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Report to the Chairman and Ranking Minority Member, Subcommittee on Readiness and Management Support, Committee on Armed Services, U.S. Senate

July 1999

BEST PRACTICES

Better Management of Technology Development Can Improve Weapon System Outcomes

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National Security and
International Affairs Division

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The Honorable James Inhofe
Chairman
The Honorable Charles Robb
Ranking Minority Member
Subcommittee on Readiness and Management Support
Committee on Armed Services
United States Senate

As you requested, this report assesses how best practices offer improvements to the way the Department of Defense (DOD) incorporates new technology into weapon system programs. It also assesses the factors that can make it difficult to mature technologies before they are included on weapon system programs and what can be done about them. We make recommendations to the Secretary of Defense on how advanced technologies can be better managed so they pose less risk when they are included in weapon system designs.

We are sending copies of this report to the Honorable William S. Cohen, Secretary of Defense; the Honorable Louis Caldera, Secretary of the Army; the Honorable Richard Danzig, Secretary of the Navy; the Honorable F. Whitten Peters, Acting Secretary of the Air Force; the Honorable Jacob J. Lew, Director, Office of Management and Budget; and to interested congressional committees. We will also make copies available to others upon request.

If you have any questions regarding this report, please call me at (202) 512-4841. Other key contacts are listed in appendix III.

Katherine V. Schinasi
Associate Director
Defense Acquisitions Issues

Executive Summary

Purpose

The Department of Defense (DOD) plans to increase its investment in new weapons to about $60 billion in fiscal year 2001—a 40-percent increase over fiscal year 1997. DOD has high expectations from this investment: that new weapons will be better and less expensive than their predecessors and will be developed in half the time. With its traditional management approach—which has produced superior weapons, but at much greater cost and time than planned—DOD will not meet these expectations. Leading commercial firms have changed their practices for developing products and have achieved the kinds of results DOD seeks. Maturing new technology before it is included in products is one of the main determinants of these firms' successes. This practice holds promise for DOD, for immature technologies have been a main source of problems on weapon systems. In response to a request from the Chairman and the Ranking Minority Member, Subcommittee on Readiness and Management Support, Senate Committee on Armed Services, GAO assessed (1) the impact of technology maturity on product outcomes, (2) best practices for managing new technologies and incorporating them into products, and (3) ways DOD can adapt these practices to get better outcomes on weapon system programs.

Background

GAO reviewed commercial and DOD experiences in incorporating 23 different technologies into new product and weapon system designs. The technologies were drawn from (1) six commercial firms recognized for their success in developing technically advanced products more quickly than the products' predecessors and (2) five DOD weapon system programs that incorporated advanced technologies, including some that did not encounter problems and some that did. GAO asked the managers of these technologies to assess the maturity of the technologies at the point they were included in product development by applying a tool, referred to as technology readiness levels (TRLs). The National Aeronautics and Space Administration and the Air Force Research Laboratory use TRLs to determine the readiness of technologies to be incorporated into a weapon or another type of system. Readiness levels are measured along a scale of one to nine, starting with paper studies of the basic concept, proceeding with laboratory demonstrations, and ending with a technology that has proven itself on the intended product.

The Air Force Research Laboratory considers TRL 6 an acceptable risk for a weapon system entering the program definition stage, the point at which DOD launches its weapon programs, and TRL 7 an acceptable risk for the

engineering and manufacturing development stage. This is an important distinction because leading commercial firms launch a new product later than DOD, after technology development is complete. They refer to this point as the beginning of product development, the point at which they commit to developing and manufacturing the product. Typically, technology is still being developed when weapon system programs are launched; the point at which a weapon system is far enough along to compare to a commercial product development is likely to be at or after the start of engineering and manufacturing development.

Results in Brief

The experiences of DOD and commercial technology development cases GAO reviewed indicate that demonstrating a high level of maturity before new technologies are incorporated into product development programs puts those programs in a better position to succeed. The TRLs, as applied to the 23 technologies, reconciled the different maturity levels with subsequent product development experiences. They also revealed when gaps occurred between a technology's maturity and the intended product's requirements. For technologies that were successfully incorporated into a product, the gap was recognized and closed before product development began, improving the chances for successful cost and schedule outcomes. The closing of the gap was a managed result. It is a rare program that can proceed with a gap between product requirements and the maturity of key technologies and still be delivered on time and within costs.

Two conditions were critical to closing the maturity gap. First, the right environment for maturing technologies existed. Key to this environment was making a science and technology organization, rather than the program or product development manager, responsible for maturing technologies to a high TRL. When a maturity gap persisted, managers were given the flexibility to take the time to mature the technology or decrease product requirements so that they could use another, already mature technology. Second, both technology and product managers were supported with the disciplined processes, readily available information, readiness standards, and authority to ensure technology was ready for products. This support enabled these managers to safeguard product development from undue technology risks. On the other hand, immature technologies were sometimes incorporated into products for reasons such as inflexible performance requirements, increasing the likelihood of cost overruns and delays in product development. Product managers had little choice but to accept the technologies and hope that they would mature

successfully. However, the pressures of product development made for an environment less conducive to maturing technology.

For several reasons, DOD is likely to move technologies to product development programs before they are mature. Science and technology organizations, which traditionally operate within fixed budget levels, do not necessarily have the funds to mature technology to the higher TRLs. Programs are more able to command the large budgets necessary for reaching these levels. The pressures exerted on new programs to offer unique performance at low cost encourage acceptance of unproven technologies. The technologies GAO reviewed indicate these conditions can be overcome on individual cases. DOD has several initiatives underway, such as advanced technology demonstrations, that could make it more feasible for science and technology organizations to mature technology before it is moved to product development programs. The challenge will be whether the lessons learned from these cases and initiatives offer an approach that has a DOD-wide application.

GAO makes recommendations to the Secretary of Defense on ways to pursue advanced technologies while lessening their potential for causing problems on weapon system programs.

Principal Findings

Maturity of Technology at Program Start Is an Important Determinant of Success

The 23 technologies GAO reviewed spanned a wide range of readiness levels—from a low of TRL 2 to a high of TRL 9—when they were included in product development programs. Programs with key technologies at readiness levels 6 to 8 at the time of program launch met or were meeting cost, schedule, and performance requirements. All of the commercial technologies and a few of the DOD technologies fell into this category. For example, Ford managed its voice-activated control technology to TRL 8—a 10-year effort—before introducing it on the 1999 Jaguar. Similarly, the Defense Advanced Research Projects Agency matured a revolutionary periscope technology to TRL 9 before it was included on the Virginia class attack submarine. DOD programs that accepted technologies at a readiness level of 5 or less experienced significant cost and schedule increases due, in part, to problems with the technologies. DOD's acceptance of technologies at level 4 or lower was not unusual. For example, the key technologies for the Army's brilliant antiarmor submunition were at levels 2

and 3 when weapon system development began. At these levels, DOD had a significant gap in technology maturity at the start of the program. The gap was not closed until well into the development program, and problems with the technologies were a main contributor to the program's 88-percent cost growth and 62-percent slip in schedule.

Controllable Conditions Affect How Well a Technology's Inclusion on a Product Can Be Managed

Closing the technology development gap before beginning product development was the result of good technology maturation practices and sound methods for moving technologies to products. The more successful of the 23 technologies were managed by science and technology organizations until they reached at least TRL 6 and more, often TRL 8 or higher. This environment was an important condition for successfully maturing technologies, as it allowed room for unexpected results such as test "failures," which are considered normal events in developing technologies. To match technology maturity and product requirements, managers also had the option of waiting until technologies matured or changing product requirements so that an already mature technology could be used. For example, Hughes deferred the development of the HS-702 satellite until critical solar cell technology had matured—a process that took over 10 years. Also, Navy managers accepted an existing weapon ejection system on the Virginia class attack submarine when technology failed to mature as expected. In contrast, performance requirements for the Comanche helicopter were inflexible; requirements mandated the inclusion of advanced sensors and avionics technologies, despite their immaturity. The Comanche program has experienced cost growth and schedule delays, partly attributable to the inclusion of these technologies.

In the more successful cases, technology and product managers were given the authority and tools to move technology only when it was at high readiness levels. Disciplined processes provided managers credible information on the status of technologies and high standards for assessing readiness. Science and technology managers developed technologies to standards acceptable to product managers who could reject those technologies that fell short. For example, Ford's science and technology managers use agreed-upon standards for judging technology readiness, and all new technologies follow the same maturation process. Ford's product managers are also empowered to say no when technologies are not deemed mature. Recently, the Jaguar vehicle team rejected night vision technology at TRL 8 because it did not meet cost objectives. DOD program managers that had to accept immature technologies had less information available to guide them. For example, key technologies for the brilliant antiarmor

submunition program bypassed Army science and technology organizations, forcing the program manager to accept the technologies with little information about their readiness. Often, the tools used to assess the technologies' status failed to identify high risks; the TRLs indicate that risks on the problematic technologies were often high. Also, the greater pressures to meet cost and schedule goals in product development provided a less forgiving environment for fledgling technologies.

Impediments to Adopting Best Practices for Technology Inclusion in DOD Are Surmountable

Leading commercial firms have put the organizations, tools, and other practices in place to foster technology development and improve the outcomes of product developments as a matter of necessity. The large investment required for a new product and the risks to that investment if the product does not meet customer needs reinforce these practices. The DOD cases that followed a similar approach—the Advanced Amphibious Assault Vehicle and the Virginia class attack submarine—have so far avoided problems with key technologies. Yet these cases are not the norm for DOD programs. DOD programs operate under conditions that make it more difficult—and less rewarding—to separate technology from product development and to allow technology to reach high maturity before being included in an acquisition program.

It is easier for weapon system programs to fund technology development at higher readiness levels because they attract much bigger budgets than science and technology projects. DOD typically does not fund science and technology organizations to take technology past the feasibility stage—TRL 5. As a practical matter, it is often necessary to move immature technology to a weapon system program to get needed funds and management support. New programs are pressured to include immature technologies that offer significant performance gains. These pressures come from the user's perception of the threat, technologists that see the program as an opportunity to apply a new technology, and funding competition that rewards weapon systems with unique features.

DOD and the services have several initiatives for improving the technology development process and reducing weapon system cycle times. These include defense technology objectives, advanced technology demonstrations, advanced concept technology demonstrations, the Army's new scout/cavalry vehicle, and the Air Force's Integrated High Performance Turbine Engine Technology Program. These initiatives are aimed at putting the science and technology organizations and funding in

place to bring technologies to higher readiness levels before they are included in weapon system programs.

Recommendations

GAO recommends that the Secretary of Defense adopt a disciplined and knowledge-based approach of assessing technology maturity, such as TRLs, DOD-wide, and establish the point at which a match is achieved between key technologies and weapon system requirements as the proper point for committing to the development and production of a weapon system. GAO also recommends that the Secretary (1) require that technologies needed to meet a weapon's requirements reach a high readiness level (analogous to TRL 7) before making that commitment, (2) extract lessons from successful technology inclusion cases for application to future technology inclusion efforts, and (3) empower program managers to refuse to accept key technologies with low levels of maturity by making decisions on individual programs that reinforce a best practice approach to technology maturation and inclusion. These recommendations appear in full in chapter 5.

Agency Comments

DOD generally agreed with the report and its recommendations. A detailed discussion of DOD's comments appear in appendix I.

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Abbreviations

AAAV	Advanced Amphibious Assault Vehicle
ABL	Airborne Laser
ACTD	Advanced Concept Technology Demonstration
ATD	Advanced Technology Demonstration
BAT	Brilliant Anti-Armor Subminition
DARPA	Defense Advanced Research Projects Agency
DEAL	Deliverables Agreement Log
DOD	Department of Defense
DTO	defense technology objective
FLIR	forward-looking infrared
NASA	National Aeronautics and Space Administration
S&T	science and technology
TRL	technology readiness level

Introduction

A central piece of the National Military Strategy is the military capability represented by advanced weaponry. The Department of Defense (DOD) plans to increase its annual investment in new weapons to about $60 billion by fiscal year 2001—a 40-percent increase over fiscal year 1997. DOD has high expectations from this investment: that new weapons will be better and less expensive than their predecessors and will be developed in half the time. These expectations frame a great challenge for managers of programs. The traditional management approach—which has produced superior weapons but at much greater cost and time than planned—will not meet these expectations. Cycle times—the time to develop a new weapon—can be so long that the technology a weapon is designed with becomes obsolete before it can be produced. Costs of new weapons have reached the point that significantly fewer can be bought than planned. These are not new issues, but they have become more pressing as the pace and sophistication of foreign and commercial technology have increased, complicating a national security environment of unknown threats.

