set of programs that gives the appearance of being layered, with differing

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[32] IBM also moved away from the central funding model in the 1990s. In 2002, 30–40 percent of IBM's central research division's budget came from the central IBM budget; 50–60 percent from IBM's product divisions; and 10–15 percent from government contracts, licensing its intellectual property, and other sources.

[33] It does, however, apply to ventures purposefully created to pursue a single, focused business opportunity.

maturities. This is a consequence of the form of the enterprise and does not necessarily address the task faced by MDA, where we must provide a layered assurance of success within a single key challenge, itself demanding a diverse implementation.

The degrees of freedom of management are thus severely restricted for MDA, and the task of managing the S&T thus involves more rigor, more like the challenge IBM faced in ensuring continued leadership in the multiproduct computer business, for example. We have been mindful of this essential difference in the work we have done, and we have tried to focus on serial innovators. We consider the best way to achieve a layered success is to proceed through a layered set of programs, under a single management, sourced through various centers of excellence. We thus emphasize the form of an organization that has access to and communication from the very top, designed to provide the maximum adaptability to changes in required capabilities and technical issues. This is being done in the context of an economic environment unlikely to support the creation of entirely new public resources.

The remaining discussion in this report assumes that there is some centrally controlled research, and the questions are addressed to matters related to that centrally controlled research. The issues range from where to perform this research to building an S&T professional cadre. The answers in most cases will depend to some extent on where the central vs. decentralized center of gravity for control is to be maintained.

b. Options for performing centrally controlled research[34]

Given a decision to centrally control some classes of S&T research as a headquarters function, the next question is where to perform this research. Continuing pressures to reduce the size of the federal work force will likely preclude establishing a new in-house laboratory of any size. Therefore, the only practical solution is to have a relatively small central-research-control group in the program headquarters to administer a portfolio of research contracts or to direct a surrogate organization that does a mix of in-house research and research contract administration. The following explores options for such a surrogate organization.

It is doubtful that the prime contractors for the various MDA development projects are good candidates to be a surrogate organization performing research that

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[34] At least for those research-management center-of-gravity options to the right of model ①, the project officers in a public-sector program face decisions about where to conduct their research analogous to those faced by managers of SBUs in the private sector. This paper does not address these explicitly.

spans several projects or is outside the scope of any project. In principle, such research may be the source of concepts that threaten the development plans of specific projects and their prime contractors, so the potential would be high for real or perceived conflicts of interest. None of this would preclude project-specific research being assigned to a development project prime contractor.

Among the options for such a surrogate organization are a (1) research prime contractor different from a development prime, (2) federally funded research and development center (FFRDC), (3) government-owned contractor-operated (GOCO) facility, and (4) division within an existing service laboratory. Each has advantages and disadvantages, some of which are related to the center-of-gravity decision made earlier. For model ④, any one of these options appears to be workable. The main driver appears to be the degree to which the public sector requires "big science," with large physical apparatuses. As an institution begins taking on more and more of the total program research load, big science is more likely to be needed.

Esstablishing a research prime contractor would be straightforward and would allow the government program the most flexibility to change or terminate the contractual arrangement in the future. In effect, it bundles into one contract a large fraction (perhaps all) of the research that the headquarters central-research-control function would otherwise have to administer through a number of individual contracts. The contractor could be a services corporation, university, or consortium. The approach begins to show some weakness as one moves left from model ④. As the work of this research prime contractor overlaps more and more areas of development prime contractors' responsibilities, sensitivities about intellectual property and proprietary information will mount.

An FFRDC is a special case of a contractor. If an FFRDC is not already affiliated with or available to the public-sector program, it is more difficult to initiate than a normal services contract. On the other hand, an FFRDC's charter can contain provisions protecting the development prime contractors' proprietary information, including claims to intellectual property. This will reduce the grounds on which development prime contractors can legitimately refuse to cooperate, and over time, an FFRDC operating under such a charter can establish a reputation that will reduce these contractors' anxieties. In principle, a research prime contractor arrangement can protect development prime contractors' proprietary competitive information from Freedom of Information Act (FOIA) release. In practice, an FFRDC is likely to provide a higher comfort level in this regard.

A GOCO becomes attractive to the extent that experiments will require expensive, long-lived equipment. Our discussions with defense contractors suggest that the appetite in that industry for participation in long-term projects with the government is inversely related to the size of the upfront industry investments involved. To some degree, this has been the case for decades. For example, the Manhattan Project (and its successor, the Atomic Energy Commission) agreed to build Knolls Atomic Power Laboratory (KAPL) for General Electric to induce the company to take on the management of the production reactors in Hanford, Wash., and to carry out research on liquid-metal breeder reactors. At any rate, if expensive, long-lived equipment is required, the public-sector program can expect to have to buy it itself and to pay someone to operate it. An appropriately structured (in the legal sense) GOCO should provide a level of assurance for development prime contractors' proprietary concerns, much as an FFRDC does.

Establishing a division within an existing service laboratory is a possible alternative to a GOCO as a home for expensive, long-lived research apparatuses. It also might provide the means to acquire a significant number of government employee "slots," if it is desirable to be staffed to carry out all the inherently governmental functions that may be required to manage research for the public-sector project. This option provides a better means to deal with development prime contractor intellectual property and proprietary information than an FFRDC, with one possible exception. It is not clear that the barriers to FOIA disclosure of competitive information are as strong. Further, our reviews of public-sector programs revealed little enthusiasm for—and sometimes downright aversion to—large-scale use of established government laboratories in carrying out intensive R&D for their programs. One reason was that program directors believed government laboratories would not be fully responsive to their program imperatives. Despite this, we do not see an a priori reason why a service laboratory funded through a capital working fund could not establish a division that is fully responsive to the program funding it. On the other hand, it is not obvious how such clarity of purpose could be achieved with a service laboratory operating within a budget line item.

c. Funding

This section addresses three related funding topics: stability of research funding, the amount of research funding, and the funding of research into potentially disruptive technologies. More immediate demands make maintaining a stable and adequate funding stream for S&T research difficult in corporations and in public-sector programs. The corporate marketing or manufacturing department and the government development project officer can always document near-term pain resulting from a failure to cover an unanticipated need or a cost overrun. The S&T researcher can only talk about opportunities postponed and difficulties that probably will not be anticipated. Nonetheless, the corporate executives with whom we met agreed that maintaining stable funding for S&T research was desirable. Corning, DuPont, GE, and IBM have all sought to maintain a level of stability in S&T funding during the recent business downturn.

Within an overall S&T budget that is relatively stable, the corporations we examined tended to reserve a portion of the budget to solicit and fund ideas that are beyond the immediate technology scope of existing divisions of the organization. Of course, within the Department of Defense as an institution, the Defense Advanced Research Projects Agency (DARPA) has been the primary vehicle for such funding for DoD as a whole. MDA is moving in this direction. A 22 February 2002 *Federal Business Opportunities* notice called for concept papers on integrated systems and technical improvements in missile defense boost during the midcourse and terminal phases. For each phase, specific research objectives included surveillance, track and discrimination, engagement planning, threat engagement, and kill assessment. The notice called for concepts in radar systems, lasers, and electro-optical systems; mathematics and computer science; electrical engineering; physics and chemistry; mechanical and aerospace engineering; and battle management and command and control. Apparently, 194 proposals came in from all kinds of contributors, and as of December 2002, these were being evaluated by the Advanced Concepts Office.[35]

d. Strategic staffing: attract and retain quality people to guide and perform research

Strategic staffing covers recruitment, training, deployment, and retention of personnel with the needed balance of motivation, skills, and experience to guide and perform research. Although it appears to be an operational matter, we treat it as a strategic implementation issue because many of the specialists with whom we talked argued that strategic staffing is the most important aspect of managing S&T research. John Crawford, Admiral Hyman G. Rickover's long-time deputy, had the strongest opinion: "When you say, 'Selecting highly qualified people and training them intensively were passions' in naval reactors, most executives will nod and respond, 'Of course,' but they have not internalized what it *really* means." But because senior executive time is a

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[35] Bradley Graham, "Out-of-the-Box Thinking at Pentagon: Missile Defense Agency Seeks Public's Ideas, and a Few May Fly," *Washington Post,* Monday, 2 December 2002, p. A19.

very valuable and scarce resource, a commitment to strategic staffing is a strategic choice. In naval reactors, for example, senior naval reactor staff and Rickover himself interviewed all officer and civilian candidates for the program. On the frequent occasions when candidates were being interviewed, the senior people involved, including Rickover, set aside all other work for the day and devoted themselves to interviewing. The point here is that committing to recruiting, training, and retaining top-notch people to conduct and guide S&T research is a strategic-level decision that will have major ramifications for the day-to-day operations of an organization.

C. OPERATIONAL METHODS

This section covers the operational aspects of S&T management, looking at how different organizations have worked to provide methods, processes, and approaches to be more effective in their S&T research activities.

1. MDA and Operational-Level Mechanisms and Processes

MDA is a government organization that does not implement technologies—it manages their development. As a program-management organization, it is intrinsically concerned with effective management of that S&T which is carried out to meet its objectives. Unlike the corporations we examined, MDA does not actually perform S&T research: this is done on its behalf, under its scrutiny. Many of the methods and approaches employed by industry to bridge the perspectives of the innovators and the implementers may be even more useful in R&D contracted by the government.

DoD has employed concurrent engineering and systems-engineering methods in its complex development programs, but mostly in the acquisition stage, not the early conceptual stage. MDA is not responsible for the acquisition aspects of missile defense—it is an R&D organization. Thus, although it can deploy test-bed initial systems, it will not manage the acquisition of the systems, creating added uncertainty for those who manage and conduct the research. Developing the processes to bridge these budgetary and organizational gaps is a major challenge for MDA.

A similar tension exists in private-sector S&T operations—that between the innovators and the implementers. In the earlier days of S&T, little attention was paid to the linkage between S&T and application, and the idea that science itself could be managed and that the science activity could be linked to the corporate product interests was at best unpopular. On the development side of the operation, there was little interest in being joined with the unrealistic and impractical scientists who did not understand what it takes to make things. Moreover, the product-development groups felt they had done quite well picking and choosing those innovations (e.g., transistors, fiber-optic materials) that had advanced to the point of usefulness. But, as competitive dynamics rendered even this idea obsolete, firms determined that new processes were needed to link innovation and product development to be effective in the competitive high-tech world.

2. Innovation Promotion

This subsection addresses three issues that concern whether relevant innovation is in fact promoted:

- The need for independent management of S&T research, especially that directed toward identifying changes in future environment that will affect mission performance and toward identifying new technologies that will render current approaches obsolete;
- The importance of networks that effectively tap internal and external sources of ideas and communicate the potential value of the S&T research being performed to the corporation or government program as a whole; and
- The use of an "innovation hub," a specific form of research-management organization that draws on both of the preceding concepts.

a. Independent management and unit involvement

For MDA, accepting the consensus that the responsibility for research into long-term matters should not be placed with project officers or business unit executives implies that long-term research needs independent headquarters-level management, at least when pursuing alternative approaches to key challenges. Doing so prevents being locked in to paths that are mere extensions of those of the current product-development organizations (project offices and contractors).

An independent office within the headquarters organization or reporting to it is typically responsible for controlling research that is to be centrally controlled, something akin to MDA's Advanced Systems Office. Research it controls on behalf of a unit or several units is typically funded by the unit(s). Central funding—usually controlled by a high-level leader or executive group—permits the organization to underwrite S&T research that is directed toward the long term, including soliciting and funding ideas that are outside the normal technology scope for existing divisions of the organization. However, in all cases we observed, this independent office also served as focusing mechanism to ensure that S&T research was product and mission oriented. MDA's Advanced Systems Office appears to be committed to carrying out this kind of mandate.

DARPA has served this role over its lifetime, working as an active broker between the technology, policy, and military communities to develop high-risk, high-payoff new approaches to national-security problems. DARPA has sought to fill gaps in S&T missed by the services, often looking for technologies and approaches that are foreign to service cultures, crossed their spheres of influence, or are longer term. DARPA also has searched for new opportunities in general, though program managers were required to explain how these searches, if successful, would be relevant to strategic military problems.[36]

Although they regularly changed with changes of administration, DARPA's S&T managers tended to be from the same mold: they were all technically trained and experienced executives from technology-oriented defense industries, universities, or government laboratories. Once they got behind a project, they worked hard to clear bureaucratic and budgetary barriers. DARPA has given considerable discretion to its program managers (PMs) to identify and develop the research portfolio. The ideas they pursued, while usually part of a broader set of "focus areas," were often brought in to DARPA by the PMs from their prior organization or obtained by them through various mechanisms to solicit new concepts, such as Broad Area Announcements. DARPA PMs are frequently picked from service laboratories—but these often are researchers who had experienced frustration in gaining support for their ideas in their own organization; had broader, more long-term focus than their service would support; or were focused on technology development in areas that were not mainstream in the existing service programs. Whether from service labs, industry, or academia, DARPA program managers have been idea driven and outcome oriented, looking for results from ideas rather than exploring them out of general interest.

Such an independent organization in MDA (and the Advanced Systems Office may well provide a home for it) could lead the effort to understand and project its key challenges, define its core technologies, and then focus resources on achieving superior capabilities in these. *To do this work, this organization needs to have an independent*

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[36] See Richard Van Atta and Michael Lippitz, *Transformation as Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs*, IDA Paper P-3698 (Alexandria, Va.: Institute for Defense Analyses, March 2003).

technical capability that is not vested in the existing programs and technical approaches. Foremost is the ability to look beyond the existing definition of technical approaches with

- Mechanisms that support continued development of identified core technologies—not just the further development of particular technical approaches (e.g., support sensing systems broadly, not just a specific sensing approach such as millimeter-wave radar); and
- Mechanisms to seek out and evaluate new core technologies that could enable fundamental new capabilities in missile defense, not only tapping and fostering relationships within the headquarters organization, but also from the contractor base, from other defense programs, and from the broader technology world, including the commercial domain.

An independent organization should have an independent source of funding for nurturing innovative ideas during their early, vulnerable stages. A "technology incubator" function is essential in technically driven organizations to prevent focusing on one technology to the exclusion of others. At the same time, within either a corporation or government organization, such an incubator function (indeed, any activity that is centrally controlled and funded, such as research, small business set-asides, and public affairs) is resented as a tax by the business units or projects. In our industry case studies, most corporations avoided this problem by involving business units at all levels of research management decision-making. The likelihood of successful transitioning to development is enhanced by such involvement. How to involve the units or projects in managing centrally controlled research without sacrificing its independence is a difficult question. The corporations we studied employed a variety of approaches, and there is no single right answer.

For MDA, the relationship issues revolve around the appropriate degree, form, and process of project-officer involvement. Our review of public-sector programs did not teach us much on these issues, and with one exception, we did not learn how project officers were involved in managing centrally controlled research. The exception was naval reactors. In that program, research was managed through various technical directorates (biological shielding, reactor physics, and the like), rather than through projects for specific reactor types. Although Admiral Hyman G. Rickover himself made the final decisions down to a micromanagement level on research (as well as everything else), he encouraged project officers to critically review technical group plans, including research plans. These reviews were uncompromising and often led to heated exchanges. Rickover himself acted as the project officer for the sort of research that would be centrally controlled. After his retirement, an advanced technology project officer was established to perform that role, in parallel with the other project officers.

The options that will be appropriate for the day-to-day relationships in research management between headquarters and units will change as the organization moves the center of gravity of S&T research management responsibility toward central control of research.[37] Thus, there is relatively little need for interaction if centrally controlled research is only in areas lying outside the purview of any project. However, there should be a mechanism in this case for the central control function to vet research proposals with various project officers to avoid duplication of effort. But the level of engagement should be higher than this minimum for two reasons. First, doing so will enhance the chances that the research conducted under central control will produce results that help the projects. Second, by providing a reasonable degree of transparency and openness to the project officers, the central control function can allay their fears (which may be well founded) that their projects will be threatened by this research.

Under model ③, the central research control function will need to understand to a greater degree what research is being performed by all projects to identify gaps and common needs, as well as to avoid "reinventing the wheel." Even in this model, when multiple contractors are involved, top-management support likely will be needed to extract from the projects even the modest amount of information required for central research planning becaise any identification of gaps or common needs will be seen as potentially threatening to the project's independence. The issue of proprietary interests will come up as well.

With respect to relations with the project offices and their contractors just identified, model ② adds a new challenge because under this model, central research competes for the project officers' research work against the development prime contractors, their subcontractors, and other outside organizations. Model ① goes further and requires the project officers to assign research work to the central control entity. This most closely approximates the practices of the successful public-sector programs we observed. Research was centrally controlled, period. It also is the extreme case of testing the project officers' tolerance for central research, a difference in kind from model ②. Under model ① the projects can conduct their own research only in very limited cases.

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[37] In view of the paucity of lessons from the government sector, this section will be based on industry practices that appear sensible for a government program, as a function of the center of gravity the program director sets.

Project officers and their immediate support staff will resent this. The development prime contractors will especially resent it because they would like be funded to perform the work without competition. We suggest that implementing model ① is probably practical only at the beginning of a public-sector R&D program, and even then it may require more top-management attention than can be justified.

Whatever the specific circumstances, getting an independent S&T management organization established within the structure of a large corporation or government organization demands concerted, determined work. To suggest how to go about this work, consider the experience of Rockwell International:

> Rockwell International Science Center in the period 1976–1986 exhibited many of the forms of intensive interaction with business units that evolved to a state of participatory research management…The director, who held various titles over the decade, personally represented the Science Center to the operating divisions of the Company at the highest possible level. He was on the road just about all the time. He was expected by the chief executive officer to access the detailed plans of the division executive's business and to comment thereon. He became a shadow of each division executive. Division executives were lobbied for the Center's next year's budget, and for agreement on major capital commitments; general consent, rather than administrative approval, was sought…Later, a strategic technologies advisory committee was inaugurated, which consisted of the senior technical officers of the major segments of the Company, with no substitutions allowed. Other than confidential appraisal information, the Center was encouraged to share its concerns with the members of this group and receive advice from them, and was required to assure that they concurred with the Center's budgetary and personnel actions…Even later the director provided a regular "State of Science and the Science Center" brief to the Board of Directors, the Executive Committee and privately to division executives and was invited to management group sessions globally, always with a new script. This communication work was of the utmost importance in providing justification for the Science Center. It was further supported by a private occasional journal, "The Sciences at Rockwell," which reported work from across the corporation.[38]

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[38] Dr. Peter Cannon commentary, 4 August 2002. Dr. Cannon directed the Science Center during this decade, holding various titles, including corporate vice president, director, and chief scientist. He took over the Science Center in 1976 with instructions from the Rockwell International CEO to make something of it or shut it down. The Science Center is now a $100 million separate corporation—Rockwell Scientific.

b. Innovation hubs[39]

As described earlier, over the last decade U.S. industry made a tectonic shift away from the freewheeling research that characterized centrally controlled (and centrally conducted) S&T research. That is, industry went from less centrally controlled research that was tightly coupled to business needs to more research controlled by business units.

Debate raged during this shift and afterward, with critics arguing that in the process of shifting, the corporations had forfeited whatever ability they had previously to produce radical innovations. Academics began to study the matter, seeking a middle ground between freewheeling research and potentially stifling control. Among these was the Rensselaer Radical Innovation Research Project, under the auspices of the Sloan Foundation and the Industrial Research Institute. Beginning in the mid-1990s, this project has followed specific innovation projects in 10 companies, including 3 we studied at a broader level, DuPont, GE, and IBM. From this project a concept has emerged that merits particular attention from MDA: the radical innovation hub (hereafter referred to as "hub").

In the MDA context, a hub, a small entity with minimal organizational trappings and associated with a headquarters central research control function, serves as a:

- Repository for the cumulative lessons about managing research to hedge against changes in the world and to identify and create radical innovations that will make current technologies obsolete.
- Facilitator at the interfaces between research projects producing potentially radical innovation and the mainstream development projects to assist transitioning research results to the projects.
- "Home base" for those who play roles in making this research productive, including
    - Members of technology strategy, key technology steering, and research oversight/evaluation groups;
    - Business opportunity (and danger) recognizers, experienced people who function as idea "hunters" and "gatherers" (the DuPont inbound marketing group is an example);

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[39] This discussion is based on *RADICAL INNOVATION: How Mature Companies Can Outsmart Upstarts* (Cambridge: Harvard Business Press, 2000), and on an 11 June 2002 presentation by and discussion with Dr. Mark P. Rice, Dean of the Babson College F.W. Olin Graduate School of Business, who had been the principal investigator on the Rensselaer Radical Innovation Research Project. The project produced the cited book.

- Innovators throughout the organization.

The roles such people and groups have played in the organizations studied are elaborated in the following sections. The hub is intended to enhance their utility by improving information exchanges, facilitating contacts among them, and providing them moral and material institutional support.

c. Networks—internal and external

In this section, we focus on three facets of networks for S&T management: the role of internal formal and informal networks, the role of external networks, and the analytic approaches corporations have employed to capitalize on information collected in both kinds of networks. Applying the approaches used by companies to MDA's situation demands caution because it is not clear how to map the corporate internal and external relationships onto MDA's relationships with, for example, its prime contractor and subcontractors. Although it is straightforward for GE to apply a lesson learned in one business unit to another unit, it may not be so easy for MDA to extract information from a contractor and use it elsewhere. The experience of government programs shows that security classifications can create their own definitions of what is internal and external, on a project-by-project basis in the extreme case. What is internal and what is external to MDA was not within the scope of this study; however, it needs to be defined before applying the industry practices summarized here.

Internal Networks. Nearly all the people with whom we discussed the matter judged free internal communications to be extremely important to the generation of ideas. Open communication was also seen as important to enhancing ongoing research and facilitating the transition of research results into development and eventually products. Some emphasized that their organizations were seamless webs in which the flow of problems, solutions, and ideas was critical to success. In these organizations, communications are both emphasized and rewarded, and systems are in place to aid communications. Approaches to promote communications across the organization found in the case studies include high-level technical councils, core technology steering groups or task forces, operations/manufacturing councils, senior fellows networks, peer-to-peer virtual networking systems, and annual corporate technical conferences. A clear concern with such mechanisms is that they do not devolve into "meeting for meeting's sake" activities.

An example of a company using modern information technology to enhance internal communications related to S&T through peer-to-peer virtual networking systems is Sun Microsystems. Sun maintains an internal Web site for collaborative work by researchers on projects that have not been officially approved. One Sun researcher described this pre-project phase as “a loose federation of tribes.” This pre-project phase was an important part of creating a consensus for launching a formally supported project. This technique was quite similar to what was described to us by a senior research leader at IBM’s Almaden laboratory.

A more traditional form is the designation of a senior researcher as liaison to a business unit. GE has done this for over 40 years. Other corporations have emulated this practice. For example, many IBM research managers also maintain their own area of research and act as a relationship manager between the entire research division and one of IBM’s businesses.

External Networks. The corporations we examined are significantly different from their mid-20th century predecessors in the degree to which they seek to draw knowledge from outside their corporate walls. They involve external customers in research. They have formal programs—the degrees of formality vary widely—to actively search for new opportunities across academe, business, and government; in the United States and internationally; and across scientific disciplines and industries. Sun Microsystems’ commitment to these search activities is captured in the remark of Dr. Greg Papadopoulos, Chief Scientist and Chief Technology Officer of Sun Microsystems, that one of Sun’s mantras is, “Innovation happens elsewhere.” His role as Chief Scientist is to “build the impedance-matching filter to exploit outside innovation.” Sun Labs has the mandate to be the “eyes and ears” for the company. Its job is to keep an eye on the horizon and to evaluate technical trends. This was one manifestation of the conviction we commonly encountered in private-sector experts: gathering information worldwide world is an extraordinarily important function.

Most of the large-scale government programs we reviewed have shared the perspective we encountered in industry. Indeed, starting in the 1990s, DoD has had a growing interest in and focus on industrial research because it has grown substantially while DoD research has remained relatively constant worldwide.[40]

The tools used to perform the external-network function ranged from simple to quite complex. For example, Defender program managers went to scientists and technologists outside the program to attract new ideas and perspectives. Such efforts included

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[40] Walter Morrow, Chairman, *Report of the Defense Science Board Task Force on the Technology Capabilities of Non-DoD Providers* (Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology & Logistics, June 2000).

sponsoring both a classified technical journal devoted to the problems of missile defense and a series of technical conferences. One tool IBM employs is location: "We used to locate our labs in somewhat remote areas, where we felt we could control how much got out," said the IBM Research Director. "Now we locate them near intellectual centers, to stimulate the flow of ideas into our labs."[41] The Polaris program conducted "idea safaris" where project managers made visits to industry and universities to solicit new ideas. DuPont has an inbound marketing group, which was established to seek opportunities outside the corporation for new technology developments. This group of six people provided 75 percent of the ideas evaluated through the corporation's screening process in 2001. Such an approach may be useful for MDA.

Today there is increased recognition in industry and government of the need to collaborate with others to identify and define new technology capabilities. A growing concern of industry and government has been that the scope of technologies that an organization needs to consider has mushroomed—so that no single organization or scientific discipline is able to track and project what the future capabilities might be. As one response, industry learned to collaborate and build expertise through external teams and partnerships—some that have been relatively stable and permanent organizations (such as NEMI, the National Electronics Manufacturing Initiative, and SEMATECH), and others that are temporary alliances. These have provided important mechanisms for combining expertise and experience to assess and project future directions.

Partnerships with universities, institutes, and other governmental S&T organizations were seen as both technical networking opportunities and as sources of future employees. To be effective, such partnerships need to have stability in goals, expectations, staffing, resources and funding, rather than being one-time pairings. Effective programs often incorporated scholarships, internships, and joint research programs with university academic faculty and research staff.

Finally, external advisory panels are widely used to draw in outside expertise. Of course, MDA has made use of the capabilities of the Defense Science Board on occasions to assist it, consistent with the public-sector cases we examined. Most of these programs regularly solicited advice on S&T issues from outside the organization. Two of the public-sector cases we studied employed a *standing* S&T advisory panel made up of

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[41] Paul Horn, Sr., IBM Research Director and formerly Almaden Center director, who has been with the company since 1979.

nationally recognized technical experts from industry and universities to provide advice. Outside S&T advice was used as a source of new ideas as well as a way to validate or critique existing approaches being considered within the program.[42] In sum, independent, high-level S&T study groups have often been instrumental in helping reach consensus on program scope and direction and in addressing global technology developments and their potential implications to the organization's mission.

Analysis. Related to networking, and information collection more generally, is assuring that the flows of ideas are in fact being tapped. In addition to the creation of an information network, it is necessary to ensure its use. More broadly, in the corporations we studied, considerable analytic effort is devoted to understanding the meaning of the information flowing in from all the internal and external networks about possible changes in the external environment and the emergence of technologies that either threaten current approaches or offer new means to mission accomplishment.

For example, IBM explicitly looks at "Global Technology Outlooks"—5- to 10-year projections—asking such questions as: What is emerging? What is a vision and feasible strategy for using this technology? What approach is needed to be the leader in this technology? These assessments are presented to top management and help drive corporate strategy. Further, IBM then asks the question: If this is where IBM must be, how will it get there? This is laid out in the "Technology Plan," in which the work plan is explicitly tied to a financial plan that drives resource allocation. To proceed with a technology plan, the technology area must be seen as vital to IBM for the future. An example is nanotechnology, more particularly, nanotubes. The key justification for pursuing this technology is that it can be directly related to concerns in information-storage technology and semiconductor microelectronics. In this last area, IBM has done fundamental research on carbon nanotube transistors.