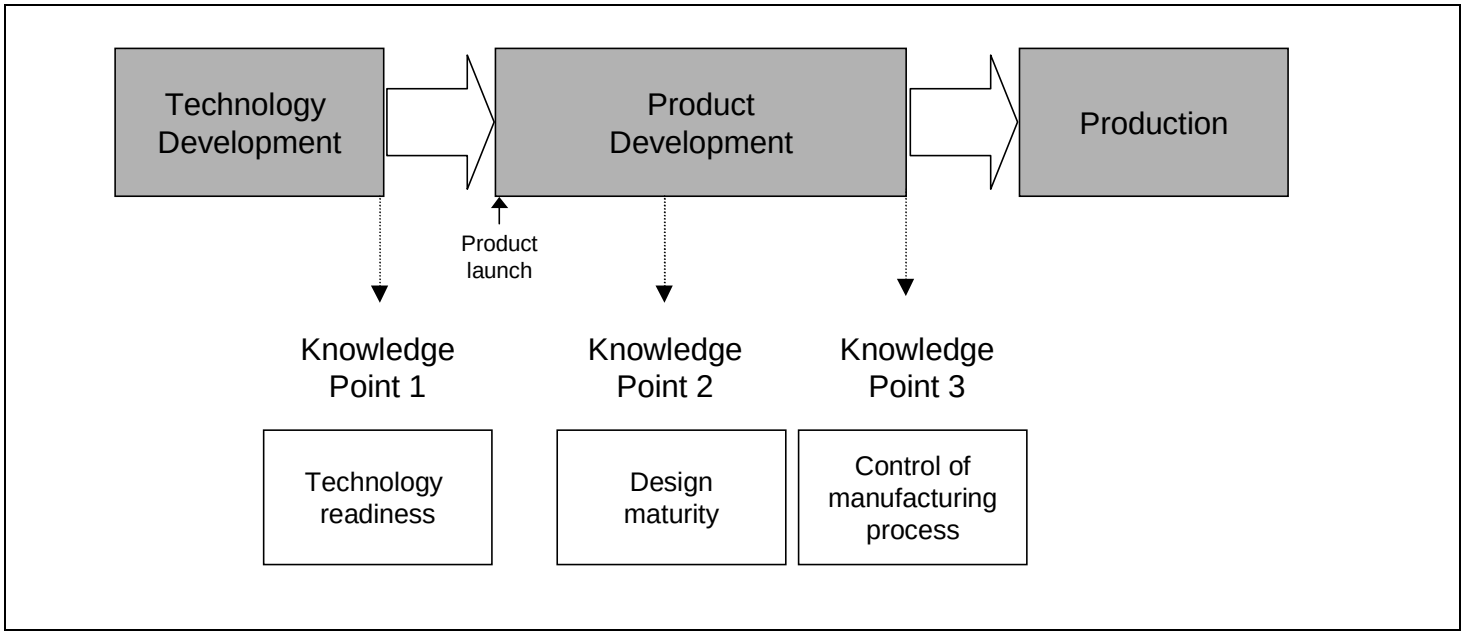
Leading commercial firms have changed the way they develop products and have achieved the kinds of results DOD seeks, often yielding more sophisticated products in half the time formerly needed. Industry experts estimate that resolving technology problems before product development begins results in 10 times the savings compared to correcting problems afterward. In this sense, technology maturity breeds product success. The practices leading firms use to mature and transition technology to products hold promise for DOD, for immature technologies have been main sources of problems on weapon systems. We have previously reported on the different elements of knowledge firms insist on to get better products to market faster. Of these, no element is more important than having technology, advanced enough to meet requirements but also mature enough to be predictably managed, available at the start of the product development cycle. Maturing new technology before it is included on a product is perhaps the most important determinant of the success of the eventual product—or weapon system. It is the topic of this report.

Separating Technology Development From Product Development Is a Best Practice

The cycle for placing better capabilities in the hands of users—both military and commercial—can be described as consisting of technology

development, product development, and production. In a 1998 report,[1] we characterized the knowledge needed on a new product as consisting of three knowledge points: when a match is made between a customer's requirements and the available technology; when the product's design is determined to be capable of meeting performance requirements; and when the product is determined to be producible within cost, schedule, and quality targets (see fig. 1.1). We found that this knowledge, when obtained at the right time and in the right sequence—technology, design, and manufacturing—was a best practice. This practice lowered product development risks, reduced cycle times and costs, and resulted in smoother production programs.

Figure 1.1: Cycle for Providing Users a Product With Better Capabilities



Leading commercial firms recognize a distinct difference between technology development and product development; accordingly, they develop technology before introducing it into product development programs. They minimize risk, improve cost and schedule outcomes, reduce cycle time, and improve quality during product development by

[1] Best Practices: Successful Application to Weapon Acquisitions Requires Changes in DOD's Environment (GAO/NSIAD-98-56, Feb. 24, 1998).

gaining significant knowledge about a technology before launching the product development. Scientists and technologists—different people than those that manage product developments—manage the development of technology until it is ready to be included in the design of a product.

Program launch is the point at which a firm defines a product's performance, cost, and schedule estimates and begins making a large investment in human capital, facilities, and materials—an investment that increases continuously as the product approaches the point of manufacture. It includes a commitment to manufacture the product. Therefore, program launch and the start of product development are synonymous within commercial firms. Protecting this investment provides a strong incentive for firms to minimize the potential for technology development problems during the product phase and cause delays. Confining delays in maturing technology to a time prior to launch—in an environment where small teams of technologists work in laboratories and are dedicated to perfecting the technology—is critical to saving time and money. If delays occur during product development, when a large engineering force is in place to design and manufacture the product, they would be much more costly. In fact, industry experts estimate that identifying and resolving a problem before product development can reap a 10-fold savings compared to correcting the problem after launch and that correcting the same problem in the manufacturing stage would be even more costly.

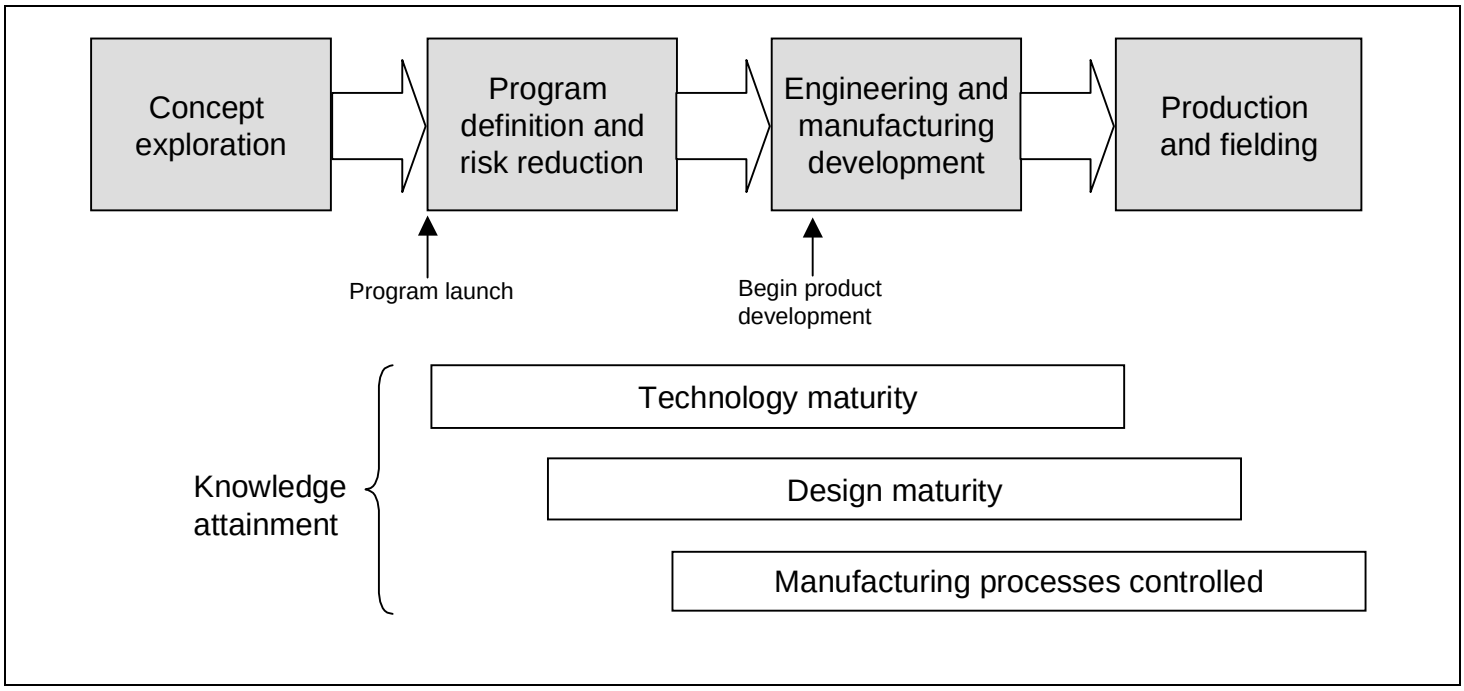
Leading commercial firms have found that managing technology development separately from and before product development is a major reason they have been able to reduce product cycle times. As a whole, 50 to 70 percent reductions in cycle times are not unrealistic achievements by leading commercial firms. For instance, leaders in the automobile industry have reduced cycle times from 7 years to 2 years, or by about 70 percent. The consumer electronics industry has recently reduced its cycle time from 2 years to 6 months, and the commercial aircraft industry has achieved reductions of 50 percent. Leading commercial firms have found that reducing the product development cycle time brings products to market faster, results in an increased market share, and helps to keep products from becoming technologically obsolete.

Technology and Product Development Conducted at the Same Time Within DOD

DOD's process for developing and manufacturing weapon systems is described as a cycle consisting of phases. These phases are concept exploration, program definition and risk reduction, engineering and manufacturing development, and production and fielding. The basic process of gathering knowledge about technology, design, and manufacturing is followed, but in practice, the DOD cycle does not make a clear distinction between technology development and product development. The launch of a program in DOD usually takes place several years before the beginning of product development does in leading commercial firms.

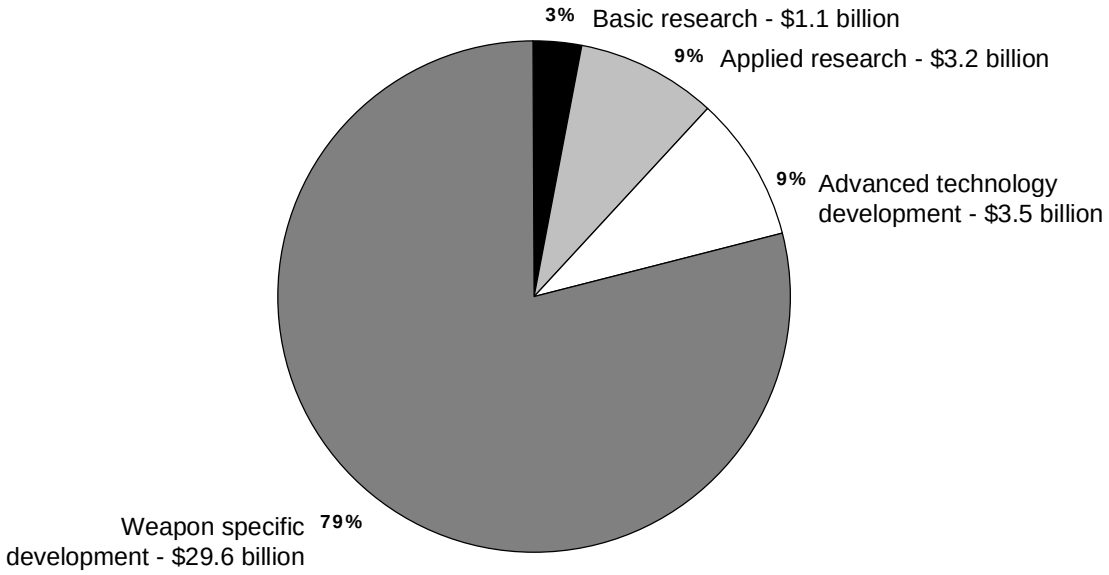
In fact, a new weapon system program is normally launched at the start of the program definition and risk reduction phase, which is often in the midst of technology development, while most product development activities do not begin until the engineering and manufacturing development phase. Consequently, technology, design, and manufacturing knowledge is attained concurrently--in the higher cost environment that characterizes product development--throughout the weapon system phases. In our February 1998 report, we noted that such technology development problems are a major cause of cost increases and schedule delays on DOD weapon system programs. The phases in DOD's weapon system acquisition cycle and the knowledge gathering process, as it is typically followed, are shown in figure 1.2.

Figure 1.2: DOD's Weapon System Acquisition Cycle



DOD's process also has organizational and budgetary implications. Activities accomplished in the first three phases of the acquisition cycle use research and development funds whereas production programs use procurement funds. Generally, DOD's science and technology (S&T) community is responsible for basic research, applied research, and advanced technology development to produce generic, rather than weapon-specific, technologies. Its goal is to conduct research, develop technology, and farm these efforts for potential military application, such as a weapon system. The S&T community also uses research and development funds, but its work generally precedes the acquisition cycle. Weapon system program managers, who receive most of DOD's research and development budget, apply generic technologies to specific weapon systems. However, they often become responsible for completing development of generic technologies as well. The allocation of DOD's fiscal year 1999 research and development funds to these categories is shown in figure 1.3.

Figure 1.3: Allocation of DOD's Fiscal Year 1999 Research and Development Funds



Source: DOD

S&T officials stated their role is to show that technology is feasible through laboratory experiments or demonstrations. It is often at this point that the technology's military potential will be identified and the technology will be harvested for inclusion on a weapon system. Because the technology is still not mature, its development will be completed as part of the weapon system's design and development, under the authority of the weapon system manager and apart from the S&T community.

Shorter Acquisition Cycle Times Are Needed

DOD's weapon acquisition cycle times average between 10 to 15 years—far longer than the cycle time for commercial products. To an extent, DOD's cycle times are longer because they start earlier than commercial cycles and often entail more complex products. Compounding the length of the weapon system development cycle is its unpredictability. Over the years, we have issued numerous reports highlighting cost overruns and schedule delays during the product development cycle, for which technology development problems were a major cause. These problems require additional technology development activities to take place at a time when

the product should be undergoing design and manufacturing development. As a result, the pace of technology advances outruns the time to develop a weapon system and some of the more mature components designed into a weapon system become obsolete before the weapon is manufactured. For example, the F-22 will have almost 600 obsolete components by fiscal year 2000 while the aircraft is still in development.

The longer a weapon system's development cycle, the more prone the program is to management and funding changes. According to DOD, an 11-year development program historically encounters a 30-percent cost growth over time. Based on historical averages, DOD calculates that the typical program will have four different program managers, eight defense acquisition executives, and seven Secretaries of Defense—all of who are major influences and decisionmakers on the program. In addition, the program will have gone through 11 annual budget cycles in which funding changes could have occurred and affected the program's content.

The Under Secretary of Defense for Acquisition and Technology has stated that cycle time reduction is necessary to meet DOD's goals of delivering emerging technologies to warfighters in less time and at lower costs. The Under Secretary has set a goal to reduce the average acquisition cycle time for all program starts in fiscal year 1999 and beyond by 50 percent over historical averages. Reductions in cycle times will (1) allow for earlier fielding of increased capabilities, (2) reduce costs, (3) free up funds for more programs, (4) reduce the potential for components becoming obsolete, and (5) take more frequent advantage of technology advances found in the commercial world. An emphasis on shorter cycle times may also reduce the tendency to add technological advances that are unproven and immature into weapon acquisition programs. To help achieve this goal, DOD is working on several efforts such as Defense Acquisition Pilot Programs, the Defense Reform Initiatives, and many acquisition reform projects. The Under Secretary has also advocated adopting the practices of leading commercial firms and taking a more evolutionary approach to developing weapon systems, which would lessen the amount of technology development initially attempted within a weapon system program.

Objectives, Scope, and Methodology

The Chairman and the Ranking Minority Member, Subcommittee on Readiness and Management Support, Senate Committee on Armed Services, requested that we examine various aspects of the acquisition process to determine whether the application of best practices can improve program outcomes. To date, we have issued reports on advanced quality

concepts, earned value management, management of a product from development to production, and management of key suppliers (see related GAO products). This report covers the inclusion of technology into weapon system programs, and is, in a sense, a prequel to our report on product development. Our overall objective was to determine whether best practices offer methods to improve the way DOD matures new technology so that it can be assimilated into weapon system programs with less disruption. Specifically, we assessed (1) the impact of technology maturity on product outcomes, (2) best practices for managing new technologies and incorporating them into products, and (3) ways DOD can adapt best practices to achieve better outcomes on weapon system programs.

Our methodology consisted of analyzing 23 commercial and DOD technologies that had transitioned or attempted to transition into product development programs. The technologies were drawn from six commercial firms recognized for their success in developing technically advanced products more quickly than their predecessors and five weapon system programs that incorporated advanced technologies, including some that did not encounter problems and some that did. We asked the managers of these technologies to apply a tool, referred to as technology readiness levels (TRLs), for our analysis. The managers used TRLs to judge the maturity of the technologies at the time they had entered product development or were included in programs. The National Aeronautics and Space Administration (NASA) originally developed TRLs, and the Air Force Research Laboratory uses them to determine when technologies are ready to be handed off from S&T managers to product development managers. We held discussions with the DOD and NASA users of TRLs to better understand their applicability to our review. They stated that TRLs can be used as general indicators of a technology's readiness level and associated risk of including the technology into a product development program, given its TRL at that time. TRLs are more fully explained in chapter 2.

To understand the best practices the commercial sector used to include technologies in product development programs, we conducted literature searches and focused those searches as the review progressed. On the basis of the searches, we identified a number of commercial firms with innovative technology development processes for including new or advanced technologies into new products. We used structured interview questions sent in advance of our visits to gather uniform and consistent information about each firm's process and practice and the results achieved. In addition, we examined four specific technology cases—Ford's night vision, adaptive cruise control, and voice activated controls and

Hughes' solar cell array—to better understand their processes and practices. The commercial firms we visited were

- Ethicon-Endo Surgery (medical device manufacturer), Division of Johnson and Johnson, Cincinnati, Ohio;
- Ford Motor Company (automobile manufacturer), Dearborn, Michigan;
- Harris Semiconductor (semiconductor manufacturer), Melbourne, Florida;
- Hughes Space and Communications (satellite and spacecraft manufacturer), Los Angeles, California;
- 3M (commercial products manufacturer), St. Paul, Minnesota; and
- Motorola Corporate Research Headquarters (communications technology manufacturer), Schaumburg, Illinois, and Motorola Land Mobile Products Sector, Plantation, Florida.

We also attended and participated in conferences and workshops with recognized leaders in the acquisition field to obtain information on how organizations are improving their acquisition processes. Finally, we interviewed officials from trade organizations concerning the application of commercial practices to DOD operations.

To better understand DOD's technology inclusion process, we selected 19 advanced technologies that had been included in 5 DOD weapon system programs that were in various stages of the acquisition process. We collected technical reports, acquisition management, and risk management documentation about the technologies. In addition, we interviewed S&T and acquisition program management officials about each technology's development history, costs, and current status. The technologies and programs reviewed were

- acoustic sensor, infrared seeker, inertial measurement unit, tandem shaped charge warhead, and processor technologies from the Army's Brilliant Anti-Armor Submunition (referred to as BAT) Program;
- rotor, engine, integrated avionics, forward looking infrared, and helmet mounted display technologies from the Army's Comanche Helicopter Program;
- nonpenetrating periscope and weapon ejection system technologies from the Navy's Virginia class attack submarine program;
- high speed planing craft, power dense diesel engine, lightweight composite armor, high power water jet, moving map and advanced navigation technologies from the Marines' Advanced Amphibious Assault Vehicle (AAAV) Program; and

- laser and beam control technologies from the Air Force's Airborne Laser (ABL) Program.

To determine relevant DOD policy and initiatives, we obtained documents and interviewed officials of the Office of the Secretary of Defense; the Defense Advanced Research Projects Agency (DARPA); and Army, Navy and Air Force Science and Technology organizations. We also had discussions with former DOD officials and industry experts about DOD acquisition policies and practices.

Even though we selected firms with product lines of varying complexity, we did not concentrate only on firms whose products had the most in common with weapon systems. Such an approach would have limited our ability to include firms recognized as the best at including new, advanced technologies into programs. In our analysis, we concentrated on the criteria and knowledge used to support technology readiness decisions. Although the approach from product to product may vary, the basic processes and standards leading commercial firms applied to technology inclusion decisions were consistent. We were limited, however, in our ability to obtain and present some relevant data that commercial companies considered proprietary in nature. This information included funding amounts for investing in technology development, details on technological innovations, and some specific data from recent technology inclusion successes. Our report highlights the best commercial practices for including technology into product development programs. As such, they are not intended to describe all commercial industry practices or to suggest that commercial firms do not have any flaws.

We conducted our review between March 1998 and June 1999 in accordance with generally accepted government auditing standards.

Maturity of Technology at Program Start Is an Important Determinant of Success

The experiences of the DOD and commercial technology development cases we reviewed indicate that demonstrating a high level of maturity before allowing new technologies into product development programs puts those programs in a better position to succeed. Simply put, the more mature technology is at the start of the program, the more likely the program will succeed in meeting its objectives. Technologies that were included in a product development before they were mature later contributed to cost increases and schedule delays in those products.

We found an analytical tool—TRLs—that can assess the maturity level of technology as well as the risk that maturity poses if the technology is included in a product development. The tool associates different TRLs with different levels of demonstrated performance, ranging from paper studies to proven performance on the intended product. The value of using the tool is that it can presage the likely consequences of incorporating a technology at a given level of maturity into a product development, enabling decisionmakers to make informed choices. TRLs proved to be reliable indicators of the relative maturity of the 23 technologies reviewed, both commercial and military, and their eventual success after they were included in product development programs.

Technology Maturity Can Be Measured and Its Consequences for Products Can Be Forecast

Successful technologies progress from initial concept to proven performance, whether they are developed in the laboratory or in the factory, by commercial industry or DOD. The Air Force Research Laboratory has adapted and uses TRLs to measure the key steps in this progression toward inclusion into weapon systems. TRLs are measured along a scale of one to nine, starting with paper studies of the basic concept and ending with a technology that has proven itself in actual usage on the intended product. A detailed description of TRLs is provided in appendix II, but the following hypothetical example about an airborne communications radio can illustrate the readiness levels.

First, the idea for a new radio is conceived. The idea reaches TRL 3 when analytical studies and some tests of the technology's elements, such as a circuit, back it up. When initial hand-built versions of all of the radio's basic elements are connected and tested together, the radio reaches TRL 5. This is sometimes referred to as a "breadboard" article; although it may function like a radio, it does not look like one because the individual parts are attached to plywood and hand-wired together. When the technology is built into a generic model, which is well beyond the breadboard tested in TRL 5, and demonstrated in a laboratory environment, the radio reaches TRL 6.

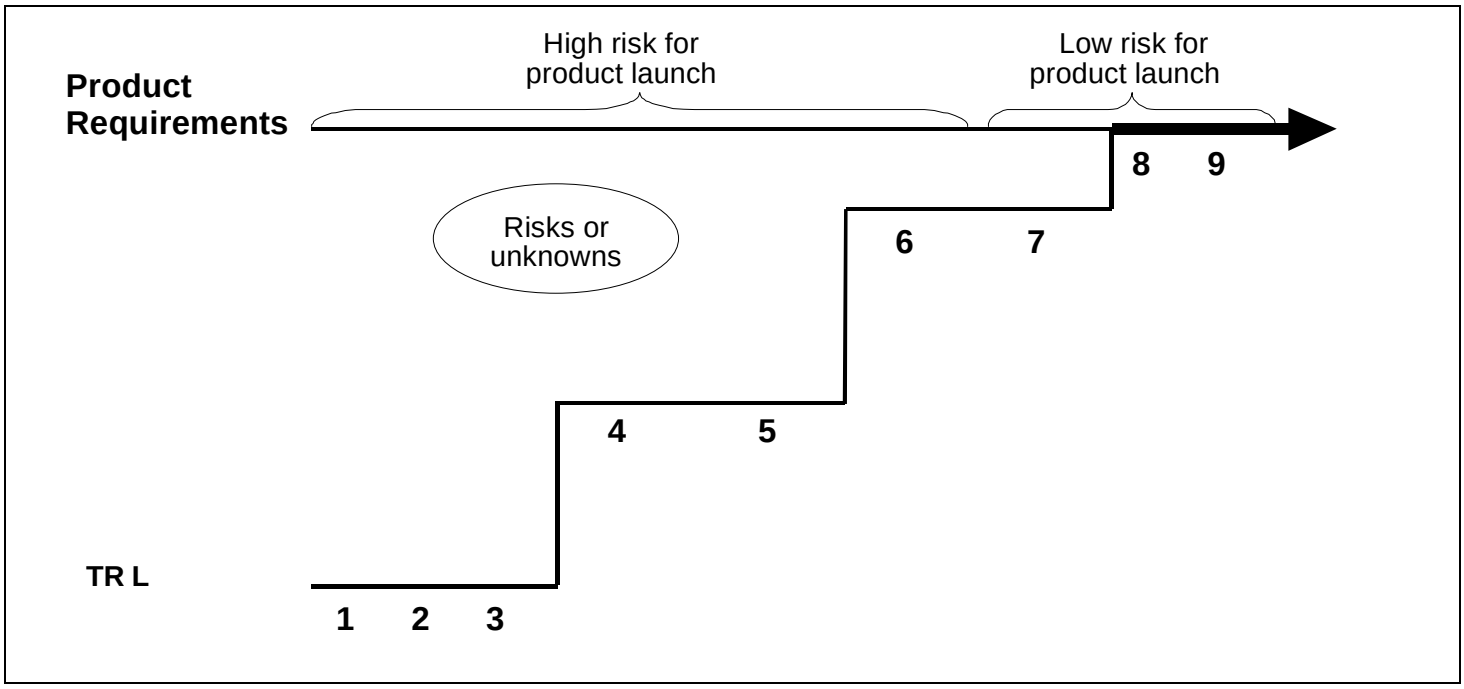
This model represents the last level of demonstration before the radio becomes tailored for application to a specific aircraft. When the components are assembled inside a case that resembles the final radio design and are demonstrated aboard a surrogate for the intended aircraft, the radio reaches TRL 7. TRL 8 is reached when the radio is put in its final form, installed in the intended aircraft's cockpit, and tested in conjunction with the other aircraft equipment with which it must interface. TRL 9 is achieved when the radio is successfully operated on the aircraft through several test missions. Unexpected problems can arise at every level, and effort must be expended to overcome them. This effort takes time and can delay the progress to the next readiness level.

Once a technology's readiness level has been established, the risks of including that technology in a product development can be assessed. Unlike S&T projects, for which the main objective is to develop knowledge, a product development's objective is to deliver products that meet strict cost, schedule, and performance targets. We found that most leading commercial firms, after they had translated their own methods of assessing risk into TRLs, determined that a TRL 8 was required before they allowed a new technology into a product development.[1] DOD launches a program in the program definition and risk reduction phase—much earlier than the leading commercial firms do. According to the Air Force Research Laboratory, a TRL 6 is required for a technology to be an acceptable risk for a program in that phase. When weapon system development reaches the engineering and manufacturing development phase, it more nearly approximates the point at which a commercial product development program would start. The Air Force Research Laboratory depicts a technology at TRL 7 as an acceptable risk for this phase—technologies at lower levels would be considered high risks.

The lower the level of technology readiness, the more ground must be covered to bring the technology to the point at which it can meet the intended product's cost, schedule, and performance requirements with little risk (see fig. 2.1).

[1]An exception to this is space systems technology. Space-based technologies are generally included on a development program once they have been prototyped and ground tested—a TRL 6, the highest level attainable short of space operation.

Figure 2.1: Using TRLs to Match Technology With Product Launch Requirements



The gap between the maturity of the technology and the product's requirements represents the risks or unknowns about the technology. As each succeeding level of readiness is demonstrated, unknowns are replaced by knowledge and the gap becomes smaller. Ideally, the gap is closed before a new technology is included in a new product's design, although the Air Force Research Laboratory accepts the amount of risk at TRL 7 for a program entering engineering and manufacturing development. Technologies that reach TRL 7 or higher at the start of product development allow product managers to focus their attention on integrating the technologies and proving out the product design. Technologies that are included at lower maturity levels require more of the product managers' attention and resources, as basic knowledge about those technologies must still be gained.

Thus, a major purpose served by TRLs is to reveal the gap between a technology's maturity and the maturity demanded for successful inclusion in the intended product. With TRLs as guides, the options available to decisionmakers can be framed. Given that a key determinant of achieving cost and schedule outcomes for a product development is the technology's maturity at product launch, decisionmakers can either (1) delay product

development until the technology is matured to a high enough readiness level or (2) reduce the product's requirements so that a less advanced, but more mature, technology can suffice. If it is perceived that the requirements of the product cannot be lowered and the product launch cannot be delayed until the requisite technology is of a sufficient readiness level, then the remaining option is to launch the product development with the immature technology. If this option is chosen, then the success of the product development will depend heavily on the product manager's ability to simultaneously close the technology maturity gap and develop the product for manufacture, which is a very challenging task.