IBM's example illustrates the formality with which many of the corporations we encountered look to the future. We encountered a similar formality in some of the government programs we examined, among them night vision and jet engines. These two government programs employed techniques to quantify their view of what performance would be demanded or could be attained in the future and used these quantifications to guide research.

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[42] Directors of the Polaris and Atlas programs also recognized the political value of winning support from leading scientists.

Scenario-based planning, one of the tools we encountered in industry, appears to have been borrowed from the military. As practiced in industry, the primary goal of scenario-based planning is not prediction; it is enhancing executives' ability to react to the unexpected. Shell, a pioneer in scenario planning, used it to posture the company for continuous learning, as opposed to simply maximizing near-term profit. DuPont's example is a variant of this approach applicable to technology:

> [DuPont] converted a conference room into a "war room"…Each wall was used as a large notepad, where specific kinds of information was captured. On the top half of one wall, for example, we captured all the identifiable major technologies and technology development efforts under way in the company…on the bottom half we captured current trends and future trends from studies conducted by futurists…The team that worked in the war room was…[composed] of people of different disciplines and from different parts of the company…Specific tools were created. First trends documents were drafted and tested…The raw material…[was] futures studies…[and] trend studies available in the literature…The second tool…was a criteria list for assessing new ideas based on…previous business launches…The third…was [a formal depiction of futures]…The first team anticipated, by a few years…anti-microbials and nutraceuticals…The corporation is in both these businesses today.[43]

Many other specific techniques and tools, technology road maps, and the like are potentially relevant to MDA. Different forms of the analytic process have been used in various combinations by industry and government research management. The main point is that they are taken seriously. For example, the Sun Chief Technology Officer recently supervised competitive analysis on six areas of focused technology; he looked at all the product division technology road maps to assess their competitive potential. The perception by their users was that such attempts to look into the future and to assess what was being said and done outside their own organizations were valuable tools for supporting S&T decisions.

3. Focusing Research

Three functions stand out as being of possible utility to MDA in focusing its research work: steering groups at a strategic level, cross-functional and cross-discipline teams at the operational level, and systems of oversight and accountability of S&T research work.

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[43] "Practicing the Future Today," by Terry J. Fadem, retired DuPont director of new business development, *Futures Research Quarterly*, Vol. 17, Number 3, Fall 2001, pp. 53–65.

a. Steering groups

At the highest level of corporate strategic management in most of the corporations we viewed, the chief technology officer sat on the corporate executive board. Here, major directions with respect to managing the research portfolio were set. In GE, for example, this was done as part of an annual regimen of meetings involving the top 40 executives of the corporation. During these meetings, all aspects of corporate strategy and performance were addressed, culminating in an annual meeting of the top 400 GE executives. This annual meeting set in motion a process of informing the entire professional staff and work force of the direction GE was taking.

Similarly, the Chief Science and Technology Officer sits on the DuPont Executive Board, which among other things establishes the main areas in which technology advances would be sought. There are now five "Strategic Growth Platforms." More generally, DuPont is a clear example of a system of steering groups that address S&T research strategy from the highest level down to the operational level. Very long range and exploratory work done in DuPont's Central R&D is selected and managed through a three-stage process referred to as "Apex." A CR&D Board of Directors led by the Chief Science and Technology Officer and including three Science Directors[44] manages the Apex process. The specific Apex projects are managed by Apex Science Boards affiliated with the five Strategic Growth Platforms. These Boards are chaired by one of the three Science Directors, include high-level business personnel, and may include outside technical experts. In addition to screening new ideas from traditional researchers, Apex research manages evaluations of programs identified by the inbound marketing group.

Core Technology Steering Group[45]

DuPont's Apex Science Boards are close kin to an approach used by ITT in the 1980s that we believe will be of interest to MDA—core technology steering groups (CTSGs). The purpose was to create explicit steering groups for core-technology development programs. The term "steering" was intentional—the concept was that each group guides an activity based on larger organizational goals. These groups were to develop and manage the S&T in specific, selected priority areas. The CTSGs were

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[44] DuPont Science Directors are senior technical executives who report to the Chief Science and Technology Officer and are responsible for broad areas of DuPont's S&T activities.

[45] The presentation of ideas on core technology steering groups is based primarily on discussions with Dr. Charles Herzfeld concerning his establishment and use of Key Technology Steering Groups in ITT during the period 1979–1985. The terms "core" and "key" are essentially synonymous.

envisioned as management activities for determining need, objectives, and technical progress. They were an active oversight activity for a research thrust of particular importance to the organization, but not involved in the specific day-to-day conduct of individual projects within the thrust. Selecting or establishing specific CTSGs was a function of the organization's high-level technology management, implying that there was a broader ongoing corporate focus on identifying and selecting core technologies.

Organization: At ITT the CTSGs reported to the Chief Scientist, who had an active role in research management and regular access to the CEO. In short, the CTSGs reported to the highest level of corporate technical management. If the number of groups gets large, it might be useful to have a committee of steering group chairs, who could provide a function of a corporate technology council, similar to DuPont's CR&D Board of Directors or IBM's Technology Council, which reports to the Director of the Research Division, which includes its Laboratory Directors.

The structure of the individual steering groups was critical—they focused on technical matters, not organizational perquisites. In its membership, the CTSG emphasized expertise and competence, not bureaucratic or organizational position. The membership, at minimum, included

- The best domain experts for the technology subject,
- Serious (potential) users of the technology to be developed,
- Main producers of the technology.

In ITT the membership was internal. Outside experts were used by ITT as guests and advisors to the CTSGs. The chairs of the groups were experts in the field. For the case of MDA, because it contracts out its R&D activities, the appropriate membership would be less clear-cut, especially where MDA might require some means of vetting alternative potential producers from the research-contractor community.

In ITT the CTSG met regularly—about once a month at the beginning and moving to once every 2–3 months later on. They became teams, not just committees. At ITT, the meetings were moved to where the work was being done, rarely at the organization's headquarters. All sessions were closed, and at ITT they were company confidential.

b. Cross-functional and cross-discipline teams

Cross-functional and cross-discipline teams are variations of the concept that people from diverse backgrounds produce synergy when they work together in teams. For example, one feature of the steering groups described in the preceding section is that they include representatives from different disciplines and organizational backgrounds to guide S&T research strategy at various levels. Cross-discipline teams tend to dominate at the early stages, when the objective is to understand better. Cross-functional teams tend to dominate when the objective is to move a concept toward implementation. Thus, the corporations we examined use cross-functional teams extensively in applied R&D work.

To help minimize risk and bring advanced technologies into real-world applications, cross-functional product-development teams are involved in the R&D process early in the applied research stage. Teams are staffed with knowledgeable scientists and able implementers. Such teams involve research, design, engineering, and manufacturing in a cooperative, joint endeavor aimed at most expeditiously moving ideas from concept to product. The balance of team membership shifts as research proceeds into development and so on. Many firms we studied have built metrics related to teaming into their personnel evaluation and reward structure.

Making such teams work in government programs appears to be more difficult than in a corporation because doing so involves contractors who have proprietary interests in the areas being addressed.[46] One area for such teams is in precompetitive research, especially research into areas that are of interest to two or more projects within a government program. Still, achieving the flexibility to blend the right mix of people (innovators and implementers) with the right set of skills (at the right time) is no less essential than in internal corporate teams, but considerably more difficult to do. Teaming in the applied R&D areas can encourage information sharing among contractors. In any case, the objective is to encourage creative thinking, which often involves the application of existing principles and concepts in new areas. These teams have to be organized and run with care so as not to stifle innovation by encumbering initial ideas with all of the practicalities of full-scale developments.

IBM Research Vice President Horn stated that he can minimize conflicts between research and development by involving product engineers in projects from the start. Cross-discipline and cross-functional teams that meld research with development are a central element in the radical innovation hub concept for inspiring creative thinking and the recognition of new business opportunities enabled by technology.

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[46] The following suggestion is based on the observation that in industry external teams and partnerships have almost always been in precompetitive R&D and cooperative efforts that look at possible future technologies.

c. Oversight and accountability

The need for oversight of S&T research and holding researchers accountable for contributing to mission objectives was a point of agreement in the government programs we examined. This was not the case in industry for most of the 20th century. The shift in industrial research in the 1980s was largely about overseeing industrial research and holding researchers accountable for producing results that contributed to the business of the corporation. It also was about measuring the outcomes of research.

Corporate measurement of industrial research focused in the 1980s and 1990s (and to some extent still focuses) on deriving financial measures of research value. As these ideas have been tested over the past 20 years, a consensus seems to have emerged that such measures are useful at a high level[47] and for development work. There also seems to be a consensus that financial measures are counterproductive when used with specific research (in contrast to development) projects. At the same time, measuring the progress of industrial research tended to be scheduled by financial managers, an idea that increasingly met resistance based on the argument that discoveries cannot be planned. Again, a consensus seems to have emerged that the rhythm of research oversight needs to be attuned to the workflow rather than the calendar.

However, the consensus on both counts includes the view that research needs to be formally evaluated and held accountable on scientific, relevancy, and common-sense grounds. Uniform centralized evaluation of all research is widely seen as helping to identify the most promising programs, reducing the number of “pet projects” and enforcing the discipline of shelving research that is not progressing. Variations of “stage gate” evaluations are common. An example of such a research project management approach is the Technology Stage Gate (TechSG).

> TechSG lies within and between the [“Fuzzy Front End”] FFE and the Traditional Stage Gate (SG™) process. The FFE represents the initial part of product development from idea generation to development of a concept that includes the primary features and customer benefits combined with a broad understanding of the technology needed…[Then] by using a TechSG process to focus on the technology development issues (with a long-term view toward business strategy, plans, and needs), the business can manage the technology development effort separately. The effort would continue until such time that it would be feasible to start product

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[47] For an example, see George C. Hartman’s, “Linking R&D Spending to Revenue Growth,” *Research-Technology Management*, Vol. 46, No. 1, January–February 2003, pp. 39–46.

> development or it becomes evident that the risks are too high or the rewards too low to pursue the technology… New technology development is by definition new, different, and unpredictable. It is difficult to capture and leverage past experience for future efforts making cycle times difficult to estimate. One cannot “schedule the technology discovery.” The range of possible experiments and their outcomes is almost limitless. Detailed overall project planning is therefore impractical. Too much structure or repetition of past work can severely inhibit creativity. It is often difficult to determine when the new technology is “ready” to transition to product development. This can be a very subjective decision arrived at through informed discussions…project leaders during new technology development need the ability to manage uncertainty and do “good science” while focusing on project goals.[48]

The greater the degree evaluations in processes like TechSG and Apex can be based on relevant quantitative information, the better. Although many have argued that the quantitative financial measures often attempted in industry were not relevant, *relevant* quantitative measures are still to be sought for purposes of overseeing S&T research. The team encountered two interesting examples of quantitative measurement in government programs. The night vision and jet engine programs both employed formal methods for modeling, in quantitative terms, system-performance parameters in the field and their linkage to physical parameters in equipment. The goal was a uniform metric of S&T value at all levels of system hierarchy.

Correlating field performance with laboratory performance became a standard practice in the U.S. Army Night Vision Laboratory (NVL) (now the U.S. Army Communications-Electronics Command [CECOM] Night Vision and Electronic Sensors Directorate [NVESD] at Fort Belvoir, Virginia) and eventually a formal subbranch of night vision technology now called Visionics. NVL used Visionics to provide a rational means of moving resources among projects, reducing or eliminating support for those that were not achieving valuable results in favor of new ideas for creating user value. According to the NVL director, in the early years, “Visionics was the backbone that guided the selection and funding of research programs for maximum payoff, provided optimization of equipment design, and established necessary testing techniques for both

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[48] Greg M. Ajamian, Senior Project Manager, DuPont Consulting Solutions and Peter A. Koen, Ph.D., Associate Professor, Stevens Institute of Technology, “Technology Stage Gate: A Structured Process for Managing High Risk, New Technology Projects,” DRAFT PDMA 2001 ToolBook Chapter (August 28, 2001), copy provided by Dr. Koen. See also Robert G. Cooper, et al., “Optimizing the Stage-Gate Process: What Best-Practice Companies Do–I,” *Research-Technology Management*, Vol. 45, No. 5, September–October 2002, pp. 21–27.

laboratory and field measurement." For instance, Visionics helped NVL decide to favor S&T research on gallium arsenide (GaAs) cathodes rather than the competing "S25" cathodes. Although GaAs cathodes cost much more, they were much more rugged, leading to a lower life-cycle cost for night-vision goggles. (Some argued that the real performance and cost savings resulted from the reduction in breakage by troops in maneuver.) Visionics also helped NVL avoid adopting measures of S&T research success that were not directly related to customer value and the goals of the organization, such as number of publications or patents. Last but not least, use of Visionics allowed NVL to make quantitative arguments that were persuasive to top management when budgets were being distributed. Beyond quantification, several particular circumstances contributed to the success of Visionics: the disposition of key people to take a long-term view was focused on users; the systems in question were relatively small by DoD standards so there were opportunities to build many prototypes and evaluate them to build insight as to their value in the field; and NVL's life cycle perspective meant that all aspects of the system—its logistics requirements as well as its near-term performance—were considered early.

The Integrated High Performance Turbine Engine Technology program (IHPTET) GOTChA[49] process defines quantitative, phased goals for technology advancement. The process was judged to be very helpful in the IHPTET. The Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program reorganized itself in the 1990s along lines parallel to the IHPTET program, including the creation of a steering committee structure.[50] Currently, the Vehicle Systems Office at NASA Headquarters is exploring the application of the IHPTET/GOTChA process to its own program structure. In discussing the applicability of such a program to MDA needs, those who had used GOTChA said that it very likely applies up to the highest mission level goals that can be quantified and thus verified. Therefore, it is less clear that the process is applicable to basic research or at the levels of planning overall architecture and large platforms, where discontinuous

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[49] Using a top-down arrangement, the GOTChA acronym stands for: overall (G)oals, which lead to technology (O)bjectives, which define (T)echnical (Ch)allenges, and then help to identify (A)pproaches to solving them.