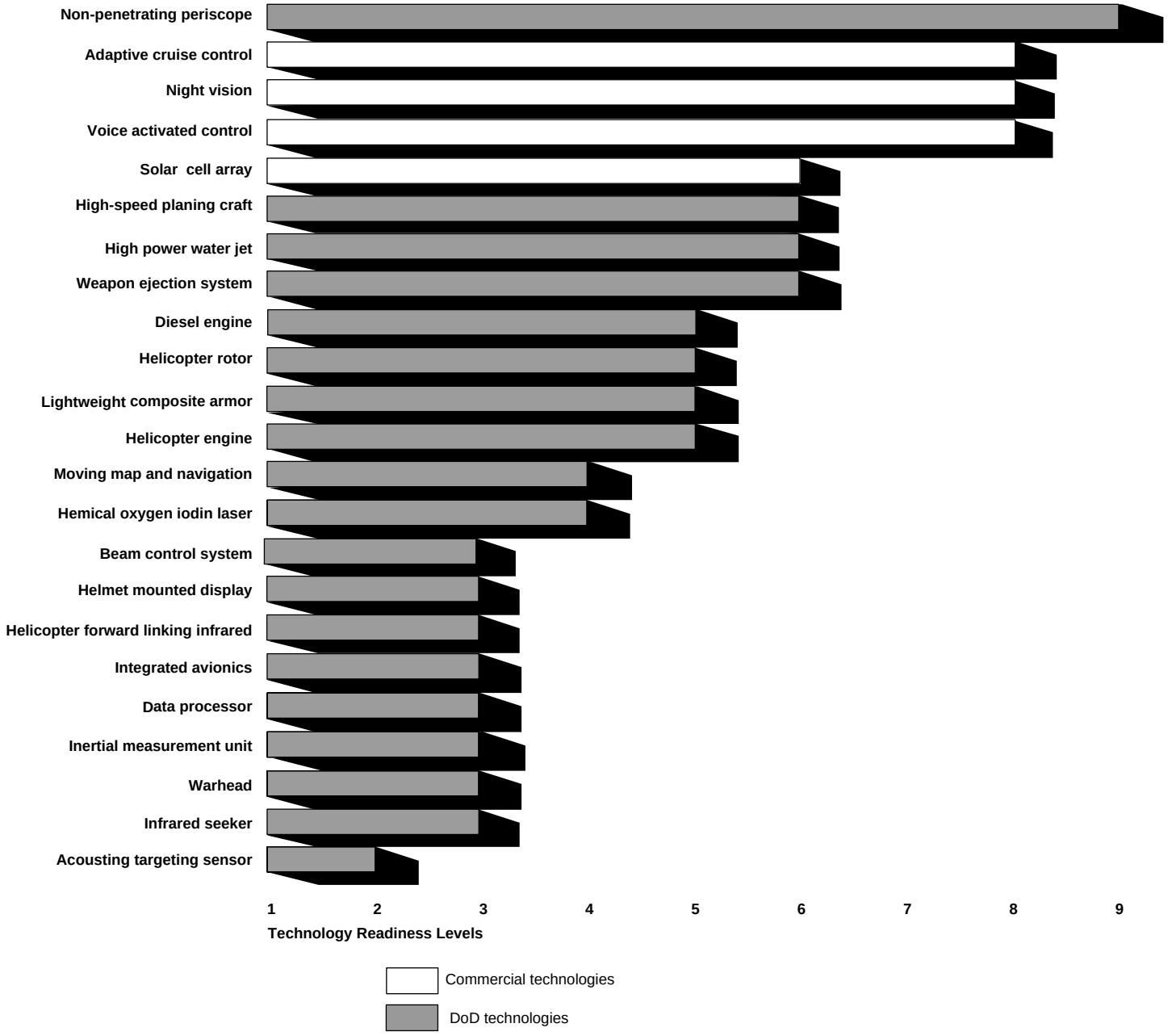
TRLs do not represent strictures that must be adhered to without exception. According to the people in DOD who have used TRLs, there are occasions when a lower than expected TRL can be accepted, such as when the product development's schedule and resources are generous enough that the technology will have enough time to mature. In other instances, a higher than expected TRL may be required, such as if the technology in question is the linchpin for the entire product. Nonetheless, we found that TRLs ably reconciled the different maturity levels and product experiences of the 23 technologies reviewed.

Technologies With High Readiness Levels at Launch Were Better Able to Meet Product Objectives

The 23 technologies reviewed spanned a wide range of readiness levels at the time they were included in product development programs. The least mature reached TRL 2 at the time it was included in a product development, while the most mature had reached TRL 9 at the point of inclusion. We observed a general relationship between TRLs and the technologies' inclusion on the intended product developments. Those products whose technologies reached high TRLs at the time they were included were better able to meet cost, schedule, and performance requirements. In fact, commercial firms informed us that maturing the technology separately from and ahead of the product was a main reason they were able to reduce cycle times on their products. An official from one of the firms termed the approach as "moving discovery to the left."

Those technologies with low TRLs at inclusion encountered maturation difficulties and contributed to problems the products experienced. Other problems, such as funding and schedule changes unrelated to the technologies, also contributed to problems in the product developments. Figure 2.2 shows the TRLs when each of the 23 technologies was included in a product design, whether at product development launch (for commercial technologies) or at program launch (for DOD technologies).

Figure 2.2: Readiness Levels of Technologies at the Time They Were Included in Product Designs



The cost and schedule experiences of some of the products or programs that inherited the technologies are shown in table 2.1.

Table 2.1: Cost and Schedule Experiences on Product Developments

		Product development	
Product development and associated technologies	**TRL at program launch**	**Cost growth**	**Schedule slippage**
Comanche helicopter		101 percent[a]	120 percent[a]
Engine	5		
Rotor	5		
Forward looking infrared	3		
Helmet mounted display	3		
Integrated avionics	3		
BAT		88 percent	62 percent
Acoustic sensor	2		
Infrared seeker	3		
Warhead	3		
Inertial measurement unit	3		
Data processors	3		
Hughes HS-702 satellite		None	None
Solar cell array	6		
Ford Jaguar		None	None
Adaptive cruise control	8		
Voice activated controls	8		

[a]The Comanche, in particular, has experienced a great deal of cost growth and schedule slippage for many reasons, of which technology immaturity is only one. Other factors, such as changing the scope, funding, and pace of the program for affordability reasons, have also contributed.

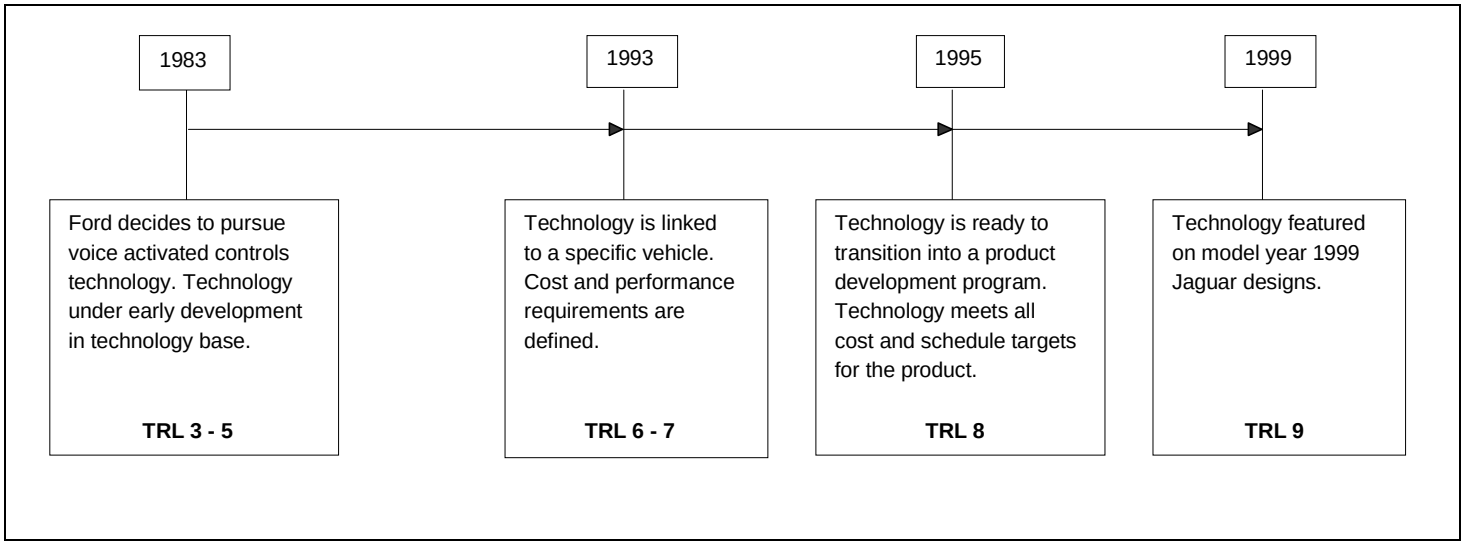
Data for three weapon system development programs, the Virginia class attack submarine, AAAV, and the ABL, were not included in the table because they had not been in the product development phase long enough to report actual consequences. To date, AAAV and the submarine have stayed within 15 percent of their cost and schedule estimates for development. The ABL, for which key technologies were much less mature at program launch, still faces challenges with these technologies. Ford's night vision technology was excluded because the firm decided not to include the technology on a product. Details on the Comanche, BAT, the Virginia class attack submarine, and Ford technology and product experiences follow.

Technology and Product Experiences on Ford and Virginia Class Attack Submarine

The key technologies for the Ford Jaguar and the Virginia class attack submarine followed the pattern of increasing TRLs until they demonstrated a low risk for transition to the product. Two examples are Ford's voice activated controls development and DARPA's nonpenetrating periscope development for the submarine. In both cases, the technologies were validated, operational prototypes demonstrated, and the technologies had demonstrated the form, fit, and function of the final article by the beginning of product development.

Ford's voice activated controls technology, which allows a driver to control certain functions such as windows and the radio through verbal commands, was under development in the technology base for over 10 years, being pushed by the firm's technology leaders. It was not until 1993 that Ford found that (1) other complementary technologies, such as processor speeds and low cost memory, had become available and (2) customers wanted more features and functions but less distractions from driving. Given this market information, Ford decided to pursue voice technology as a strategic technology in terms of product differentiation, recognizing the importance of being first to market with this enabling technology. Figure 2.3 shows the time line for developing this technology.

Figure 2.3: Time Line for Ford's Development of Voice Activated Controls Technology



Between 1993 and 1994, based on discussions with customers, Ford developed cost and performance requirements for the technology. Ford has

never relaxed them. By September 1995, when Ford allowed the technology into the development program for a new Jaguar design, voice activated controls had been demonstrated as an integrated system in the appropriate form and fit for the Jaguar. Ford officials stated that the product has met all cost and cycle time targets established at the outset of its development. Figure 2.4 shows the Jaguar.

Figure 2.4: Jaguar

Ford demonstrated voice activated control technology in the appropriate form and fit before incorporating it into the Jaguar.

Source: Ford Motor Company.

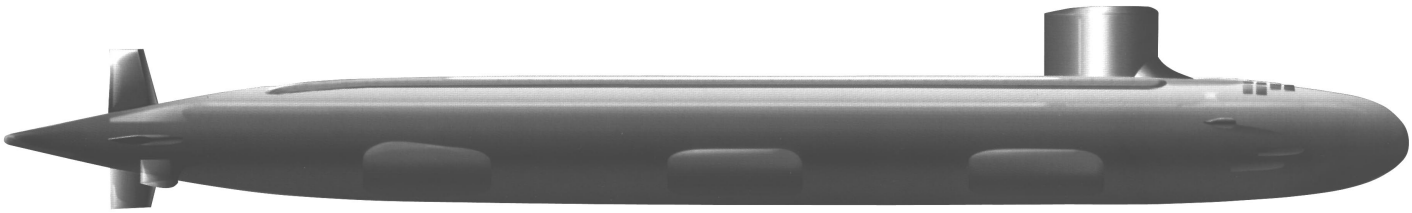
DARPA began developing the nonpenetrating periscope technology as part of its submarine technology development efforts after recognizing, in 1988, along with the Navy, that the nonpenetrating technology would enhance operator visibility, provide greater submarine design flexibility, and be stealthier than conventional masts and periscopes. At the time, the Virginia class attack submarine program had not been initiated. Once the decision was made to include the nonpenetrating periscope, it became a key feature of the submarine and was a major design driver for the submarine's overall configuration.

Nonpenetrating refers to the fact that the periscope is essentially a group of sensors that are linked to the submarine via fiber optic and other cables. This technology uses infrared imaging and advanced sensors to replace conventional periscopes and frees up physical space compared with a conventional periscope. A conventional periscope relies on a series of telescoping shafts and reflecting surfaces to see above the water's surface.

When the periscope is retracted, the shafts take up a column of space from the top of the submarine to the bottom, through all decks. Its location virtually dictates the design and placement of the control and other rooms. If the nonpenetrating periscope technology did not become available, then the submarine would have to be drastically redesigned to accommodate the space required by a conventional periscope.

The new nonpenetrating periscope and photonics mast technology underwent land testing in 1991—a TRL 5. The Navy actually tested the new technology at sea on the U.S.S. Memphis in 1992 and 1993. According to program officials, these sea trials demonstrated the highest level of technology readiness: proving the actual system through successful mission operations. This readiness equated to a TRL 9. Yet, this technology was not included in the Virginia class attack submarine requirements until 1995. Figure 2.5 shows an artist's concept of the Virginia class attack submarine.

Figure 2.5: Virginia Class Attack Submarine



The Navy demonstrated a key technology at the highest readiness level before including it as a requirement for the Virginia class attack submarine.

Source: DOD.

The high readiness level of the nonpenetrating periscope afforded the Navy the opportunity to develop an improved version of the periscope to a TRL 9. This was a relatively low-risk endeavor as the baseline periscope was sufficient to meet the submarine's requirements. Program officials believe that having knowledge about key technologies, such as the nonpenetrating periscope, for the Virginia class attack submarine at program launch made a short program definition and risk reduction phase possible. This phase for the Virginia class attack submarine was about 75 percent shorter than those of previous acquisition programs. Based on its demonstrated maturity, we anticipate that the nonpenetrating periscope to be less likely to impact the cost and schedule of the submarine's development program. There are, however, several other technologies that

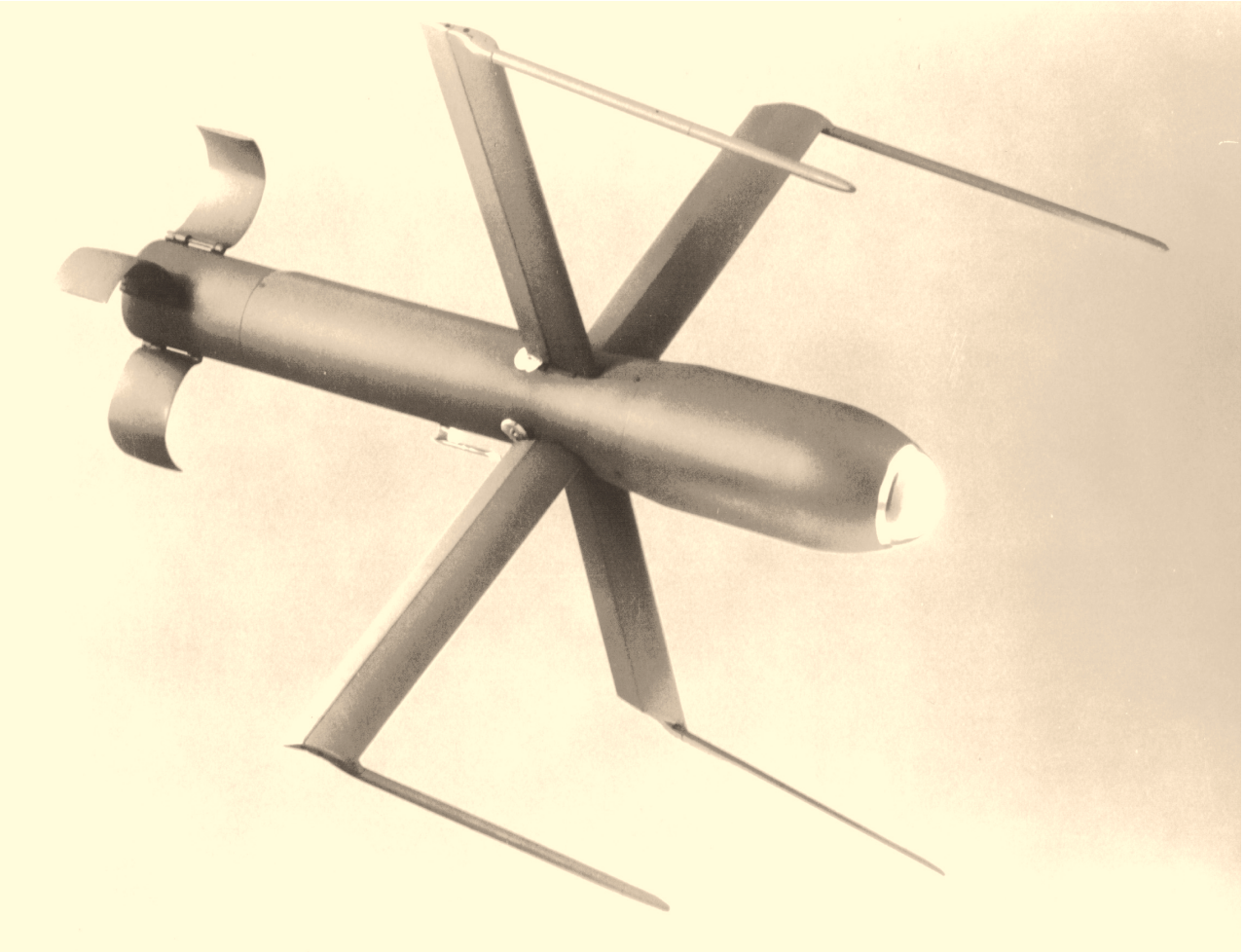
are critical to the submarine program. We did not examine these technologies and cannot predict their likely outcomes.

BAT and Comanche Cases

Key technologies for the BAT and Comanche programs had much lower readiness levels at the time the product developments were launched. Consequently, they did not reduce the gap between their demonstrated maturity and the maturity needed to meet product requirements until after program launch. For some technologies, the gap was not closed until well into the product development program. For others, the gap has still not been closed.

Five key technologies included in the Army's BAT program had low TRLs when they were included on the program. The level of readiness for most of these technologies at program launch was characterized by the program office as experimental in nature but with major uncertainty remaining—a TRL 3. The acoustic targeting technology was the most important enabling technology needed to meet the weapon's performance requirements. This technology provides BAT the capability to locate targets from great distances based on the sounds generated by the target, such as moving tanks and vehicles. At the time the program was launched, the Army knew little about the feasibility of using this technology on this program. In fact, the technology was still being defined in paper studies—a TRL 2. The Army did not prototype this technology until after the program had entered the engineering and manufacturing development phase, more than 6 years after program launch. As of December 1998, the BAT had experienced significant development cost and schedule increases, which program officials attribute at least, in part, to unknowns about the new technologies. Figure 2.6 shows the BAT.

Figure 2.6: Brilliant Anti-Armor Submunition



At the time the program was launched, the Army knew relatively little about the performance of several key technologies for the BAT

Source: DOD.

Two technologies key to meeting the Comanche helicopter's requirements–integrated avionics and forward-looking infrared (FLIR) technologies—were included on the program when they were still conceptual in nature. The integrated avionics technology replaces individual radios, navigation, and other communication equipment with a modular system that shares a common processor. The FLIR is a second-generation version that uses infrared sensors to improve the pilot's ability to see at night and in bad

weather. Program officials stated that both had TRLs of 3 when the helicopter program was started. Despite the low readiness levels of the technologies, the Army included the technologies on the program to meet weight, cost, and performance requirements.

The development of these technologies has taken longer than the Army expected it would. The contractor for the integrated avionics has had difficulties in getting the multiple avionics modules to work simultaneously within required size and weight parameters, and the FLIR technology has undergone several design and performance requirement changes. As of September 1998—approximately 10 years after program launch—neither the integrated avionics nor the FLIR technology had advanced past a TRL 5. Problems with the maturation of these technologies have contributed to the program's cost and schedule increases. In contrast, the advanced rotor and engine technologies, which were the most mature of the Comanche technologies we reviewed, have experienced fewer problems in maturation and have not contributed significantly to the program's cost and schedule increases. Figure 2.7 shows the Comanche.

Figure 2.7: Comanche Helicopter

The Army included two key technologies in the Comanche when they were still considered conceptual to meet weight, cost, and performance requirements

Source: DOD.

Controllable Conditions Affect How Well a Technology's Inclusion on a Product Can Be Managed

Closing the gap between technology maturity and product requirements before a product is launched—and baselines are set—distinguished the more successful cases. Notably, closing the gap before product launch was a managed result; it put product managers in a better position to succeed. Two conditions were critical to achieving this kind of result. First was an environment that put the primary responsibility for maturing technology in the hands of S&T managers and provided them considerable flexibility to make decisions. Second was having the quality information and standards needed to make good technology handoff decisions, coupled with giving the product manager the authority to refuse new technology that did not meet product requirements. When these conditions were not present, the handoff to the product manager was compromised, with negative consequences for both technology and product.

In each of the successful cases, S&T organizations played major roles in bridging the gap between technology maturity and product requirements. Flexibility provided by requirements communities and resource providers enabled S&T and product managers to delay the inclusion of technology if it was not ready or to reduce product requirements to match what mature technology could deliver. This environment was better suited to the unexpected results and delays that accompany technology development. Moreover, technology maturation was managed within a disciplined process that provided good information to be judged against clear and high standards, like TRLs. Armed with the tools and the authority to make technology inclusion decisions, both S&T and product managers functioned as gatekeepers to safeguard the product development.

In the more problematic cases, S&T organizations disengaged much earlier, and product managers had little choice but to accept immature technologies. Accordingly, less information about the technologies was available at the point of inclusion. Often, the tools used to assess the technologies' status failed to identify high risks. In retrospect, TRLs indicated that risks were in fact high and perhaps unacceptable from a product standpoint. Also, pressures to meet cost and schedule estimates in product development provided a less forgiving environment for technologies in the discovery process.

Providing the Right Environment Is Critical to the Successful Maturation of Technology

While most new technologies—commercial and military—are initially managed by the S&T community, the more successful cases we reviewed continued to be managed by S&T organizations until they reached at least TRL 6 and more often TRL 8 or higher. These technologies were provided the environmental advantages an S&T project has over a product development. This environment availed S&T managers and product managers of the less risky options of waiting or trading to get the match between technology maturity and product requirements—rather than forcing the product launch and gambling on the completion of technology maturity. In contrast, the more problematic technologies did not have as benign an environment. Often, the technologies were handed off early by S&T organizations because inflexible performance requirements for the product demanded their inclusion. Product development managers launched the product development and hoped that the technology development would succeed.

Once in a product development environment, external pressures to keep the program moving become dominant, such as preserving cost and schedule estimates to secure budget approval. For example, DOD policies require that a program be funded in the current year and that funds be made available over the next 6 years in the DOD planning cycle. If, during the program definition phase, a program manager were to decide that an additional year was needed to overcome unexpected technology problems to reach the desired level of maturity, the delay could push the start of engineering and manufacturing development back. This delay could jeopardize the funding for that phase, thus risking the funding support for the entire program. Consequently, the program manager may be more likely to accept the risk of not getting the technology to the desired level of maturity and starting the engineering and manufacturing development phase as planned, rather than risk the rest of the program. These conditions compete with and detract from the needs of technology development. One acquisition official stated that these conditions cause the weapon system program "to pull double duty," inventing new technology while integrating it into a product. In general, he believed there is an equal amount of difficulty in both tasks.

Technologies Matured by S&T Organizations Made Smooth Transitions into Product Developments

In the most successful cases that we reviewed, S&T organizations bridged the gap between immature technology and the maturity needed for either program start in DOD (TRL 6) or product development (TRL 7 or higher). These cases and the responsible organizations are shown in table 3.1.

Table 3.1: TRLs of Technologies Managed by S&T Organizations

Technology	TRL at handoff	Responsible S&T organization	Receiving product development program
Nonpenetrating periscope	9	DARPA	Virginia class attack submarine program
Adaptive cruise control	8	Ford Advanced Vehicle Technology Office	Jaguar vehicle team
Voice activated controls	8	Ford Advanced Vehicle Technology Office	Jaguar vehicle team
Solar cell array	6	Hughes Laboratories	HS-702 satellite program
Weapon ejection system	6	Office of Naval Research	Virginia class attack submarine program
Diesel powered engine	6	Office of Naval Research	AAAV program
High-speed planing craft	6	Office of Naval Research	AAAV program
High-power water jet	6	Office of Naval Research	AAAV program

Despite the different circumstances between the commercial and DOD sectors and among the DOD cases themselves, the results were similar: having S&T organizations bridge the maturity gap reduced technology-related problems in the products. For the leading commercial firms we visited, it is standard practice to have S&T organizations responsible for the bridge. In the DOD cases shown in table 3.1, the S&T organizations played atypical roles in managing the bridge between technology and product by delivering the technology to a TRL 6 or higher. Different pressures and incentives that are brought to bear on the commercial and DOD product developments explain why DOD product managers become responsible for more technology development than their commercial counterparts. These influences are discussed in chapter 4.

Having an S&T organization manage a technology to maturation means more than just having a different group of people involved than a product development. S&T projects operate in a different environment than product developments. The process of developing technology culminates in discovery and must, by its nature, allow for unexpected results. S&T provides a more forgiving environment in which events—such as test "failures," new discoveries, and delays in the attainment of knowledge—are considered normal. It is also a less costly environment, making external pressures to develop knowledge on a schedule less keenly felt. On the

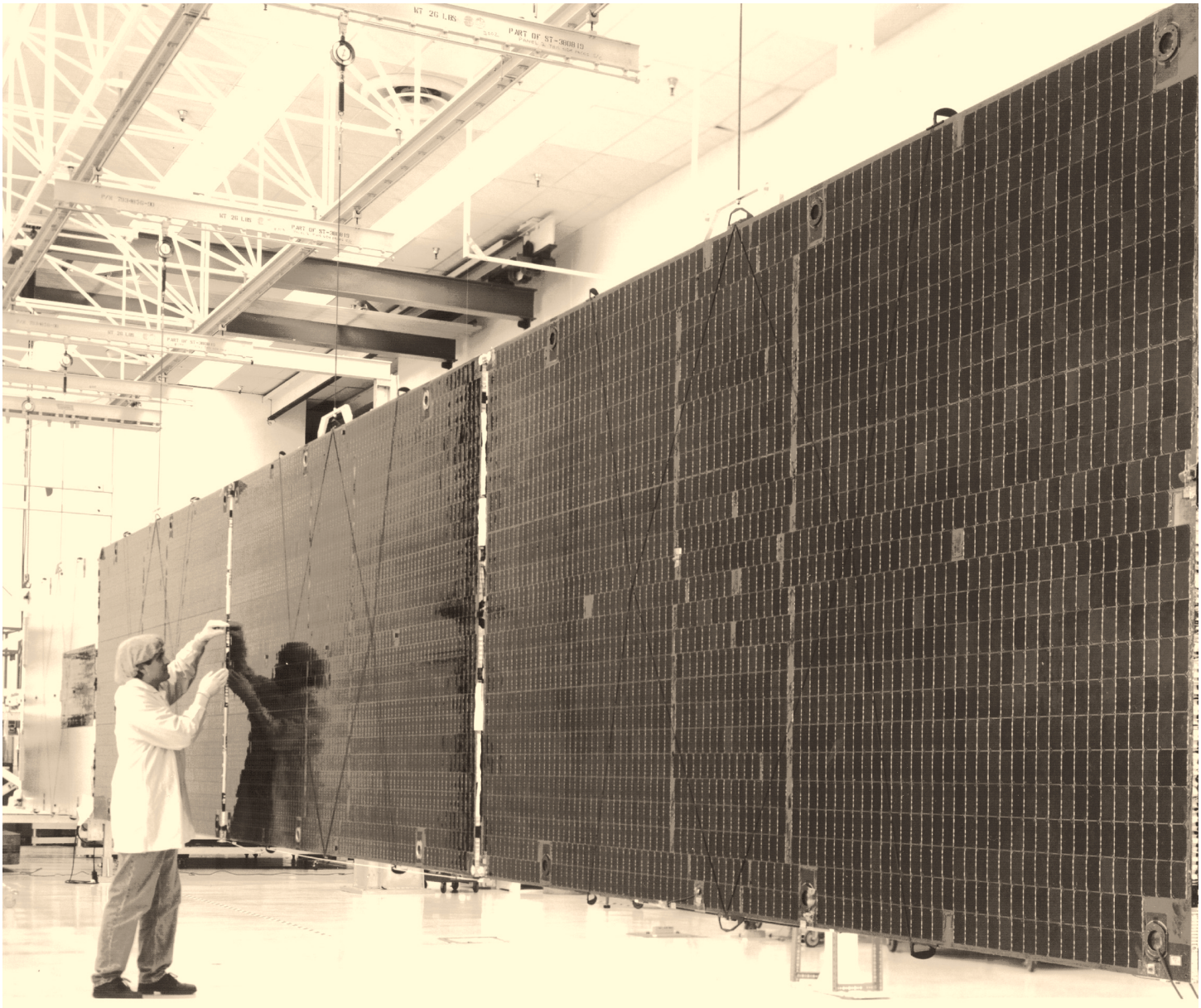
other hand, the process of developing a product culminates in delivery, and thus gives great weight to design and production. The same events and unexpected results that are considered normal for technology development represent problems in the product environment; they can jeopardize achievement of cost and schedule objectives and draw criticism to the product. The ups and downs and the resource changes associated with the technology discovery process do not mesh well with a program's need to meet cost, schedule, and performance goals. This situation has been described as attempting to "schedule inventions."