[50] Richard Weiss (retired Director, Air Force Rocket Laboratory), in a November 2002 discussion, reported that the quantitative, goal-oriented approach of the IHPTET management model (with GOTChA), applied to the rocket programs under IHPRPT, produced mixed results for several reasons. In contrast with the air-breathing propulsion industry, the rocket community suffers from (1) lack of a truly commercial industry for rocket propulsion; (2) less settled technology options available until the systems-development stage; (3) less overall government support at a steady funding rate, whether in the military or civilian (NASA) agencies; and (4) lack of a conscious effort on the part of the government to set aside funds to support more fundamental, radical ideas.

capability improvements are sought. In short, the extent to which the GOTChA process (or similar quantification approaches) can apply to S&T research depends on the ability to define quantifiable goals. Where MDA can identify missile-defense architectures (even notional or strawman architectures) that will help define technologies and goals to pursue, the GOTChA process (for one) likely will serve, at minimum, as a proven starting point.

While the specific examples above illustrate a range of approaches, the most important point is that the companies and government organizations we examined had review processes with similar purposes, but employed different mechanisms. There were processes at the single project level and at one or more overarching levels above projects, and they were integrated with more or less formality and documentation in various organizations. These included reviews of technical programs to educate top management on key activities and needs, demonstrate top-management interest, ensure quality tracking at lower levels, and generally guide resource allocation. The evaluation processes were very much judgmental at the early stages of research, leaning heavily on the technical judgments of scientists and the broad judgments of experienced practitioners. As an S&T research project progressed, evaluations became more quantitative and gave increasingly more weight to the judgments of "downstream" specialists; in corporations these were developers, manufacturers, and marketers.

4. Technical Personnel Management

A survey of 114 industrial R&D organizations within major U.S. corporations in 2001 suggested four ways to attract and retain scientific talent:

> 1. Create a distinctive employee value proposition for R&D to develop a work environment in which R&D talent can thrive. An employee value proposition is what employees receive from a company in return for their services (for example, some companies emphasize highly challenging work, while others emphasize higher pay). Those organizations that emphasize the work itself and the unique work culture are at a distinct advantage….
>
> 2. Look for opportunities to tie career advancement to leading-edge skills development and demonstration. The old-style technical career ladder that was based on time in job…is being replaced…today the career track is based on demonstrated skill….

> 3. Form effective teams. The work environment also plays a large role in producing a high-performing R&D workforce. As the survey indicates, teamwork is becoming more important….
>
> 4. Revise recognition systems for R&D staff…to reinforce discovery, invention, collaboration, and other drivers of innovation rather than… reinforcing cost reduction, customer satisfaction, and other factors common in recognition and reward programs. In addition, the nature of the rewards may differ for scientific/technical staff. Where other types of staff may be motivated by short-term cash rewards, scientists place more value on longer-term rewards such as stock options…discretion in technical decisions, increased budget, new tools, educational opportunities….[51]

Of course, the implementation of such operational guidance is related to the strategic decisions that have been made for the organization, such as those made with respect to central vs. decentralized control of research.

The next three subsections address three aspects of managing S&T researchers and people in the headquarters-level S&T research-control function: incentive systems; selection, education, and training; and assignments.

a. Incentive systems

To be effective, personnel management, accountability, and incentive systems must be congruent with the organization's strategy and goals. A written strategy defining both the long-term mission and intermediate measurable goals should be tied to appropriate performance measurement and feedback systems that reward results and teamwork.

Because management and accountability systems communicate an organization's priorities to its employees, they must be clearly connected to the organization's strategic plan. These systems should be designed and administered to encourage broad support for and engagement in long-term goals and immediate objectives, as well as to ensure participation by key program directors and executive staff in setting and achieving those long-term goals. Awareness and engagement of the entire organization can sharpen strategic focus and encourage innovation.

The motivation and incentive systems we encountered in corporations were specifically designed to support organizational goals and encourage desired behaviors. In the corporate world, rewards include long- and short-term career opportunities,

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[51] James Kochnaski, Paul Mastropolo, and Gerry Ledford, "People Solutions for R&D," *Research-Technology Management*, Vol. 46, No. 1, January–February 2003, pp. 59–61.

including advancement opportunities within the corporation (building loyalty, stability, security, and teamwork). One such opportunity is an outlet, such as an "intrapreneurship" mechanism for those whose ideas outstrip the current product-management organization.

These systems considered rewards and motivations appropriate to particular teams and individuals. For example, as noted in the Industrial Research Institute survey, potentially effective incentives may also include management recognition (formal and informal), opportunities to participate in prestigious internal or external activities or technical conferences, support for proposed innovations, and access to information and scientific equipment. In the public sector, rewards for significant contributions appear to be similar and include high-level recognition, continued grants, or appointments to key commissions or bodies.

In IBM, the Research Division conducts detailed evaluations of staff member performance, ranking an individual's performance within a group from 1 to 100 in terms of contributions across such traditional S&T categories as patents and publications, but also such activities as collaborative teaming, product-division support, and customer support. Salary and personnel advancement decisions are directly linked to these evaluations. The Research Division has conducted this review process for 30 years. The major change in the last decade has been the strong focus on product-division interaction and support and customer involvement. Mentoring is also a major focus. Most new hires are new Ph.D.s, but IBM will hire some experienced researchers from other companies and organizations—more so today than in the past, especially in new research areas.

As a final note on incentives, we observed that Corning, IBM, and DuPont all have fellows, successful scientists given wide latitude to pursue their scientific instincts, who mentor and guide younger professionals.

b. Selection, education, and training

Systems to select, educate, and train new team members, team leaders, and managers and integrate them into the team, the communications networks, and the organization are important elements of strategic staffing. The Polaris program recognized the importance of getting the highest quality people and then making their advancement dependent on the success of the program. The same management philosophy applied to contractors as well. Some members of the Special Projects Office later recalled that selecting the right people was one of the most important factors in the program's success.

The idea that recruiters should be familiar with the organization's technical goals and the teamwork and "chemistry" desired in the work group is commonplace. However, the Industrial Research Institute survey noted earlier showed that this cannot be assumed. The surveyors found disparities between the answers received from industrial research managers and human resources (HR) managers:

> On some measures the differences were stark:
>
> - Some 71 percent of HR leaders believed that the organization "has the information it needs to manage talent like a product or financial asset," but only 29 percent of R&D business leaders agreed.
> - Most HR leaders (76 percent) believed that the organization "has unique attributes that make it a magnet for the best talent," while only 45 percent of [R&D] business leaders agreed.
> - Nearly half (47 percent) of HR managers agreed that the organization "has enough professional technical/scientific R&D employees with leading-edge skills," yet only 16 percent of R&D leaders agreed.

This seems to reinforce the practices observed in such organizations as naval reactors, in which line managers were deeply involved in recruiting and training.

Many organizations have found the best sources of new employees to be university partnerships, internships, and scholarships, as well as relationships with users and suppliers. For example, after a short start-up period, the naval reactors program has drawn its headquarters experts primarily from ROTC programs; they serve their obligation in the naval reactors program and often remain on as civilian employees. Senior managers are often directly involved with recruiters in attracting and selecting new professionals.

The NVL also maintained a program to recruit qualified technical personnel with assurances of hands-on immediate experience in R&D, product engineering, laboratory and field testing, as well as opportunities to engage in relatively underdeveloped science fields.

c. Assignments

The personnel-deployment systems that were described to us by industry consciously balanced the team's and organization's needs for skills and experience. Teams require both expertise in specific technical fields and application areas and an understanding of multiple programs, applications or user areas. Deployment plans, which were consciously used to support development of "organizational memory," included continuity and replacement planning for key positions and leadership. The results were sometimes quite striking. For example, over 75 percent of DuPont senior leaders hold degrees in technical fields, and most have over 20 years with the corporation in technical, manufacturing, and business roles. These leaders were intentionally developed through both training/education and experience in multiple DuPont businesses.

Some case studies suggested the utility of deploying or redeploying professionals, both to overcome organizational resistance to change and to link needed capabilities "cross-functionally" to marry an innovative concept with application needs. Several firms—IBM and Sun among them—have put in place personnel approaches designed to "move the people with the ideas." In such cases researchers were transferred to an existing or new product development organization to join with product engineering personnel to bring the idea into fruition. In some organizations this was a career move—there was no automatic return to research. Those who made this move were dedicated to success of the business endeavor and were to be rewarded according to its success. Such practices appear to be relatively new; how well they work out in terms of successfully deploying the technology as product and in terms of maintaining innovative personnel within the firm is not well tested. Overall, many people we talked with about personnel management emphasized the importance of longevity and the cultivation of a corporate memory.[52]

D. RECOMMENDATIONS

To tailor these S&T management methods to MDA, we recommend pilot program that addresses specific technical challenges. This pilot effort could entail the following:

1. Use the recent Defense Science Board (DSB) report and other documentation to identify MDA's key long-term challenges.
2. For *selected* key challenges:
    - Specify each challenge in terms of critical parameters,

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[52] This is in contrast to DARPA, which seeks a 4- to 5-year tenure in its project managers. Most S&T organizations face a dilemma—perhaps government more than industry—in seeking *both* new innovative technologists who are at the frontier of knowledge *and* a basis of experienced and savvy researchers who know practicalities, have established working relationships within and across the research and product organizations, and can provide leadership and direction. While longevity is valuable, it is also a potential burden if it leads to ossification and a reduced interest and ability to explore new concepts and take risks. Maintaining this balance of S&T personnel is one of the greatest challenges for technology organizations.

    - For each challenge identify key capabilities with performance specifications,
    - Develop two or more conceptual system designs that provide the capabilities, and
    - Use these designs to define specific *technology* goals that need to be achieved to make the designs feasible.

3. For up to 10 candidate core technologies selected on the basis of their potential contributions to key challenges:
    - Perform a technology readiness assessment that includes a gap assessment. For those related key challenges for which a performance specification was derived, perform a gap analysis and value and risk assessments;
    - Form a Core Technology Steering Group for some set of core technologies and have each group
        - Assess the state of research in the technology against the MDA mission and identified key challenges,
        - Propose specific potentially high-payoff research thrusts, and
        - Make an initial draft of an investment plan for the core technology.
4. In the course of the work described above
    - Collect information on existing S&T management processes in MDA and its projects, elsewhere in DoD, in corporations that have more detail to offer, and among academics;
    - Assess methodologies for analyzing future prospects and directions, S&T portfolio management, and research oversight for utiity to MDA; and
    - Articulate how the radical innovation hub (or alternative concepts) might be adapted to MDA.

E. CONCLUSIONS

The concept of capabilities-based acquisition must be correctly understood. It is not merely to provide the capability that can be achieved currently. Rather, a capability-based approach defines a needed capability that does not depend upon a particular definition of *the* technical solution (which may be wrong) or a particular definition of the threat (which may change). Instead, it states an overall capability goal that provides a basis for driving or steering development efforts. The example for MDA is "the capability to defeat all missiles…of all ranges…in all stages of flight." With the statement of the capability goal, the approach to achieving it uses spiral development and requires a robust S&T effort to achieve improvements from current capabilities toward the goal.

From this standpoint, MDA must have an S&T program appropriate to the capability goal. The 2 January 2002 Missile Defense Guidance fundamentally changed the picture and focus from one where it could be argued we had the technology in hand to one where goals were set for capabilities that were well beyond what we have. MDA has to transition this new perspective—and this is not likely to occur without strong, focused attention to determining how to provide the innovation needed for achieving significant new capabilities for future blocks. The experience of the industrial firms and the DoD programs reviewed in this study indicate that appropriately focused, sufficiently independent, and robust S&T, based on concerted and systematic processes of technology management, is required.

GLOSSARY

ARPA	Advanced Research Projects Agency
BMDS	Ballistic Missile Defense System
CECOM	Communications-Electronics Command
CR&D	Central R&D
CTSG	Core Technology Steering Group
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DSB	Defense Science Board
FFRDC	federally funded research and development center
FOIA	Freedom of Information Act
GaAs	gallium arsenide
GOCO	government-owned contractor-operated
GOTChA	Goals, Objectives, Technical CHallenges, Approaches
IDA	Institute for Defense Analyses
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IHPTET	Integrated High Performance Turbine Engine Technology
KAPL	Knolls Atomic Power Laboratory
MDA	Missile Defense Agency
NASA	National Aeronautics and Space Administration
NEMI	National Electronics Manufacturing Initiative
NVESD	Night Vision and Electronic Sensors Directorate
NVL	Night Vision Laboratory
PM	Program Manager
R&D	research and development
S&T	science and technology
SBU	subordinate business unit
TechSG	Technology Stage Gate

APPENDIX A

DoD PROJECTS CASE STUDIES

TURBINE JET ENGINE CASE STUDY

Focus: We focused on the development of turbine jet engines from the 1960s through the establishment of the Integrated High Performance Turbine Engine Technology (IHPTET) program in the mid 1980s. The IHPTET process that enabled U.S. companies to establish a position of leadership in the production of air-breathing propulsion technologies. The case study concentrates on how S&T management principles established during that period may have affected the process by which these technologies were introduced.

Technical Challenges

Propulsion is one of the major enabling technologies for aerodynamic vehicles. Early jet engines offered the promise of revolutionizing civilian and military aircraft, but suffered from serious drawbacks: (1) poor weight-to-thrust ratios, (2) excessive fuel consumption, (3) poor reliability, and (4) unacceptably short periods between routine engine changes. Joint government-industry efforts over a 20-year period translated into world leadership for the United States in jet engine technology—leadership that provided significant comparative operational, logistics, reliability, and maintainability advantages over foreign military and commercial competitors.

Lessons and Conclusions

The S&T management structure for developing jet engines had the following characteristics:

- Joint inter-Service programs (e.g., the Air Force and Navy in the JTDE, followed by IHPTET, which also included Army and NASA participation) that allowed work toward common problems but with separately defendable budgets within each organization.
- Technically competent government personnel involved in programs management, who could challenge field personnel (both other government and industry) to work outside of their "comfort zone."
- Senior management personnel, who provided program stability (including the laboratories and in the Pentagon), in some cases for 20 years or longer.

- A closely monitored succession of leadership, so that the basic approach/ philosophy remained stable.
- Small, focused teams with minimal levels of management, with strong leadership working at the technologies level. This is applicable to either government or industry laboratories.
- Developed open communications and levels of trust between personnel in the government and in the companies; the latter could thus feel that their own competitive advantages would be safeguarded by the former.
- Encouraged competitive development by the engine companies on common problems, even when not all the companies were selected for particular contracts.
- Eventual tie-in of "6.2 and 6.3 type" development programs to a transition plan for systems applications, with "buy-in" by the user communities.
- In a similar vein, a sufficient number of development opportunities (including engine acquisition programs) were available for technology transfer, providing a path forward to anticipate future development needs.
- Prioritized the anticipated required technologies so that planning and execution could be brought to fruition at the correct time. This avoided (for most cases) situations where development programs were halted, until the appropriate technology breakthrough occurred.

Beyond the management characteristics, several recurring themes were found in this case study's examination of the history of aircraft engine development in the United States between 1960 and 1985:

- Basic research is most valuable for providing science, models, methods, and tools to predict the performance of a design configuration. Such tools allow designs to be refined before they are implemented in hardware.
- The most worthwhile expenditures were on full-scale demonstrators to evaluate the maturity of technologies, prototype component designs, and system-integration issues. These demonstrators also vetted technologies, sometimes showing that investment in a once promising technology should be ended.
- Tight-knit teams with a vision, long-term commitment, and minimal hierarchy can discover and deliver major technical advances. Early on, the promise of radical technologies is not clear. Support is often a matter of faith as much as reason. This is what distinguishes radical from incremental advances. Such technologies cannot survive layers of top-level reviews. They depend on champions and trust. When an agency funds a tight-knit team and depends on trust, rather than reviews, there is a significant risk that there will be little to show for the investment. On the other hand, small, tight-knit teams

can develop technology so rapidly and so inexpensively that a much higher failure rate is tolerable. However, when layers of oversight and reviews are used, there is almost no chance of successful radical innovation.

- A product can be placed in service with a minimum level of capability and then improved through ongoing technology development.

NIGHT-VISION CASE STUDY

Focus: This case study focuses on the efforts of an evolving government R&D entity known as the U.S. Army Night Vision Laboratory (NVL). Having developed important force-multiplication technologies for the United States, NVL is widely recognized as highly successful. The laboratory also contributed to the formation of a dynamic commercial market that the U.S. DoD has been able to leverage to improve the quality and cost-effectiveness of a wide variety of night-vision systems.

Technical Challenges

Efforts to develop night-vision capabilities took two different technical paths: (1) near-infrared image intensification and (2) forward-looking infrared (FLIR). Striking success was achieved in both areas.

Lessons and Conclusions

Consistent attention to organizational issues was one of the key management principles. Methods to achieve that goal included the following:

- Systematic efforts to keep abreast of technology changes;
- Continuous field demonstrations of NVL systems for members of Congress and their staff, along with representatives of DDR&E, (D)ARPA DA, AMC/DARCOM, ECOM/CECOM, and others;
- Active leadership by NVL personnel in pertinent meetings and conferences organized by U.S. DoD with participants from all services;
- Cooperation and utilization of night-vision technology developed by other U.S. DoD laboratories, R&D entities and services;
- Active participation and cooperation in the selection, insertion, and configuration management of night-vision technologies in various weapons systems.

Intensive, detailed attention to user needs was another important management principle. Methods employed to achieve that goal included

- Development and rigorous, comprehensive use of methodical systems analysis (“visionics”) to understand the relationships of physical parameters to final system performance in the field;
- Sending personnel onto actual battlefields to work directly with users on both immediate needs and long-term goals;
- Use of visionics for the design, product engineering, and testing functions of night-vision devices;
- Focus on cost-reduction techniques, to permit wide application among soldiers.

Forward-looking management of technology development was a third cornerstone principle. This was achieved by:

- Systematic review of multiple, deliberately redundant night-vision technologies for the short, intermediate, and long term;
- Emphasis on design and fabrication of prototypes for intensive testing (in laboratory and field) and support to the troops in the field;
- Pioneering application of configuration and concurrent-engineering management, with an emphasis on application of modular concepts.

Building in-house expertise and leveraging it to manage contractor efforts was a fourth basic principle. This was done by:

- Deliberate program to recruit qualified technical personnel with assurances of hands-on immediate experience in R&D, product engineering, laboratory and field-testing, as well as opportunities to engage in relatively under-developed science domains;
- Continuous technical training and promotion of technical personnel;
- Formation of project teams and extensive use of “team leader” concept (not defined or prescribed by the U.S. Civil Service);
- Temporary exchange of technical project personnel among NVL, other U.S. Army laboratories, and other DoD and commercial (contractor) entities;
- Procedures for information exchange among contractors both to advance S&T and provide for competitive procurement;
- Changing contractors and the focus of R&D activities in response to successful development.

POLARIS SUBMARINE-LAUNCHED BALLISTIC-MISSILE CASE STUDY

Focus: We examined the development of the first-generation of Fleet Ballistic Missiles from the inception of the idea in the late 1940s through the fielding of the Polaris series of submarine-launched ballistic missiles in 1960. The study concentrated on the role S&T played in an engineering-oriented program, as well as how the Navy's Special Projects Office managed that S&T component.

Technical Challenges

The Polaris program office had to resolve several major technical challenges simultaneously. Major technical issues included developing (1) a small, lightweight warhead with a high yield; (2) a precise navigation system to determine the launch point accurately; (3) missile guidance and control; (4) underwater launch techniques; and (5) a long-range, solid-fuel, submarine-launched ballistic missile. All these challenges need to be resolved on a very tight program schedule (approximately 5 years from project initiation to IOC of the first missile). Developing the missile was the major challenge, given that the Soviets began a counterpart program to develop a solid-fuel submarine-launched ballistic missile 3 years after the Polaris project began but could not field a satisfactory operational system until 20 years after Polaris A–1 missiles entered the inventory of the U.S. Navy.

Lessons and Conclusions

- Developing this missile required creating a new organization to develop a Fleet Ballistic Missile—one outside the existing Navy acquisition structure.
- The Navy emphasized developmental engineering first, but circumstances later forced it to support research into S&T issues, perhaps to an even greater extent than it wished.
- All aspects of the project "involved pushing back the frontiers of science to a degree and scope which had never before been done." Theoretical and experimental research was authorized to rectify problems. Applied research was necessary to build equipment for proof-of-concept testing of key components.

- Striking the right balance between engineering and science was one of the fundamental managerial problems. The relative impact of scientists varied over the course of the project, but never disappeared.
- Scientists participated in a number of activities, including:
  - Evaluating technological plans;
  - Validating and encouraging engineers' approaches to problems as well as providing a sounding board for engineering proposals;
  - Identifying technology opportunities and estimating the time lines when immature technologies would become available so that program managers could plan on the basis of those expectations;
  - Studying key phenomenological problems (e.g., the impact of wave-induced motion on a missile moving to the surface from various depths);
  - Estimating the expected parameters for subsystems still to be built;
  - Providing public validation of the scientific reasonableness of the Polaris program and its various concepts to the public, the administration, and Congress.
- The Chief Scientist maintained liaison with the scientific community to ensure that outside advice would be intelligently evaluated and interpreted. Program managers recognized the political importance of winning support from leading scientists who often become the final arbiters of whether a major defense project should be pursued.
- To build trust (or silence critics), the Navy ensured that each technical branch always had some money set aside to follow up on suggestions of outside scientists.
- The Navy pursued multiple technical approaches simultaneously, seeking to achieve at least a marginally satisfactory initial operating capability to meet the developmental schedule. At the same time, the Navy identified, evaluated, and developed alternative technologies that offered better operational capabilities to meet the ultimate operational requirements for a fleet ballistic missile.
- The program benefited from the earlier investments of others in applied R&D.
- The Navy recognized the importance of getting the highest quality people and then making them totally dependent upon the Polaris project succeeding. The same management philosophy applied to contractors as well. Some members of the Special Projects Office later claimed that selecting the right people was one of the most important factors in the program's success.

- The Navy made a consistent and sustained investment in S&T research over time, even though the precise amount invested varied over the years.

ATLAS ICBM CASE STUDY

Focus: Atlas was selected because, as the first U.S. intercontinental ballistic missile (ICBM), it represented a watershed for U.S. strategic capabilities not previously possible with the engineering and technological know-how then extant. The result was "the greatest single research and development undertaking in the history of the United States, exceeding in scope even that of the Manhattan Project," according to the U.S. Air Force. This case study concentrated on how S&T related to engineering development and how the S&T component was managed in the Atlas Program.

Technical Challenges

The developers of Atlas faced three primary kinds of technical challenge: (1) those where the basic phenomenology of the matter was not understood, (2) those where additional technical investigation was need to support engineering solutions, and (3) those where testing was required to identify unknowns and to perfect system integration. Some of the technical challenges included the dynamics of reentry vehicles, need for more precise inertial guidance, development of a successful boost vehicle, engine design, staging, control, and alternative methods for fabricating the airframe.

Lessons and Conclusions

- The Air Force created a new organization to manage development of the Atlas ICBM, one outside existing bureaucratic lines of authority.
- Although primarily an engineering development effort, the program conducted a significant amount of S&T to deal with the three kinds of technical challenge listed above.
- Significant and sustained investment was made in R&D over the course of the project. Each year, the program managers allotted $20 million for R&D. Although the amount of money budgeted for R&D remained constant, as a percentage, the funds devoted to R&D declined from a high of 12.5 percent in the first year to only 4 percent in the last year.
- The Program's director believed that maintaining the scientific community's interest and participation was essential for success. Consequently, the Program tried to attract the best and brightest scientific talent to the project.

- To ensure that no single technology proved unworkable (thereby jeopardizing the program's success), project managers contracted for alternatives to each of the major subsystems. In some cases, this also meant employing separate contractors to work the same problem concurrently. Little information was shared between them as a way of further promoting competition (and quickening the pace of development).
- Atlas program managers emphasized experimentation as the desired approach to system integration and testing because they believed that it was impossible to predict how different parts of the overall system would function together based upon the theoretical knowledge of the day.
- Panels of scientific and technical experts from academia and government research institutes periodically advised the Air Force about specific problems and offered new approaches to those problems.
- Even though a specialized Air Force command was charged with doing R&D, the program relied primarily upon contractors to perform the work.

NAVAL REACTORS PROGRAM CASE STUDY

Focus: This case study examines the joint Atomic Energy Commission-Navy program to develop and field nuclear reactors for submarines. This program lay at the intersection of two continuums—the development of nuclear power and the world of submarine technology. The study concentrates primarily upon the early years of the program (1949 through 1959), with some observations of how the program evolved after the initial nuclear power plant was fielded.

Technical Challenges

Development of naval reactors posed challenges in terms of nuclear power and submarine technology. In the field of nuclear power, the Naval Reactors program grappled with such as issues as (1) whether to use gas, liquid metal, or water to cool the reactor; (2) type of power plant; (3) appropriate materials; and (4) size, weight, reliability, and safety concerns. Most of these issues involved probing the boundaries of existing scientific and engineering knowledge.

Lessons and Conclusions

- The Naval Reactors Program was created as a new organization that functioned outside the existing Navy acquisition program-management structure.
- Program managers regarded hiring highly qualified people as a central task. Consequently, the training and education of its headquarters personnel was given first priority. These highly qualified personnel
  - Set technical requirements in sufficient breath and depth to assure that research products met performance objectives.
  - Used sound technical judgment in evaluating project results and determining its progress.
- S&T project progress and results were frequently scrutinized and judged on technical grounds, after often tough, sometimes bruising, debate.
- The Naval Reactors Program was a demanding customer in its management of government-owned/contractor operated (GOCO) laboratories, universities, and contractors performing research.

- Clear definition of program performance goals and systematic, strict evaluation of the projects led to well defined technology gaps and to focusing research where it was most important to the overall goal.
- Clear program technical and schedule requirements were set early and, in turn, drove S&T project decisions on how much research was enough. Requiring research to support development schedules was instrumental in delivering working systems on time.
- In its quest for solutions to an entirely new set of technical problems, the Naval Reactors Program maintained a strategy of pursuing several technologies simultaneously, thereby reducing long-term technical risk. The strategy was applied at several levels from overall concepts to specific materials and from fundamental research through engineering development and operations at sea.
- R&D (including the S&T component) also benefited from stable budgets, most of which came from the Atomic Energy Commission. The internal budget-setting process ensured that decisions to cut or fund additional projects were viewed as how those affected the overall program goals. When a new idea got a priority, "everything was up for grabs, not just research." That meant that the S&T research budget was not automatically cut when additional money was needed elsewhere.
- Research management at the Program's headquarters was under the directors of technical groups (physics, materials, etc.), not project officers.
- Employee turnover was low:
  - In sharp contrast to the then normal current personnel rotation in the federal government, people typically stayed with Naval Reactors Program for many years. As a result, the program possessed an extraordinary "corporate memory." The knowledge accumulated through experience in the headquarters technical groups and dedicated laboratories was invaluable; many difficult technical problems required long-term commitment to solve.
  - The long tenure enjoyed by the program's technical leaders encouraged them to think long term, because they would still be around to reap the benefits or suffer the consequences of S&T research management decisions.
- The director of the Naval Reactors Program was directly involved in managing research. He defined the technical areas of research concentration, reviewed individual projects, and actively managed the research portfolio.