Successful Cases Afforded Flexibility to Decisionmakers

In the early 1980s, Hughes Space and Communications began developing dual junction solar cell technology that had the potential of greatly increasing the electrical power on satellites. By 1985, a Hughes laboratory had demonstrated the technology by ground testing prototypes, a TRL 6, which is considered an acceptable level of demonstration for space-based technology. Nonetheless, Hughes was not satisfied that the supporting infrastructure (materials, reactors, and test equipment) was mature enough to sustain development and production of the new technology on a satellite. The infrastructure was seen as critical to meeting the cost and schedule requirements of a product. As a result, Hughes did not hand off the technology to a product. Instead, the firm kept it in a research environment, away from cost and schedule pressures.

In the early 1990s, Hughes established requirements for a new satellite—the HS-702—that would use the solar cell technology to leapfrog the competition. After a laboratory demonstration in 1993, Hughes successfully used the new technology on a high-powered version of its existing HS-601 satellite before it began product development on the HS-702 satellite. By 1994, it had determined that the business base was available to sustain development and production of the HS-702 satellite. In all, the firm waited 10 years for the demonstrated technology to meet the requirements. This experience closely resembled that of Ford's voice activated control technology because, in both cases, the new technology took 10 years to mature enough for product readiness. Thus, the firms' approach was not to accelerate technology development but to shorten product development by maturing the technology first. Figure 3.1 shows the solar cell arrays installed on the HS-702.

Figure 3.1: Hughes Solar Cell Arrays



Hughes successfully proved solar cell array technology on a predecessor satellite before beginning product development of the HS-702

Source: Hughes Space and Communications.

The Navy made trade-offs in choosing a technology for the weapon ejection system, which is used to deploy weapons like torpedoes, of the Virginia class attack submarine. Because of quietness, weight, and cost requirements, the Navy preferred a new elastomeric (rubber-based) technology. However, this technology failed endurance testing, and product managers determined that the technology was too risky to be included in the first product. Product managers could have declined this technology and its attendant risk without delaying the submarine's schedule because the Navy accepted marginal increases to the cost and weight requirements for the system so that the proven Seawolf ejection technology could be used as a substitute. Using proven technology on the first submarine has allowed the Navy S&T community to continue developing the elastomeric technology, which is to be incorporated into the new system on the fourth production submarine. As discussed earlier, decisionmakers also had the flexibility to wait for the nonpenetrating periscope technology to reach TRL 9 before including it in the submarine's requirements.

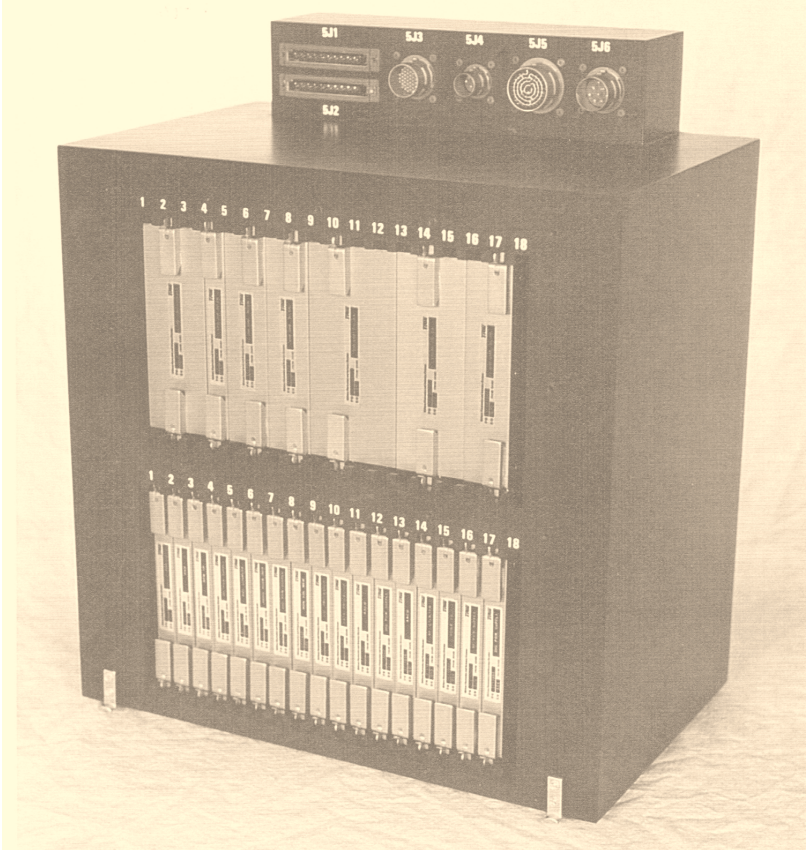
Problematic Cases Provided Little Flexibility to Managers

According to Army officials, the FLIR and integrated avionics technologies required for the Comanche helicopter were critical for providing an increased operational capability over existing Army helicopters. The advanced FLIR technology was needed to meet the user's requirements for increased targeting range and for improved piloting capabilities in bad weather and at night. It represented a quantum leap from existing capabilities. Integrated avionics technology was expected to replace separate radios, navigation systems, and other communication equipment on the helicopter with a modular system that uses central processors.

These technologies were needed to meet weight and size requirements for the aircraft as well as improve communications. Both were critical elements of a mission equipment package that was supposed to reduce the pilot's workload while improving capabilities. Requirements were inflexible. Thus, requirements managers informed us they were unwilling to accept the product manager's request to trade requirements that was prompted by his concerns that the technologies could not advance in time to meet the program's schedule. They believed the product manager to be too risk averse and said they would not take no for an answer. Not only did the user consider the technologies nontradable, they became even more confined by weight and cost restrictions that were placed on the program. For example, a more mature FLIR technology that could possibly meet performance requirements but also weighed more was rejected.

The technological solutions that could meet the strict requirements were limited. According to Army officials, the only viable option was to develop the new technologies, which were in a very immature state, to the required performance levels because no suitable back-up technologies existed. When the Comanche acquisition program was launched, the FLIR and integrated avionics technologies had a TRL 3, barely demonstrated in a laboratory. This level placed the burden on the Comanche program manager to complete their development during the acquisition program. The only ways for the program manager was to slip the schedule or increase development costs. Figure 3.2 shows an early model of the integrated avionics component for the Comanche.

Figure 3.2: Integrated Avionics for Comanche Helicopter



The Army launched the Comanche program with immature technologies, placing the burden on the program manager to complete technology development

Source: DOD.

Similarly, the acoustic sensor technology on the BAT was critical to the submunition's performance because it provided breakthrough improvements in the capability for precision attack of targets at ranges of up to 500 kilometers and in most weather. There was no flexibility for the program manager to ease requirements to substitute a more mature technology because the Army had no existing capability to perform this mission. Thus, the technology, which had a TRL 2 at program launch, was the only solution for locating and acquiring targets. Its feasibility was based on an engineering analysis in the form of studies. Key challenges for the acoustic sensor were to reduce noise to an acceptable level, develop microphones with sufficient range, and reduce the size of the sensor so it would fit into the BAT delivery system. The technology development that was necessary to have the sensor meet requirements had to be accomplished during the schedule-driven, delivery-oriented product development program. The development program encountered technical problems that left the program manager with no choice but to slip the schedule and increase the cost. By the start of the engineering and manufacturing development phase, program officials stated that the acoustic sensor had a TRL 5—still a high risk using the Air Force Research Laboratory's criteria.

Good Technology Handoff Decisions Depend on the Tools and Authority Given to Managers

With the right environment as a precondition, managers on the successful cases benefited from disciplined technology development processes that linked the technologies to products and provided credible information on the status of technologies. They also had standards that were both clear and high for assessing readiness. Once a technology's feasibility and usefulness were demonstrated, it was linked to a product through an early agreement with the product developer to use it if it could be fully developed. Ideally, as technologies approached the higher readiness levels associated with the bridge, S&T managers and receiving product managers agreed to more specific terms for accepting or rejecting a technology. These agreements were early links to the product that were needed for the technology to succeed. If a product manager was not willing to make such an agreement, then the investment to bring the technology to higher readiness levels might not be made. S&T managers were responsible for ensuring that information at key junctures was sufficient and that the technology was ready for inclusion on a product. They saw their role as to screen and develop technologies to standards acceptable to product managers. Product managers were responsible for ensuring that the product could be developed and brought to market within cost and performance targets. They saw as their role to encourage the successful

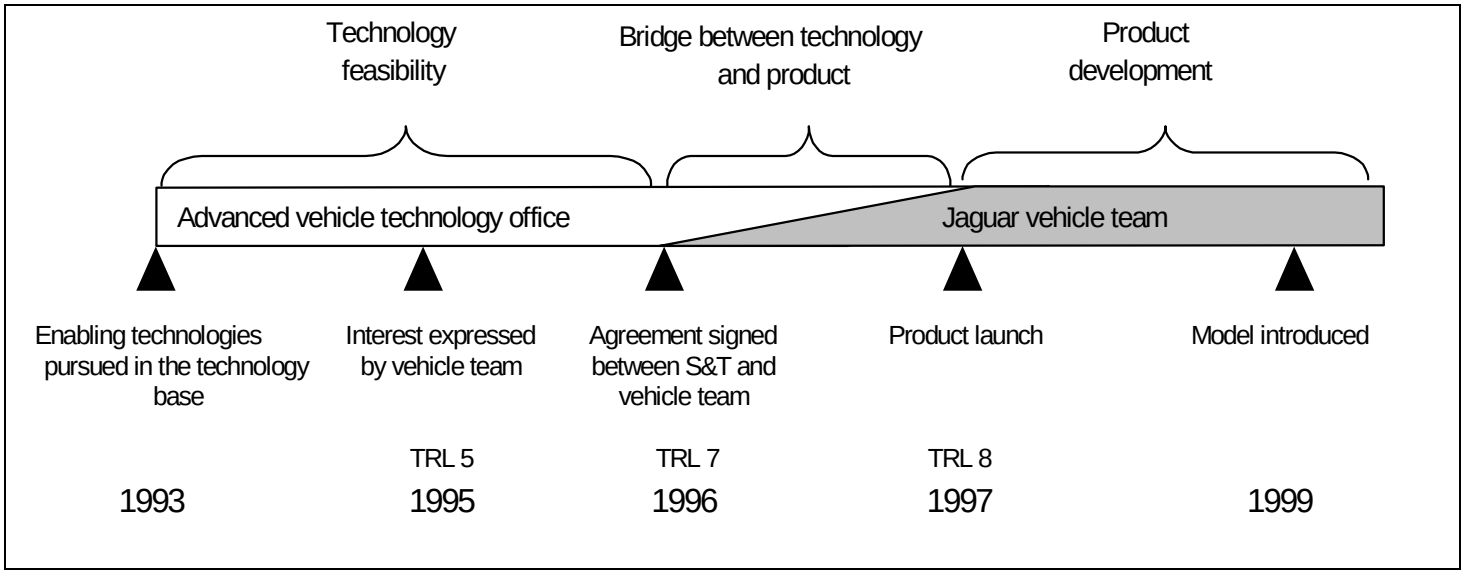
development of new technology but to decline the handoff if it did not meet product performance, cost, and schedule requirements.

When an S&T organization disengages from a technology at a low TRL, the S&T manager gives up much of the ability to be a gatekeeper. In the event that unyielding requirements or other pressures force product managers to accept technologies before they have matured, they are weakened in their ability to safeguard the product development from technology risks. For the cases in which technologies had problems transitioning to products, decisionmakers were disadvantaged by the incomplete information available to them, yet were not empowered to say no to the handoff. Their situation was further degraded by risk assessments that embodied lower standards for accepting undemonstrated technology readiness. In the case of the BAT, the S&T community was bypassed altogether, as the weapon system and its enabling technologies were proposed by a contractor and assigned directly to a program manager.

Successful Cases Benefited From Strong Gatekeepers, Disciplined Processes, and High Maturity Standards

All new technologies at Ford, regardless of whether they are proposed by inside or outside sources, take essentially the same path and gates into products. Initially, technology proposals pass through a process that prioritizes them according to customer needs. The proposals are then passed on to the Advanced Vehicle Technology Office, an S&T organization that determines the readiness of the proposed technology and fits it into Ford's path of technology demonstration. Once approved, the technology follows a structured process that includes two development phases: concept ready and implementation ready. This process results in a smooth transition from the technology development environment into a product, once the technology is mature. Ford's adaptive cruise control technology went through this process, as shown in figure 3.3.

Figure 3.3: Process for Closing the Gap Between the Readiness of Adaptive Cruise Control Technology and Jaguar Requirements



According to Ford officials, technologies for adaptive cruise control existed as separate projects in the technology base from about 1993 to 1995, when the Jaguar vehicle team identified a strong demand for the capability. Ford's S&T community inventoried the ongoing projects and demonstrated the technology as a laboratory breadboard—a TRL 5. By August 1996, the technologists had built a prototype that could demonstrate the technology in a relevant environment—a TRL 7. This work comprised the concept ready phase, in which the technology was taken from concept to where its feasibility was demonstrated to potential users. At the end of this phase, S&T representatives proved that it could work, and cost, schedule, and performance targets were established. Also, a target product and sponsor were identified, linking the technology to a product. The sponsor agreed that it would accept this technology if specific cost, quality, schedule, and performance targets were met. The medium for this acceptance was the Deliverables Agreement Log (DEAL), which was signed in September 1996 by Jaguar's chief engineer based on the prototype demonstration.