PROJECT DEFENDER AND EARLY BMD RESEARCH

Focus: This case study examines early programs to investigate ballistic-missile-defense-related technologies from the late 1950s through the late 1960s with special emphasis on Project Defender.

Technical Challenges

Project Defender conducted groundbreaking R&D into a wide range of enabling technologies for missile defense. Its research program included advanced sensor, interception, kill, and battle-management technologies. In the interest of understanding ballistic-missile phenomenology, the program also investigated the characteristics and effectiveness of penetration aids (penaids) in conjunction with designers of U.S. ballistic missiles.

Lessons and Conclusions

- The roots of Project Defender lay in the findings of an ad hoc national-level panel composed of science and technology experts.
- Unlike most of the other cases, Project Defender was conceived as an R&D program rather than a systems-development effort. Consequently, the largest part of the program (40 percent) was devoted to research into the phenomenology of ballistic-missile flight from launch to reentry.
- The program was managed by an entirely new and independent organization, the Advanced Research Projects Agency (ARPA), initially reporting directly to the Secretary of Defense.[1]
- Program managers took a long-term perspective when considering R&D and so emphasized.
- The managers of Project Defender insisted that all S&T projects have a direct bearing upon problems of interest to missile defense.

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[1] ARPA was created in 1958 with a charter focused on three "Presidential Initiatives": space, missile defense, and nuclear test detection. See Richard Van Atta, Seymour Deitchman, and Sidney Reed, *DARPA Technical Accomplishments*, Volume III (Alexandria, Va.: Institute for Defense Analyses, July 1991), p. II-1.

- The approach to R&D was to contract the actual work to existing government and private-sector laboratories. As part of that process, ARPA created several "centers of excellence" within those some of those organizations.
- Although Project Defender was a broad national program to look into missile defense, it was conducted as a series of more narrowly defined subprojects (e.g., radars, architectures, penaids).
- Program managers reached out to scientists and technologists outside the program in an effort to attract new ideas and perspectives. Such efforts included sponsoring a classified technical journal devoted to the problems of missile defense and sponsoring a series of technical conferences.

APPENDIX B

INDUSTRY CASE STUDIES

DUPONT CORPORATION

Focus: For a corporation of this size and complexity, growth through productivity is not sufficient. DuPont's S&T objective is to employ science to provide a continuous flow of new concepts, materials, applications, and services, all of which should bring significant growth in both sales and profitability.

Some of the significant challenges include

- Balancing innovation programs and resources to support existing business units and diversifying into new S&T-based products and emerging markets.
- Dramatically accelerating output and effectiveness of innovation programs.
- Improving management processes, S&T resource allocation, and business linkage without stifling innovation or missing opportunities.

Application Example Case: Development and qualification of Kevlar for military uses.

Lessons and Conclusions

DuPont is the largest chemical company in the United States (second largest globally) and now ranks 70th on the Fortune 500. In its 200-year history, the primary product lines evolved from explosives to chemicals, then to polymeric materials and fibers. The major research emphasis is now in biology, work at the interfaces of sciences, and sustainability. Its unusual long-term success is due to strong and consistent adherence to its core values and culture, combined with a significant ongoing investment in science and corresponding evolution in management structure and practices. Factors in this success include the following:

- *Significant commitment to R&D:* $1.2 billion annually (4.4 percent of sales), over 40 R&D and customer-service labs in the United States, and over 35 labs in 11 other countries.
- *Technically capable leadership with significant longevity:* Over 75 percent of senior leaders hold degrees in technical fields, and most have over 20 years with DuPont in technical, manufacturing and business roles.
- *Organizational patience and long-term vision:* DuPont spends years on new products and applications. There is broad recognition of the need for R&D with a range of time horizons.

- *Management systems to support and facilitate effective technical programs:* Key systems include stage-gate processes for developments and alliances, the Apex Research system for the discovery process, and a formal Technical Effectiveness Process to review Business Unit S&T resource allocation and effectiveness. Corporate councils and the annual technical conference support technical networking and communications.
- *Ability to capitalize on new scientific discoveries and to improve management processes continually:* Through self-analysis, study of best practices, and innovative leadership, DuPont maintains its position in the marketplace.

Case Summary

DuPont defines itself as a science company and takes on significant R&D challenges to achieve and accelerate sustainable corporate growth. Its history of ventures into entirely new fields has often resulted in entirely new businesses. Long-range R&D and partnerships are more highly regarded today than 5 years ago, when some business leaders questioned the value of central R&D. Long-range R&D is recognized as essential for the future of the company. DuPont's past reputation was that it commercialized only products invented internally. Today, many more concepts and businesses are acquired or developed through partnerships, joint ventures, and alliances with outside companies and universities.

Organization for S&T

Near- and intermediate-term S&T is currently highly decentralized, while major new long-term programs and specialized support services remain centralized. The strategic business units (SBUs) manage and fund their own unique R&D work and are held responsible for results. Some R&D personnel are now located at SBU sites. Challenges in this model include balancing near- and long-term projects, maintaining current knowledge and connections to the outside scientific community, and sharing technologies across business units.

Central R&D is responsible for programs in the 5+ year time horizon (many of which do not support existing business units), technical support services, and internal consulting services. Funding for central R&D is a non-optional component of corporate overhead that is allocated to the business units.

Management of S&T

A Technical Effectiveness Process (TEP) employs analytical and database tools to ensure that appropriate levels of resources, staff, and business function support are assigned. SBUs must present their TEP analyses to the chairman of DuPont annually. Corporate impact of this process was described as “tremendous.”

Business unit managers may choose from a portfolio of best management practices. Programs managed by “Stage Gate” processes appear to be more robust, being structured to withstand changes in personalities, management, and organizational structures. They have clear definitions of resources and expectations, early and ongoing business participation, and structured revalidation of assumptions. Thus, the transition from innovation to commercial use flows more smoothly.

Very long range and exploratory work done in central R&D is selected and managed through the Apex process. A top-level central R&D board manages this process, and Apex projects are reviewed and advised by teams associated with the major business units. The central R&D “Inbound Marketing” group seeks new concepts and opportunities. (These six people provided 75 percent of the ideas screened last year.)

DuPont’s experience shows significant benefit from periodic review by and support from experts and resource personnel from within and outside the company, as well as periodic testing of underlying assumptions. Review teams often include experts from other parts of the company, DuPont fellows, or professors doing grant work for DuPont.

DuPont leaders repeatedly stressed that “so much depends on the people involved,” and in getting the right people into the right assignments. Examples were cited of the need to move people to overcome organizational resistance to change and to align skills with needs. Moving managers to a variety of positions within the SBU and, as needed, across the corporation encourages communication and helps the managers develop new perspectives and experiences.

Mechanisms to facilitate internal technical communications include an annual internal corporate technical conference, corporate technical councils (responsible for technology management and personnel development), and a manufacturing council. The DuPont Fellows Forum, which meets monthly, allows recognized long-term excellent individual technical contributors to play a role in S&T across the corporation.

Resource Allocation

SBU leadership teams are heavily involved in resource allocation for business-unit S&T work. They are held accountable for their results both through business results vs. strategies and the TEP. Some business-unit personnel are also involved in longer range programs through Apex and other processes.

The absolute level of funding for central R&D is set by the DuPont executive committee and approved by the board of directors. This funding level arises from review of the long-term strategy and the recommendations and input of the Apex board, balanced with analysis of business results. Central R&D budgets have been relatively flat in spite of economic softness. In the last 2 years DuPont has implemented several new processes to optimize S&T results, spending, and business linkages.

IBM

Focus: Transformation of IBM's approach to innovation/S&T as a critical component of a major transformation of the global business. The IBM R&D process was further illuminated through a study of IBM's development of X-ray lithography.

Lessons and Conclusions

IBM, an $86 billion information-technology corporation, has been fundamentally transformed over the past decade from a supplier of computer mainframes to an organization focused on systems solutions to customer problems. Corporate financial results were also significantly improved. The refocusing of corporate R&D was a critical component of this transformation.

Lessons learned from this study include the following:

- Understanding of a company's unique strengths is critical in a transformational strategy. IBM's deep vertical integration, the basis for its decades-long dominance of computer systems, remains a fundamental strength in the new business model. The decision not to break up the company was essential to IBM's successful transformation.
- A long-range innovative vision of the future is critical to setting strategic direction, defining key technologies, and identifying high-leverage points. IBM's 5–10-year global outlook identifies "fundamental technology building blocks" and investments required for scientific/technology leadership in those areas.
- Innovation and scientific excellence are not sufficient—an organization must have mechanisms to link innovation to the businesses and customers, as well as to transition new developments from R&D to operations and the marketplace.
- A key reason to do research is that it pays—in addition to significant product innovations, IBM received $1.6 billion in revenue from its patents in 2001.
- Performance expectations and evaluation systems are more effective when they include desired behaviors (teamwork, customer involvement, business unit support).
- Major research efforts that are successful technically but not widely adopted in the marketplace may still reap significant benefits for the company in

transferable scientific knowledge and skills, market knowledge, and intellectual properties.

Case Summary

Over the past three decades, the information-technology industry has evolved from centralized mainframe computers used in narrow business and scientific applications to ubiquitous computing in which individuals interact by means of multimedia information systems in nearly every facet of life. While IBM maintained a dominant position in large-scale computers, especially for business applications, it lagged, and thus had to reposition itself, in the dynamic world of internetted computing systems. Key in this repositioning were a decision not to break up IBM and a reaffirmation of the company's technical heritage by revitalizing IBM research and development.

Early in IBM's history, S&T was conducted in a closed and largely defensive posture, based on the company's dominant position in the computer industry. Although IBM had S&T work underway on many of the ideas and technologies that led to the revolution in the information age, the company often did not take full advantage of these innovative technologies. IBM's fundamental transition over the past decade is illustrated by shift in sales: for the first time, hardware is less than 50 percent of revenue, services are 44 percent, and software is 13 percent.

IBM was a highly vertically integrated company: products from IBM R&D were manufactured in IBM facilities using IBM processes and technologies, sold through IBM distribution channels, and supported through IBM service. This deep vertical integration, which was the basis for IBM's decades-long dominance of computer systems, has been transformed through a sweeping process of redefinition of both the business model of the company and the relationship of technology development to this refocused business model.

IBM made a strategic decision to retain its technology-development operations, redefining how they do business. The IBM research division now has an explicit customer focus, where "customers" are both in the marketplace and internal (those who develop the innovations into product results). IBM is committed to leadership in fundamental technology building blocks such as microelectronics and storage technology, and it invests in studying the fundamental science underlying these technologies. IBM seeks world-class status in targeted technology areas, establishes partnerships with world leaders in fundamental technologies, and supports basic research at universities to lead the development of these technologies.

IBM took the following steps to redefine the Research Division:

1. *Leveraging intellectual property:* IBM aggressively patents and protects its intellectual property. In 2000, it received over $1.7 billion in royalties.
2. *Restructuring staff roles and expectations:* The academic environment was replaced with greatly increased emphasis on bottom-line impact. Research managers also manage relationships with an IBM business, serving as primary points of entry for that business to the entire research organization. This broadens business-unit understanding and helps move research discoveries from lab to market.
3. *Changing funding:* While much of IBM's research budget still comes from corporate, significant funding now comes from IBM business units (30–40 percent corporate, 10–15 percent government/DARPA, remainder from product divisions). Thus, IBM researchers are now more sensitized to the needs of IBM's businesses, and the businesses work more closely with researchers, because these funds now flow directly from their profits and losses. The 2001 R&D spending was $5.3 billion (6 percent of revenue), relatively consistent despite the economic downturn.
4. *Connecting researchers to customers:* IBM's "First of a Kind" program assigns an IBM research scientist to a carefully selected customer to develop a solution to the customer's problem. This program recently expanded into the Emerging Business Opportunities program, in which IBM Research works directly with customers to create advanced solutions to complex problems.
5. *Opening up to the outside:* IBM now licenses and sells technology, even to competing companies, and services and supports equipment and software from any company. These changes give IBM more channels for its intellectual capital to get to market. IBM also works in Java (invented outside IBM) and the open-source Linux operating system.
6. *Increasing the flow of ideas:* This includes locating labs near intellectual centers to stimulate the flow of ideas into the labs.

IBM's 5–10-year global technology outlook projections include vision and strategy for using a technology, approach needed to lead, and high-leverage points. The Technology Plan, which is then tied to a financial plan, drives resource allocation. Because IBM believes that without a leadership position in the basic core technologies, it cannot effectively compete in the information technology industry, it invests to keep itself two to three generations ahead of its competitors in the key building blocks (e.g., nanotech and quantum computing) of its future competitive position.

Some developments come from corporate guidance to penetrate new areas (e.g., Internet applications). Other new ideas originate with research scientists, who have freedom for exploratory work. Moving from concept to project (~$1M and 4–5 people) requires analysis of costs, potential results, people needs, time to expected results, and return on investment. Movement to the next level of investment and effort requires a detailed business case assessment. The program is then usually transferred to a business unit with research team members.

An overarching driver for research is that IBM is in business to make money—there is a singular goal of developing and producing products that further the company's competitive position by connecting research to applications and implementation. Measurements include patents and publications, as well as assessments of how well researchers partner with product divisions and how well they supported moving ideas into product applications. Salary and personnel advancement decisions are directly linked to evaluations.

GE

Focus: This case study focused on the management of the corporate R&D center (CRD). The study also focused on the relationship over a quarter century between the CRD and GE Medical Systems (GEMS), an SBU that has much in common with large, long-lived defense development programs.