Ford uses the DEAL as a tool to maintain visibility over a new technology as it progresses through the development process and to assess its readiness and acceptability for inclusion in a vehicle program before handing it to a sponsor, the vehicle center, or team. The DEAL formalizes

the content of the two development phases and establishes agreements between the technologists managing the project and those with authority to accept the technology into a product. According to Ford officials, the DEAL is important to this process because it is a contract between the parties that addresses the technology's performance, cost, quality, weight, producibility, and maintainability targets that must be met before the end of each phase. It has been invaluable in getting parties to agree on what is expected by the giver and receiver of a technology during the process.

Once these targets are established, the technology moves to the implementation ready phase. For the Jaguar, the Advanced Vehicle Technology Office matured the technology to a high level of readiness by prototyping it in demonstrator vehicles—a TRL 8. The technology passed the implementation ready milestone in February 1997. At that point, the vehicle team accepted the technology for inclusion on a Jaguar product development.

Ford used this decision-making process to develop the night vision technology, but with a different result. Since 1991, Ford has been working on this technology to provide a wide field of view and depth perception for the driver at night, similar to that provided by a FLIR. By 1998, the Advanced Vehicle Technology Office brought the technology to a TRL 8. However, the vehicle center did not agree to include the technology on a product because the technology did not meet the cost targets established in the DEAL.

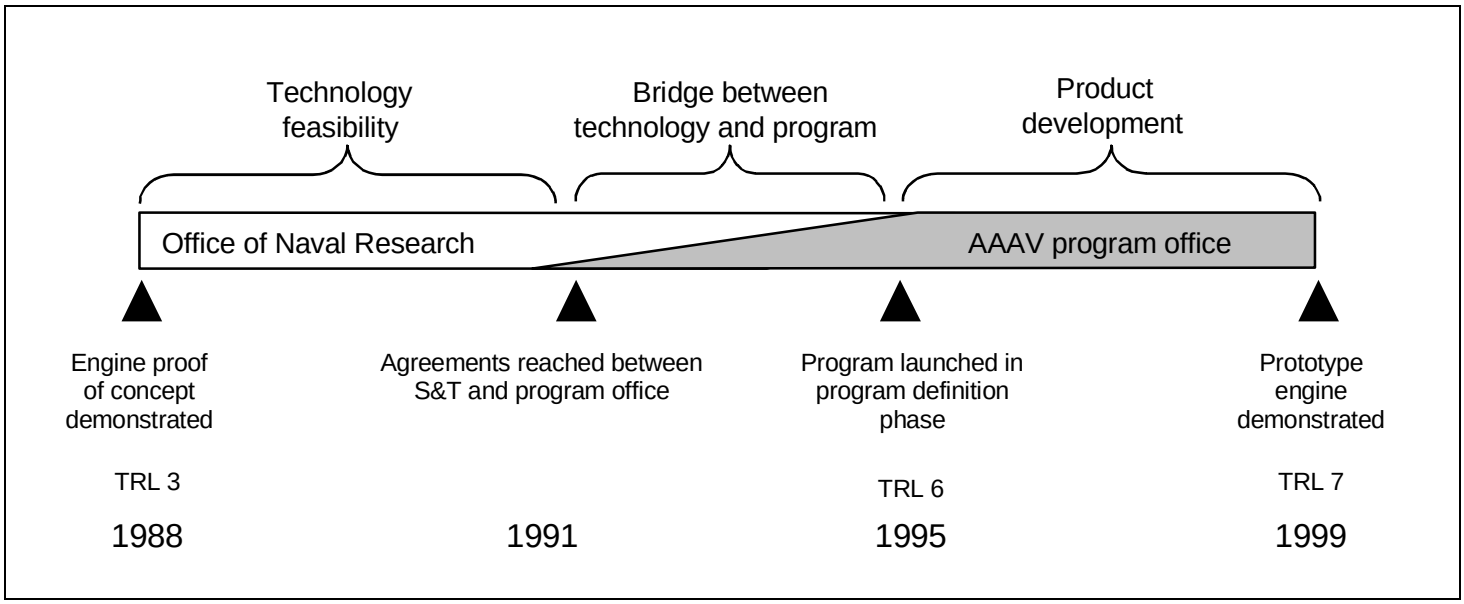
Other companies we visited had similar practices for supporting technology inclusion decisions. For example, 3M takes technology from its technology base when it believes it has a customer need. The gatekeeper responsible for moving technology into a concept phase—analogous to TRL 3 or 4—is the S&T organization of a business unit. That business unit monitors the technology's progress until a new product requirement is identified and decides whether there is interest from a product center to "pull" it. If an interest exists, it begins a feasibility phase that refines requirements through quality functional deployment and builds working prototypes of the new product—a stage that would be analogous to TRL 7 or 8. This phase culminates with an agreement between the technologists and the product developers—the receivers—as to the specific cost and schedule targets that must be met for the technology to be included into a product. To help facilitate the transition, 3M establishes a product development team that includes people from research and development,

marketing, manufacturing, and other functions that transfer with the new technology and ensure it is integrated into the new product.

3M also has high standards for measuring the readiness of a technology before the product developer accepts it. For example, 3M officials told us that they are developing a fuel cell technology for which they have built 15 prototypes for testing purposes—a TRL 7 or higher. However, because the technology has not yet met all of the cost, schedule, and performance targets for product development, they have not allowed it to be included on a new product, despite demand from the marketplace.

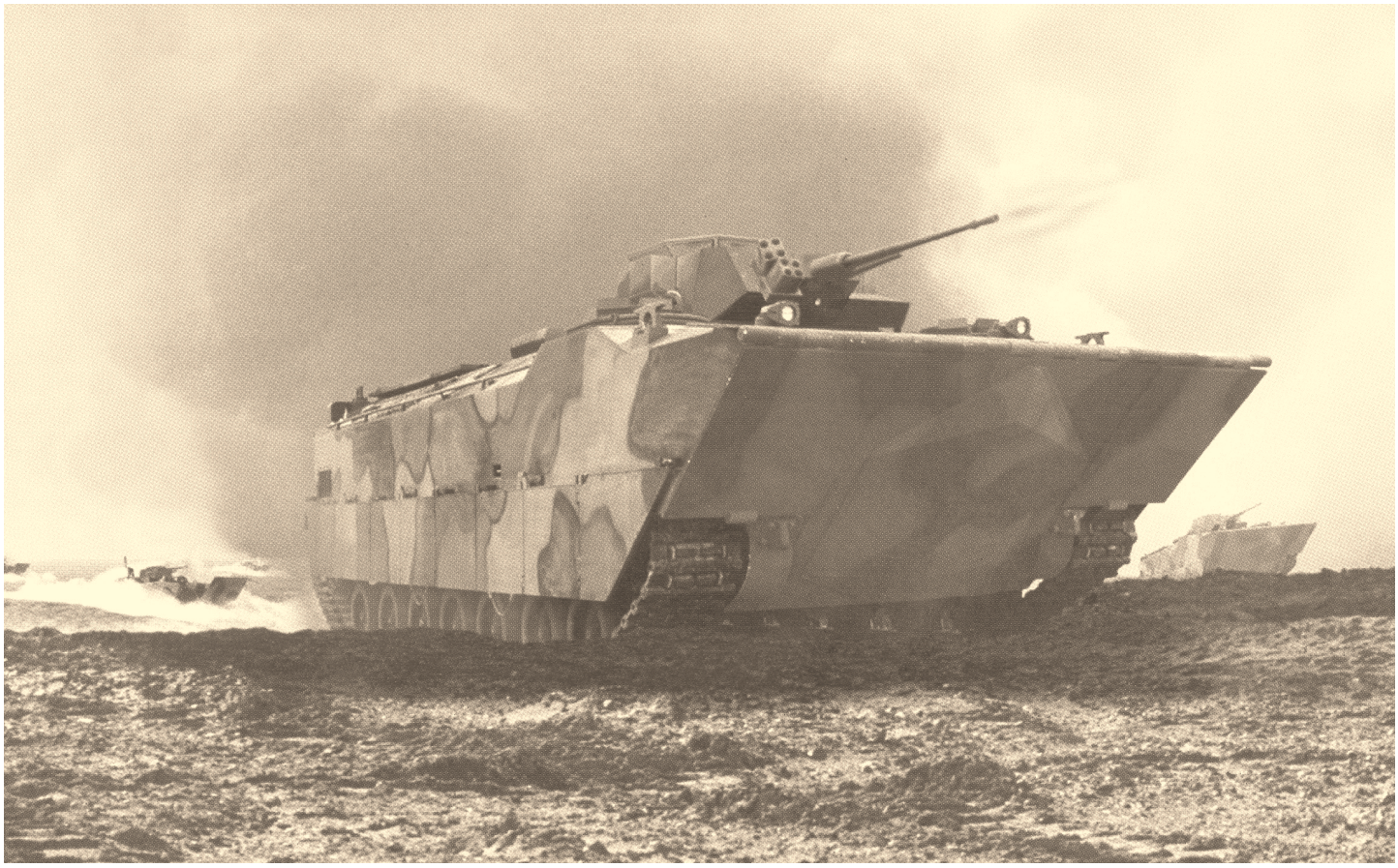
Among the DOD cases, the process followed and the roles played on the AAAV program had several features that enabled good technology inclusion decisions. For almost 3 decades, the Marine Corps has stated a need for an amphibious vehicle with far greater capabilities than the current vehicle. Specifically, the requirement to achieve a speed of 20 to 25 knots in the open ocean made advances in propulsion technology key enablers for the AAAV program. For a vehicle of the planned size and weight of the AAAV, this requirement meant achieving 2,700 horsepower with a relatively compact engine that must operate on land and in water. The Corps had been exploring propulsion technologies for such a vehicle in its technology base for many years. Despite this, the Office of Naval Research, an S&T organization, assessed the propulsion technology and advised that it was not mature enough to warrant inclusion on a program. Based on this assessment, Marine Corps and Navy decisionmakers delayed program launch from 1991 to 1995, until the technology could be brought to higher readiness levels. Figure 3.4 illustrates the process used to transition this technology.

Figure 3.4: Process for Closing the Gap Between the Readiness of Propulsion Technologies and AAAV Requirements



The S&T community and the product managers agreed on what had to be done before the program could be launched. The S&T community then took the lead in maturing the engine to a TRL 6—a level the Air Force Research Laboratory considers acceptable for starting the program definition and risk reduction phase. Thus, the assessment by the Office of Naval Research provided both the information and the criteria that enabled decisionmakers to say no to launching the program given the low readiness of the propulsion technology. This was coupled with the flexibility to wait for the technology to mature and the decision to give an S&T organization responsibility for managing the bridge to product readiness. Figure 3.5 shows the AAAV.

Figure 3.5: AAAV



The Marine Corps and Navy delayed program launch by 4 years to develop key technologies to a higher readiness level

Source: DOD.

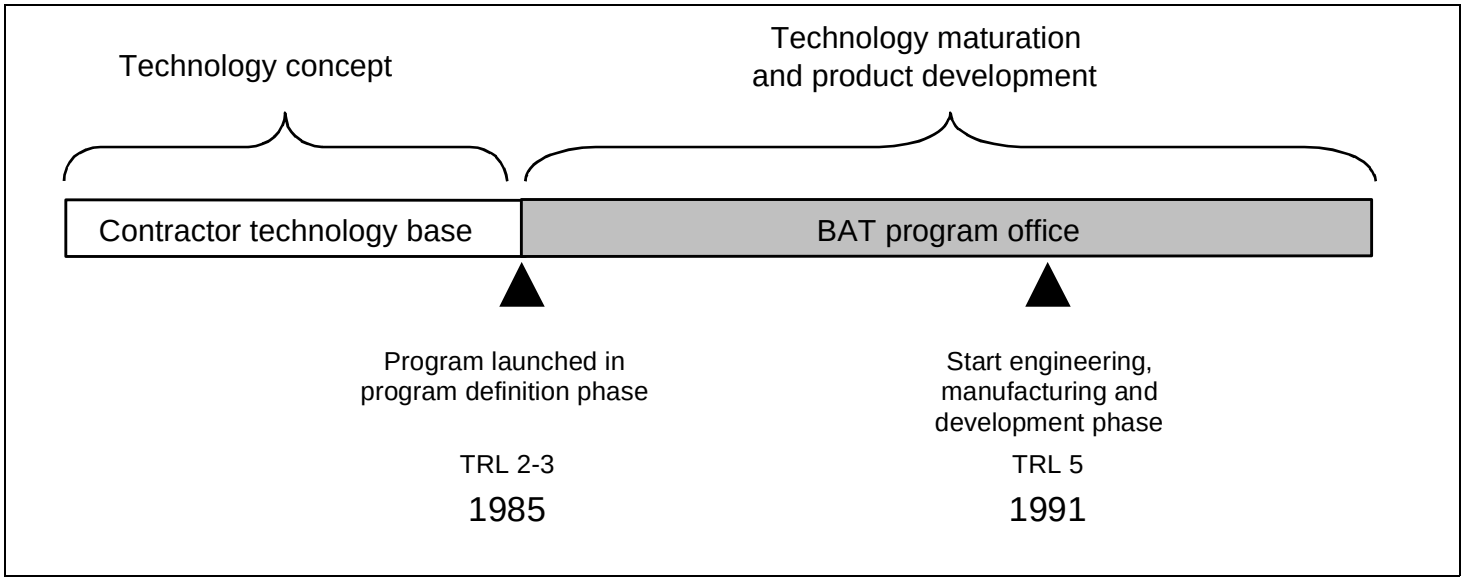
Even with an urgent need for the AAAV, the Marine Corps remained disciplined in its development approach, allowing the technology to mature to the level of the requirement. Two years before program launch, a Navy S&T organization demonstrated the technology in a full-scale prototype engine. By program launch in 1995, the required 2,700 horsepower was demonstrated by a near prototype engine—a TRL 6. The remaining risk was limited to marginal weight and size reductions, although the demonstrator engine could be used as a backup if the size and weight reductions could not be obtained. In early 1999, the AAAV program office demonstrated a

prototype engine at 2,700 horsepower that met size and weight requirements—a TRL 7.