Lessons and Conclusions

The study paid special attention to the GEMS business because in practice its mission—to be the leading medical diagnostic equipment maker in the world—was sufficiently narrow and technical to make GEMS quite comparable to a long-running U.S. Government development program. The lessons taught by the GEMS experience are similar to those taught by the government programs cited elsewhere in this report. Among them:

- Because operational managers tend to focus on the short term, they shortchange S&T until disaster looms.
- Centrally managed research that looks beyond the needs currently recognized in business units or project offices is essential for long-term success.
- Top corporate or government program executives must protect long-term S&T until such time (usually in a crisis) as the business unit managers or project officers recognize the need to adopt new technology quickly.
- Managerial stability produces strategic consistency, both of which give technology development steady direction.

GE has always paid attention to the relationship between CRD and the SBUs. GE's industrial laboratory was the first to maintain a dedicated liaison cadre. By the mid-1950s, CRD scientists were assigned on rotation to serve as consultants to the general managers of the client SBUs and as sales detail men for contract work. The changes made in the late 1980s and early 1990s involved a commitment to closer relations with the GE SBUs in which balances were struck that favored near-term support of business and mechanisms were created to involve businesses in S&T. For example, progress toward meeting key objectives in work for GE SBUs was monitored regularly on a red-, yellow-, green-light basis, and at the end of each year CRD polled its GE customers on whether its achievements toward the key objectives met, exceeded, or failed to meet their expectations. Further, most CRD research was done with the participation of representatives of one or more SBUs to facilitate transition of the technology to an SBU. Also, project personnel often transitioned with their project, and it was common for CRD to maintain a considerable number of people on a project for extended periods after transition to assure continuity.

In the 1990s, GE CRD demonstrated that it is possible for a centrally controlled facility to carry out a broad corporate mission, one involving six components:

- *Teaming:* As noted above, R&D, engineering, manufacturing, and marketing worked as a team from project initiation, working multiple product generations concurrently.
- *Training:* CRD served as a source of top technical people for GE.
- *Problem solving:* CRD specialists often work directly with customers to help solve GE's critical technical challenges, a major departure from the traditional view of CRD as bench scientists.
- *Sharing:* CRD promoted potentially useful technology across businesses.
- *Source:* CRD searched for technology for GE businesses wherever it might be found, including sponsoring research at universities worldwide.
- *Game-changers:* CRD sought out new technology platforms that would create opportunities for major new products and services.

Case Summary

GE's business strategy has been aggressive, both in general terms and in terms of R&D. Using the advantage of size to take risks but never letting this size become a burden have been key factors in this approach. In its 2001 Annual Report, GE asked, "Can such a thing as a $126 billion growth company exist?" It answered,

> It does exist because GE always plays offense. We don't run this Company as a "$126 billion blob..." We run it as an $8.4 billion Medical Systems business...a $1 billion Ultrasound business within it...and as seven separate operations within Ultrasound, ranging in size between $50 million and $250 million. These operations are run by people who are obsessed with growth and achieve it by creating new markets and technology. Backing them are our systems, our initiatives, and a strong balance sheet that allows them to take risks for growth.

GE used portfolio analysis very early, investigating how each of its ventures was doing and only perpetuating or acquiring those that were market or technology front runners. By applying this approach to a broad spectrum of fields and different industries, GE sought to limit uncertainty, ensuring long-term survival while bringing immediate rewards. This implied that SBUs worked on individual strategies, basically competing for their share of the corporate resource pie. Like separate companies submitting proposals for a contract, they had to prove their worth through visible growth, earnings, patents, or whatever output they intended to create. Based on SBU submissions, centralized overseers allocated corporate funds. A huge amount of effort was required to arrive at realistic and useful metrics. On the manufacturing side, the accounting of value added vs. expenditure of labor cost and benefits was a key. The passion to measure was applied to CRD as well and produced some extraordinary efforts to measure research, such as the calculation of the average rate of return of the projects CRD transitioned over 1982–1987.

GE's total 2001 R&D expenditures were $2.3 billion. Of this, $2 billion was funded by GE. Customers, principally the U.S. Government, funded the rest. Aircraft Engines accounted for the largest share of these funds from both GE and customer funds. Medical Systems, Power Systems, Transportation Systems, and Plastics were the other major users. The budget for CRD (renamed the Global Research Center) was about $200 million.

Corporate S&T strategy, as well as overall strategy, are established in an annual process consisting of quarterly Corporate Executive Council (CEC, the top 30–40 officers) meetings, an October/November corporate officers (top 100–140) meeting, and a January Boca Raton meeting of the top 400–500 executives. These meetings are the venues that allow GE to set and abruptly change the corporation's agenda and to challenge and test strategies. Some participants have described the CEC sessions as "food fights" or "free-for-alls"; relatively unfiltered information was displayed, the organization's triumphs and failures were openly shared, and GE's top players were challenged and tested.

This, however, was high-level S&T strategy. Because SBUs differ from one another so much, the hard work of S&T strategy typically was done business by business. An example is thinking about long term vs. near term. Jet engines are very different from refrigerators. For engines, long term is 10 years. For refrigerators, long term is "next Friday." Thus, there was not one single process for CRD. Of CRD's approximately $200 million total funding, one-half came from the SBUs, one-quarter from outside (mainly the government), and one-quarter from Corporate. The general parameters for deciding what was to be done for these "customers" were as follows:

- How the money from an SBU is to be used is very clear. The SBUs tell CRD what they want done. The laboratory works on their problems. The director of CRD has some control, and there is feedback to the SBUs. CRD does not want to waste funds on projects that do not make technical sense, and it also can tell the SBUs if their projects are too near term.
- The outside funding might be either near or long term. Government-funded research is long term. However, any money CRD takes from outside has to be in a strategic area for GE.
- The one-quarter of the total money that comes from Corporate is thought of in CRD as being in three piles:
  - The first pile is for working on multigenerational products: Doing technology work to get ahead of the competition, producing the technology the SBU wants and needs for the future of their current product line.
  - A second pile is given for working on particular technical areas in the laboratory most likely to produce a return for the company.
  - The third pile is investment in "game changers." They are high risk, could be very long term, but to be justified, they have to have great expected payoffs. In GE the threshold for payoff return is $200 million.

The quintessential feature of the GE CRD approach, running through all three main categories above, is to think about multiple generations of products rather than to think short term vs. long term. The multigenerational approach is always focused on a product and a market. With this approach, a (cross-functional/cross-disciplinary) team focuses on improvements over time using an overall roadmap. GE senior research executives have found that under this approach S&T people can think better when they do trade-offs on cost or technology grounds. The decision to change and go to the next generation is made on cost, performance, and quality criteria.

Determining the specific research to be done, of course, differed among the categories of research. With respect to the business units, an SBU is free to acquire technology anywhere—internally or from a university, national laboratory, competitor, or CRD. CRD projects and funding from the SBUs are determined through an "objectives process." Working with key customers in businesses, CRD identifies 100+ key objectives at the beginning of each year. These objectives form the basis for SBU-funded projects; project details are worked out in negotiations between CRD and SBUs. Projects for government customers are determined through marketing efforts familiar to government contractors, usually conducted jointly by CRD and an SBU. The research funded by Corporate is determined within the flow of the annual strategic-management cycle. For example, in early 2002, the GE 2001 Annual Report announced that molecular imaging, distributed energy, advanced composites and sensors had been selected as areas for future CRD emphasis.

With respect to game changers, there is not a single system for finding concepts. Ideas came from a variety of sources. One part of the CRD mission is to look for technology worldwide, wherever it might be found. Also, the SBUs have their own facilities worldwide, which collectively form a rich potential source.

CRD is uniquely responsible for the progress that falls in between existing markets or technologies. For example, CRD frequently has discovered ideas with multiple applications. Exploiting synergy is seen as a major function that CRD should exercise through its involvement in the multiple-generation projects of many SBUs. To create support from marketing and developmental divisions, conceptualizers are urged to remain within the boundaries of business strategy.

GE always has been serious about CRD relations with the SBUs. GE's industrial laboratory was the first to maintain a dedicated liaison cadre. By at least the mid 1950s, about a dozen scientists and managers on rotation from their science work were assigned to client SBUs. There, they served as consultants to the general managers and as sales detail workers for contract work. GE executives had no doubt that this cadre was essential to the acceptance and survival of CRD. The changes made in the late 1980s and early 1990s involved a commitment to closer relations with the GE SBUs. The key-objectives-selection and performance-evaluation processes described earlier are the formal manifestations of CRD's intention to be responsive to SBU needs. Further, most CRD research was done with the participation of representatives of one or more SBUs. This was intended to facilitate transition of the technology to an SBU. Project personnel often transitioned with their project. Also, it was common for CRD to maintain a considerable number of people on a project for extended periods after transition to assure continuity.

Considerable attention was paid in the case study to a traumatic change common to U.S. industrial research in the 1980s. Tremendous pressures to show immediate financial results brought into question the very existence of centrally controlled and executed industrial research, such as that represented by CRD. In the end, GE continued to do S&T because after this vigorous challenge, top management was persuaded that GE could not afford to abandon it. GE has continued to do S&T, but of a very different kind:

- Balances were struck that more strongly favored near-term support of businesses,

- Long-term S&T was continued at a reduced level under more intensive oversight,
- Mechanisms were created to involve businesses in the S&T that remained.

CRD funding shifted from the pre-1988 state, when two-thirds was corporate funding and one-third contracted by businesses. After 1988, one-quarter of annual CRD funding came from “contracts,” and the corporate one-quarter was designated for exploratory work outside current businesses. In 1997, one-quarter of funding was corporate, one-quarter came from external sources, and one-half came from SBU contracts. The corporate funding continued to enable high-risk work in areas for future growth. (The case study did not address R&D resource allocation within SBUs, which was 90 percent of GE’s total R&D expenditures of $2.3 billion in 2001.)

CORNING CORPORATION

Focus: Develop an optical fiber to enable communications using light rather than electrons. The goal was to develop glass fiber with an intensity loss less than 20 db/kilometer. The case also examined the development of Corning's business and the central role played by R&D.

Lessons and Conclusions

R&D is central to the Corning culture. The Houghton family (owners and later major shareholders) believed in R&D investment in both good and bad times. They considered it essential for the company future and established an R&D culture from the mid-1800s forward.

Long experience at Corning, however, shows that the development of landmark new products is almost always dependent on knowledge gleaned from previous exploratory research.

Corning's development of optical fibers demonstrated that:

- A strong support of R&D is part of the corporate culture. R&D is considered to be essential for the long-term survival of the company, not an optional activity whose budget can be cut without consequences.
- Top-management leadership is required to build core competencies and protect long-term S&T projects through the inevitable technical setbacks or lengthy searches for seemingly unattainable solutions.
- Clear definition of performance goals provides focus and measurements for progress and success.
- Successful transition of the technology from the laboratory environment to commercial markets requires sustained effort by, and communication between, technology, business, and manufacturing leaders.
- Success in major development programs was often based on capabilities and expertise developed in earlier projects. Organizational memory and the experience of long-term technical personnel were significant factors in this success.

Case Summary

Because Corning management considers establishing core competencies in specialty materials to be essential, it has systematically accumulated in-house knowledge by consistently supporting fundamental R&D and retaining a work force with significant longevity (sometimes 50 years). This strategy has been repeatedly demonstrated to be effective. Expertise in high-temperature-ceramics processing developed during an unsuccessful gas turbine regenerator program was instrumental in developing catalytic converters, a major success and significant contributor to Corning revenues. Research on flat glass for windshields was foundational in the highly successful development of flat screen displays for laptop computers.

Corning believes this accumulation of in-house R&D knowledge plays an important role in innovation. Corning has not outsourced R&D or acquired start-ups because this does not result in accumulating knowledge and corporate memory. As Corning also found that separating R&D from the main organization in a “Skunk Works” approach was not effective, it returned to an integrated S&T process, where R&D is imbedded in the organization’s values, policies, procedures, and processes.

Developing Optical Fibers for Commutations

In the late sixties, Corning technology scouting managers identified an opportunity for radically new communication methods using light; these required low-intensity-loss optical fibers (<20 db/kilometer). In a 4-year R&D effort, Corning scientists produced a fiber with a loss of only 4 db/kilometer by applying innovative concepts based on existing in-house expertise in light transmission and scattering of light in glass (expertise acquired in previous R&D projects).

Corning spent many years addressing daunting problems in manufacturing, business, and patent litigation. A major risk was the management decision to build a production plant before the market developed, successfully positioning Corning to deliver optical fiber for the first commercial orders from MCI. Corning became the undisputed leader in production of optical fiber. Sixteen years were required to recoup the initial investments in fiber production, demonstrating upper management vision and patience and the perseverance of the scientists and business developers.

Corning's Innovation Process

The Corning Innovation Process was formally established based on its experience with the optical-fiber development effort. The process involves first setting strategic direction, then applying a stage-gate approach to develop successful products. Determining strategic direction requires two steps:

1. Create a technology road map by projecting future technology trends, analyzing Corning's strengths and weaknesses, and defining target areas for development.
2. Using the technology road map, establish a portfolio of projects and rank them by priority. Entrepreneurial managers who understand the business environment must be engaged in this task.

Once the portfolio of projects is established, the Five Gates Model is implemented:

1. Knowledge accumulation;
2. Applied research/proof of concept, feasibility experiment;
3. Prototype development (pilot development with limited production);
4. Pilot production;
5. Manufacturing/commercial operations.

The Five Gates process involves a cross-functional team with evolving roles as the program proceeds through these steps. Technology leaders drive steps 1, 2, and 3, and are involved in 4 and 5. Manufacturing specialists drive steps 3, 4, and 5, and business managers are involved in the process from gate 2 forward.

SUN MICROSYSTEMS

Focus: A corporation based on the development and exploitation of innovations.

Lessons and Conclusions

Sun, which has a 20-year history of bringing innovative ideas to market, is known for its business philosophy of open standards and open programming interfaces.

1. S&T is fundamental to Sun's future success.
2. The Chief Scientist must constantly assess the level of technology attained by peer/competitive companies, understand the product divisions, and advise senior management. The Chief Technology Officer (CTO) also needs authority to distribute R&D dollars.
3. R&D's role is to develop core technologies for breakthrough products, transfer technology, evaluate technical trends, attract technical expertise, be "intellectual trading posts" for technology within and outside the company, and provide internal consulting within Sun.
4. Turning research into products, a key competency, is "difficult, complex, and a social as well as a technical problem." Technology transfer from advanced development to product development is accomplished by moving people from Advanced R&D into the product divisions.
5. Innovation is not linear and may require many years to yield tangible results. Sun Labs pursues high-risk, high-potential projects, accepting that some will not work out, while a few will have a significant payoff.
6. Sun promotes networking and internal education through seminars, semi-annual technology leadership conferences, and an internal Web site where researchers collaborate on new concepts.

Case Summary

Sun Microsystems, Inc., was founded in 1982 with DARPA funding to Stanford University (the Stanford University Network) and commercialized through a venture capital startup. Today, Sun has 43,000 employees in 170 countries, revenues of $18 billion, and ranks 125th on the Fortune 500 list. In 2001, approximately $2 billion was spent on R&D, primarily within existing product-development organizations. Two to three percent ($50 million) was allocated directly by the Chief Technologist for advanced-technology developments not directly related to current products.

Sun's business is scalable computer systems (including high-performance supercomputers), high-speed microprocessors, and high-performance software services, as well as support for network computing environments. DARPA encouraged commercialization of Sun's RISC processor-based workstations by supporting their purchase by several universities conducting research for DARPA's VLSI project.

Sun institutionalizes innovation by CEO and CTO oversight over all R&D. The CTO has responsibility for all R&D spending. There is a close and continuing relationship between the CEO and the CTO. Sun's Chief Scientist, a company founder, pursues cutting-edge S&T concepts with a long-term perspective.

Technology transfer from advanced development to product development, an important mission at Sun, is characterized as "a contact sport." Sun accomplishes this by moving people: Each year 10–20 percent of Advanced R&D people move into the product divisions, and they are replaced by product-division personnel. Some make several such loops as projects move from research to product development. Return to the lab is not automatic. Some Advanced R&D staff are seen as "idea people" and are not expected to move with projects.

One of the most important roles of the Sun Microsystems CTO is "always to be looking outside." He manages Sun's technology and architecture standards, the Science Office, and advanced development programs. The CTO has direct oversight over all R&D spending, and personally manages 2.5–5 percent of Sun's total budget for advanced development.

Sun pursues an active program of education and seminars to refresh the organization, and it actively promotes networking. A semiannual technology leadership conference is designed by the CTO, with about 250 people attending each event. An internal Web site allows researchers to collaborate on projects not yet officially approved. This pre-project phase is an important part of creating a consensus for launching a formally supported project.

Sun Laboratories was established in 1990 in spite of CEO reservations about the prospective return on investment. Concerted effort was required to convince product managers that R&D should not be viewed as an external activity. Now Sun credits the laboratories with a key role in the growth of the company.

Sun Labs employs over 200, including 180 scientists and engineers at facilities in California, Massachusetts, and France. It also maintains collaborative relationships with universities, entrepreneurs, government, and other research institutions. Sun expects R&D to develop core technologies for breakthrough products, provide effective technology transfer, attract technical talent and expertise, act to exchange technology and know-how within and outside the company, and provide internal expertise and consulting within Sun. The Labs also evaluate technical trends.

New concepts are generated by both the product divisions and the CTO staff. An advocates program stimulates interaction between the labs and product-development organizations. Scientists are expected to bring new problems back to the labs from the product groups, and the advanced development staff is expected to investigate new solutions.

Project termination is handled as a simple zero-sum game, governed by ranking of projects and adjudicated by the CEO and the CTO. However, Sun tries to ensure that lab principal investigators have more than one project to lead, so that termination of an individual project does not reflect personally on the career or ego of the principal investigator.

Sun Labs' strategy is to develop technologies that are relevant to customer problems, feasible (in terms of time, money, and technical resources), and of direct benefit to Sun and its customers. While economic times have forced more selectivity in the projects funded, Sun still views its laboratories as a key part of its corporate strategy.

DAIMLER-CHRYSLER LIBERTY, THE ADVANCED–TECHNOLOGY DIVISION

Focus: Create an autonomous R&D organization to effectively pursue long-range radical innovations. The case examined development of the fuel-cell-powered car as an example of Liberty's advanced-technology process.

Lessons and Conclusions

Daimler-Chrysler's Liberty division provides a flow of innovations to the product divisions and serves as a focal point for radical innovation development programs, acquisitions, and partnerships. This experience demonstrated that for Daimler-Chrysler,

1. An independent, autonomous organization is needed to create innovative products. Such a "stand-alone" organization has the capabilities to support innovative culture that is not restrained by existing bureaucracy, so that application and production people do not inhibit the innovative long-term development work.
2. Top-management support and championship are important factors for guaranteeing long-term stability of the innovative projects.
3. Consistent funding provides a stable work environment and encourages technical risk-taking.
4. Simultaneously pursuing several technologies can mitigate long-term technology risks.
5. Successful transition of innovative technologies in to application requires teamwork between original developers and application engineers.

Case Summary

Chrysler founded Liberty in 1983, after GM and Ford had already established advanced-technology divisions to better compete with Japanese automakers. Liberty is an autonomous organization, with its own charter and budget. Liberty's mission is to develop advanced innovative technology for automotive applications by looking 5–10 years ahead and inventing new technologies for the future. Liberty's 50 Chrysler employees and 35 contract employees pioneered many products currently in commercial use, including die-cast magnesium instrument panels, hybrid power trains, and automatic tire-pressure-monitoring and control systems.

Liberty's budget is officially a part of the total engineering budget. Funding has been steady at about $30–35 million/year ($27 million in 2002). This budget is negotiated between the head of the Liberty division (a Daimler-Chrysler VP) and Daimler-Chrysler's Executive VP of Product Development.

The Liberty organization was built from scratch with personnel hand-picked to create a unique culture focused on innovation (similar to Skunk Works). To ensure that Liberty has expertise in many different technology areas, Liberty selects people with solid basic foundation in science and engineering who are quick learners and able to work well in teams.

The innovation process in Liberty is described as simple: you get an idea, sell it to the management, and go do it. Most project concepts are internally generated. No formal system for ranking and selecting projects is in place—the division head personally approves all new projects. The organizational culture and relatively stable budget encourage an open forum: people are not afraid to take risks, and they may criticize anyone or anything.

Although the organizational structure of Liberty appears flat, it has been described as a "tip of the iceberg structure." That is, the small Liberty group achieves high productivity by utilizing resources of many other organizations outside Daimler-Chrysler. Suppliers often contribute parts and hardware for projects, reducing Chrysler's costs and providing the suppliers an "in" to Chrysler's advanced technology. The Chrysler University Research program ($1–2 million/year) gives Chrysler a broad look into the academic advanced research world. Liberty's people are highly regarded in the Chrysler organization because of the effectiveness of this structure.

Other organizations within Daimler-Chrysler do R&D as well; however, duplication of efforts is minimal because different projects are undertaken. An advanced technology group in Germany also looks at time frames of 5–10 years, with some 250 projects under way. Liberty's approach to R&D is unique in that the development team carries the project through to implementation, spending time in operations to assist in implementation before returning to Liberty project work.

Advanced Technology Example: Fuel-Cell-Powered Car

Most major automakers are currently developing fuel-cell-powered vehicles. GM, Ford, and Daimler-Chrysler invested in Ballard, a Canadian company, to develop fuel cells with appropriate costs and performance characteristics to power their cars. (Chrysler's equity in Ballard is 25 percent, and Ford has about 20 percent.) One billion dollars has already been spent on fuel cell development. Liberty's role is to adapt the fuel cells to Chrysler's needs.

The big unknown with fuel-cell-powered cars is how to supply hydrogen. The current alternatives are to create a commercial hydrogen infrastructure or provide on-board hydrogen generation. The former alternative necessitates on-board hydrogen storage—a difficult technological problem. The latter alternative is currently addressed by developing reformers to convert gasoline to hydrogen—not an optimum solution from cost and efficiency standpoint.

Because it is not possible to predict which alternative will be adopted commercially, Liberty mitigates this risk by pursuing technologies for both alternatives simultaneously (this approach is typical for Liberty). Liberty is developing both ultrahigh-strength, low-cost fibers for high-pressure hydrogen storage cylinders and sodium borohydride for on-board hydrogen generation (with Millennium Ev and Dow). A fuel cell/sodium borohydride car called Natrium with a 300-mile range has been developed.

ROCKWELL INTERNATIONAL

Focus: Transformation of a small research function to a Science Center of great benefit to the company and the U.S. Government.

Lessons and Conclusions

Rockwell transformed its central S&T activities with tremendous benefit to both the company and its U.S. Government clients (e.g., NASA, DoD).

1. "If you want to do something different, you must in fact do something different."
2. Interpretation of mission, preparation of action plans, and responsibility for their execution can be successfully assigned to a contractor firm that is willing to commit major competence S&T resources. This requires trust built through personal integrity and long-term intense management cooperation between client and executor.
3. Transformation required significant changes in management personnel: in the year following appointment of the new director, the Science-Center management team was completely replaced with a mix of people from the divisions and outside.
4. The transformation was led by the Science-Center director and his subordinate CTOs, who were given great freedom and responsibility and strong top-management support.
    - The Science-Center director took a direct role in relationships with key customer and operating division leaders, emulating GE's liaison scientist role and McKinsey partner behavior.
    - Subordinate CTOs, who were carefully selected and trained, were critical in developing and managing client relationships and balancing needs.
5. A long-range research and planning function is an important factor in avoiding operating unit overreach or unrealistic acceptance of emotion as real demand.
6. The Strategic Technologies Advisory Committee, composed of the senior technical officers of all the major corporate segments, provided significant guidance to the Science Center and ensured business unit interaction and support.

7. Competitive tension between research centers required continual renegotiation of division of responsibility, but enhanced the competitiveness of both centers.
8. The role of key leaders of defense contractors like Rockwell in implementing and sometimes influencing or helping set national policy is unique and significantly different from the typical corporate responsibility.

Case Summary

Rockwell inherited a research laboratory as part of an acquisition. Although over one quarter of Rockwell's sales volume was in science and technology, the laboratory (Rockwell International Science Center) was less than 1 percent of the size of the firm.

From 1970–1990, the Science Center was brought into working partnership with the company's various businesses. The case details the transformation of the Science Center as the company experienced acquisitions and divestitures, the removal of the original owners, major national programs, and increases of 5 times in sales volume and 10 times in net worth.

Key points of the case are restoring the lab from near oblivion, building partnerships in an entrepreneurial environment, codification and acceptance of funding and management, and the emergence of the Science Center staff as a significant source of planning service and advice at the highest levels. The strategies involved are still apparent in the successor organization, Rockwell Scientific. The individual who led the Science Center from 1976 to 1989 is the author of the full case report.

This transformation required time and consistent leadership: It took 3 years (1976–1979), to establish the viability of the Science Center, another 5 years to build to a size sufficient to take contract cosponsorship risks, and the remainder of the time to establish internal recognition and respect. The Science Center director attributed much of the success of the Science Center to a half-dozen carefully selected and trained subordinate technology managers.

Rockwell senior management gave the Science Center's director and staff exceptional freedom and responsibility, especially in the years leading up to 1979. By contrast, the Electronic Research Center was significantly more structured, and programs requiring greater flexibility were sometimes transferred from the Electronic Research Center to the Science Center. Competitive tension between the Science Center and the Electronic Research Center required continual renegotiation of division of responsibility, but enhanced the competitiveness of both organizations.

The Science Center was chartered to do work expected to mature in 3–8 years. Tenure of division presidents averaged 5 years, and Rockwell preferred that longer term issues be handled by an independent organization. The culture within operating divisions was intensely committed to task execution, and most practicing engineers and scientist within the divisions were concerned with results in the 1- to 3-year timeframe.

The Science Center was involved in commercial and governmental S&T programs, creating some complexity in administration. Science Center performance was measured on the volume of business, technical content, relevance to division business plans, and management of the overall net cost to the corporation. Incentives included sharing the gross profit from large-scale partnered programs, which created extra financial flexibility for the Science Center. By 1990 the Science Center had developed ongoing partnerships with a dozen divisions and was accepted as a full partner in shared contracts. This made possible a retained profit at the Science Center, which in addition to a capped corporate contribution, gave the Science Center director substantial budgetary freedom.

An annual planning system led by the Science Center involved input from every responsible engineer in the company (about 25,000) on technology needs and anticipated sources for the ensuing year and 5 years forward. This interactive process identified gaps to be addressed by the company's internal research technology programs. The consolidated plan and financial interpretation was reviewed by the office of the president and chairman, and became part of the resource-allocation scheme of the company.

Following the departure of the Rockwell family from the Company in 1979, a Strategic Technologies Advisory Committee, consisting of the senior technical officers of all major segments of the company, was inaugurated. The Science Center was encouraged to share concerns with the Strategic Technologies Advisory Committee and to receive advice from them. The Strategic Technologies Advisory Committee was required to ensure that they concurred with the Science Center's budget and personnel actions.

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The Missile Defense Agency (MDA) tasked IDA to study and assess management methods and organizational structures that have proved successful in the development of technologies, with an emphasis on the roles of longer-term science and technology (S&T) work and radical innovation in support of ongoing systems development. To do so, this report reviews and analyzes the experiences of several (1) public organizations that undertook large-scale systems developments and (2) large private companies that have been consistently technically innovative. This provides the groundwork for consideration of specific management and organizational options for MDA.

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