Technology Handoffs Were Compromised When Managers Had Limited Information and Authority

In the BAT program, neither the S&T community nor the product manager had the opportunity to act as a gatekeeper between product requirements and the maturity of enabling technologies. All of the technologies for the BAT came to the program after the contractor, in 1985, had proposed a weapon concept for carrying out unmanned, deep strike missions to attack enemy armored vehicles. Army leadership accepted the concept and drafted requirements for the BAT, and the acquisition program was launched after the proposal was accepted. Thus, the technology for the weapon came directly from the contractor's technology base into the acquisition program, with little or no review by the Army's S&T organization. The process, information, and standards that were critical to successful technology inclusion decisions in other cases were not employed on the BAT. The process followed is shown in figure 3.6.

Figure 3.6: Assimilation of New Technology Into the BAT Program



The program office accepted the acoustic sensor, infrared seeker, and navigation technologies included on the BAT program. In retrospect, the levels of demonstration at the time posed high risks to the product development because the acoustic sensor technology had a TRL of 2 and

the infrared seeker and navigation technologies had TRLs of 3. Program officials stated that a significant amount of technology development was required during product development due to the lack of visibility over technology readiness before program launch. As a result, the development program's cost and schedule significantly increased over original estimates.

An interesting sidelight to the BAT experience concerns the inertial measurement unit, a navigation component of the submunition. When the contractor first proposed the BAT concept, the design included a mature inertial measurement unit in production on other systems. However, after the program was launched, the contractor substituted a new quartz rate technology. At the request of the BAT program manager, the Army's Missile Research and Development Engineering Center, an S&T organization, assessed the maturity of the quartz rate technology. The Center concluded that the new technology had not demonstrated a high enough level of readiness and recommended that a more proven existing technology be used in the program. Eventually, the new technology was dropped, and an existing technology that was at a higher readiness level was used.

We observed additional cases in which decisionmakers relied on comparatively low standards for including technologies. The Army assessed the FLIR, integrated avionics, and helmet mounted display technologies as having moderate risk when they were included in the Comanche program. Army officials stated that they required only the existence of an ongoing S&T technology project as acceptable, as long as the technology was projected to be ready by the engineering and manufacturing development phase. According to program officials, demonstrated maturity was considered but not required; proof that the projects were progressing as scheduled was enough. These technologies, however, had TRLs of 3 at the time of launch—a high risk for the program definition and risk reduction phase. This risk assessment is more consistent with the actual experience of the technologies' maturation in the program.

The standards used for accepting the laser technology into the ABL program also appeared low when compared with the standards used on the more successful cases. While the Air Force had established demonstration standards for the laser to meet prior to program launch, these standards were met if scale models of the laser technology in a laboratory demonstrated they had the potential to produce the energy needed for an operational system. This level of technical demonstration equated to a TRL of 4, representing a high risk for inclusion into an acquisition program.

Impediments to Adopting Best Practices for Technology Inclusion in DOD Are Surmountable

Although product developments—commercial or defense—fare better when key technologies are matured before they are included in the product design, the more traditional approach within DOD is to mature technology during a product's development. Rational explanations are behind this tradition. S&T organizations, operating within fixed budget levels, are not necessarily accustomed or equipped to manage the bridge between technology feasibility and product readiness. Programs are more able to command the large budgets necessary for reaching higher levels of technology readiness than S&T projects. Also, pressures are exerted on new programs to offer unique performance and acceptable cost and schedule projections, which encourage premature acceptance of unproven technologies.

The Under Secretary of Defense for Acquisition and Technology not only supports shorter cycle times and a more aggressive pursuit of technology outside of programs, but also use of commercial best practices to get these results. DOD has several initiatives underway that could make conditions more favorable for S&T organizations to mature a technology further before it is included in a product development. One Army project calls for an S&T organization to manage all technology maturation and integration tasks for a new combat vehicle up to the engineering and manufacturing development phase. Other initiatives may make the S&T community a more integral participant in matching user requirements with technology and tying S&T projects more closely to product development paths. Whether these efforts are effective and can be applied on a broader scale remains to be seen.

Several Factors Make It Difficult to Mature Technologies Before They Are Included on Weapon Systems

Budgetary, organizational, and other factors within DOD make it difficult to bring technologies to high readiness levels before being included in weapon systems. These factors encourage S&T organizations to disengage from technology development too soon and weapon system program managers to accept immature technology. Factors other than these encourage leading commercial firms to keep technology development out of the product developers' hands and in those of S&T organizations. The differences in these factors and in the management of technology development stem from differences in what helps commercial and DOD programs to succeed. They do not stem from capabilities commercial firms possess that DOD does not.

Budget and Organizational Factors

Budget realities within DOD—the fact that weapon system programs attract higher levels of funding than S&T projects—make these programs a more advantageous setting for funding technology development to the higher readiness levels. As a practical matter, it is often necessary to move immature technology to a weapon system program to get needed funds and management support for maturation. Normally, DOD S&T organizations do not see their role as going beyond demonstrating the feasibility of a technology for generic—versus product specific—application (a TRL 5). However, as seen in several of the cases we reviewed, even this level often is not reached before a product development organization takes over. The S&T organizations that helped to bridge the gap from technology feasibility to product readiness on the more successful cases had gone beyond their typical role.

One of the reasons that S&T organizations disengage relatively early is that S&T work is traditionally funded as a percentage of the overall DOD research and development budget. S&T organizations receive about $8 billion annually, or about 20 percent, of DOD's research and development budget. This money funds several thousand projects, providing less than $1 million per project on average. As a result, a project needing $100 million or more to mature technology to higher readiness levels than normal—not unreasonable sums—would command a fairly large share of an S&T organization's budget, thereby reducing funds available for other projects. Under the current scenario, the remaining 80 percent of DOD's research and development funds, approximately $30 billion, is spread out over a much smaller number of specific weapon programs. A typical weapon system program can receive several hundred million dollars annually and occasionally over $1 billion to fund development. A major program, such as the F-22, can command $15 billion or more in total for product development, receiving sometimes more than $2 billion in a year.

Events on the Air Force's ABL program illustrate these realities. Originally, the Air Force had planned the ABL as a technology development project to be managed to high readiness levels by an S&T organization. The project was started in 1992 as an advanced technology transition demonstration to design, fabricate, and test a single demonstrator weapon system and was to take 8 years to complete. The pacing technologies, the laser and the beam control, were to be matured to a high level—equivalent to TRL 6 or 7—before being included in a product development program. Requirements had not been fixed. In other words, the planned approach resembled what

we have described as the more successful cases in our review. Figure 4.1 shows the ABL.

Figure 4.1: Airborne Laser

The Air Force used relatively low readiness level standards to include a key technology into ABL

Source: DOD.

In 1996, the Air Force abandoned this approach and decided to launch ABL as a weapon system development program, not because technologies were sufficiently mature but because of funding and sponsorship concerns. At this time, the two key technologies were at TRLs 3 and 4. According to the retired manager of the S&T project, a product development program was deemed necessary to make the technology development effort appear real to the users and not a scientific curiosity. Within the Air Force, the perceived lack of support by the users placed the project in a constant state of funding jeopardy. This perception was important because the S&T project was costly, with a total estimated cost of $800 million, with some annual funding requirements approaching $200 million. The annual funding requirements would encompass a large percentage of the Air Force's S&T budget unless additional funds were made available from weapon system budgets or elsewhere. By transitioning to a weapon system program linked to user requirements, the ABL was more likely to get these funding levels.

This approach was successful—the program won user support and the desired funding. However, sacrifices were made in technology development. According to the former project manager, the new program focused less on the elemental technology hurdles and more on meeting all

user requirements. More expensive demonstrations were necessary to meet these broader requirements without necessarily doing more to demonstrate basic technology readiness. It became a more traditional program with technology and product development proceeding at the same time, with attendant higher risks. In March 1999, we reported that, while the ABL has made progress in developing these technologies, it still faced technical challenges.[1]

Other Incentives

Pressures exerted on weapon system programs can make it advantageous to include in their design immature technologies that offer significant performance gains. One traditional source has been the perceived threat. Users can demand performance improvements that necessitate the application of unproven technologies, particularly when a fielding date is mandated, to stay ahead of the threat. Another source is technologists, whether from S&T organizations or contractors, who see a new weapon system as an opportunity to apply a new technology. Also, the competition for funds can encourage performance features—and requisite technologies—that distinguish the new weapon system from competitors.

The F-22 was justified as being faster, stealthier, and more lethal than other fighters, such as the F-15 and F-117, were. As a result, the F-22 is being designed with several advanced technologies, including a very sophisticated suite of avionics that is critical to its performance features that distinguish it from the other fighters. However, at the time the F-22 program was launched in 1986, the avionics technologies were immature; they have since been a source of problems on the program. We recently reported that the development of the F-22's integrated avionics systems continues to experience cost growth and schedule delays, more than 12 years into the program.[2]

A different set of incentives causes leading commercial firms to make their S&T organizations responsible for maturing technologies to higher readiness levels. Commercial firms are aware of the risks associated with the high investment that product development requires. They have a strong incentive in the realization that if a product is late, costs more, or performs

[1] Defense Acquisitions: DOD Efforts to Develop Laser Weapons for Theater Defense (GAO/NSIAD-99-50, Mar. 31, 1999).

[2] F-22 Aircraft: Issues in Achieving Engineering and Manufacturing Development Costs (GAO/NSIAD-99-55, Mar. 15, 1999).

less than expected, the customer could walk away from the product and the investment would be lost. Minimizing the possibility of technology being the cause of such problems is thus a top priority. Having their S&T organizations reduce those risks is essential to putting product developments in the best position to succeed. DOD does not have the same incentives. DOD programs are not penalized if a product is late, costs more, or performs less than expected, because the customer does not walk away.

Services Encouraged to Use Best Practices

Over the past several years, DOD has encouraged the services to use best practices to streamline the current process for acquiring new weapon systems in order to make them faster, cheaper, and better. Shorter acquisition cycle times are seen as critical to making the best use of advances in technology. To encourage change, DOD has set a goal to reduce the average acquisition cycle time for all program starts in fiscal year 1999 and beyond by 50 percent over historical averages. DOD has several initiatives to improve its technology development process and to move technologies to the warfighter faster and less expensively than the traditional means. The initiatives also attempt to put the organizations and funding in place to bring technologies to higher readiness levels before they are included in programs. These initiatives—defense technology objectives, advanced technology demonstrations, and advanced concept technology demonstrations—call for S&T organizations to play a bigger role in managing technologies closer to the point of product readiness, matching requirements to technology projects, and making better use of demonstration standards.

Defense Technology Objectives

Defense technology objectives (DTO) are used to bring more discipline to S&T projects and to link them more closely with weapon system development programs. A DTO typically involves a particular technology advance, such as high temperature materials for turbine engines and high fidelity infrared sensors. It can also group several technologies into a larger demonstration. Each DTO identifies a specific technology advancement that will be developed or demonstrated, the anticipated date of the technology availability, the ultimate customer, and the specific benefits resulting from the technology. It places a corporate attention and commitment on the technology project by having the technologists, product developer, and customer involved in the project.

According to DOD, the focus of its S&T investment is enhanced and guided through DTOs. Each DTO must go through a formal review and approval

process within DOD and must be directly related to advancing the operational concepts depicted in DOD's "Joint Vision 2010" planning document. According to DOD officials, those requirements have helped to eliminate instances in which technologists work on projects of particular interest to them, but with no military application, because the projects should be linked to a specific warfighter need. For fiscal year 1999, DOD established approximately 350 DTOs, which accounted for $3 billion, or less than 50 percent, of the funds DOD had allocated to S&T projects. The remaining funds were allocated to projects under the jurisdiction of each military service or other defense agencies and did not go through the same review and approval process.

Advanced Technology Demonstrations

Advanced technology demonstrations (ATD) are intended to more rapidly evolve and demonstrate new technologies so they can be incorporated into a product, if warranted. An ATD has four characteristics that distinguish it from a conventional S&T project. They (1) require large-scale resources; (2) involve the user; (3) use specific cost, schedule, and performance metrics; and (4) identify a target product for inclusion. An ATD is managed by an S&T organization and should conclude with an operational demonstration of the potential capabilities of the technology, equating to a TRL 5 or 6. The original approach to the ABL was essentially an ATD approach. Most ATDs use laboratory hardware to demonstrate the potential capability of nonproduct specific technologies and not prototype hardware. If the technology is determined to be feasible and provides some military use, then it may proceed to the program definition and risk reduction phase of an acquisition program. From that point, the product developer completes the technology development for a specific product.

Advanced Concept Technology Demonstrations

In 1994, DOD initiated Advanced Concept Technology Demonstrations (ACTD) to help expedite the transition of mature technologies from the developers to the warfighters. ACTDs are intended to help the DOD acquisition process adapt to budget constraints while developing technology more rapidly. The purpose of an ACTD is to assess the military use of a capability, such as a weapon, comprised of mature technologies. Typically, ACTDs last 2 to 4 years and consist of building and demonstrating a prototype to provide a warfighter the opportunity to assess a prototype's capability in realistic operational scenarios. From this demonstration, the warfighter can refine operational requirements, develop an initial concept of operation, and determine the military use of the technology before it proceeds to the product development process.

According to DOD, ACTDs, which are managed by S&T organizations, will be a key mechanism to ensure technology development is separated from product development. In related work on unmanned air vehicles, we found that ACTDs provided decisionmakers credible data that they used to terminate efforts or transition the demonstrator to an acquisition program. In these cases, ACTDs put decisionmakers in a better position to be gatekeepers. However, we have reported that the ACTD program needs to be improved.[3] We found that DOD's process for selecting program candidates does not include adequate criteria for assessing the maturity of proposed technology and has resulted in the approval of projects that included immature technologies. We found that the use of specific criteria for determining maturity was a best practice in the most successful technology development cases we examined.

Two Unique DOD Projects May Provide Lessons on How to Enable S&T Organizations to Manage Technology Further

Two DOD projects are using S&T organizations to manage technology development to higher readiness levels. One, the Army's Future Scout and Cavalry System, is using a modified ATD to mature technologies and make performance trade-offs in the more flexible environment provided by S&T. The other is a joint government and industry program, which the Air Force Research Laboratory is managing to reduce the risks associated with new jet engine technologies. These projects may provide insights on how S&T organizations could routinely play a bigger role in maturing technologies enough for safe inclusion on weapon system programs. They may also clarify the concern that playing a bigger role in technology maturation could cause S&T organizations to do less basic research and technology development.

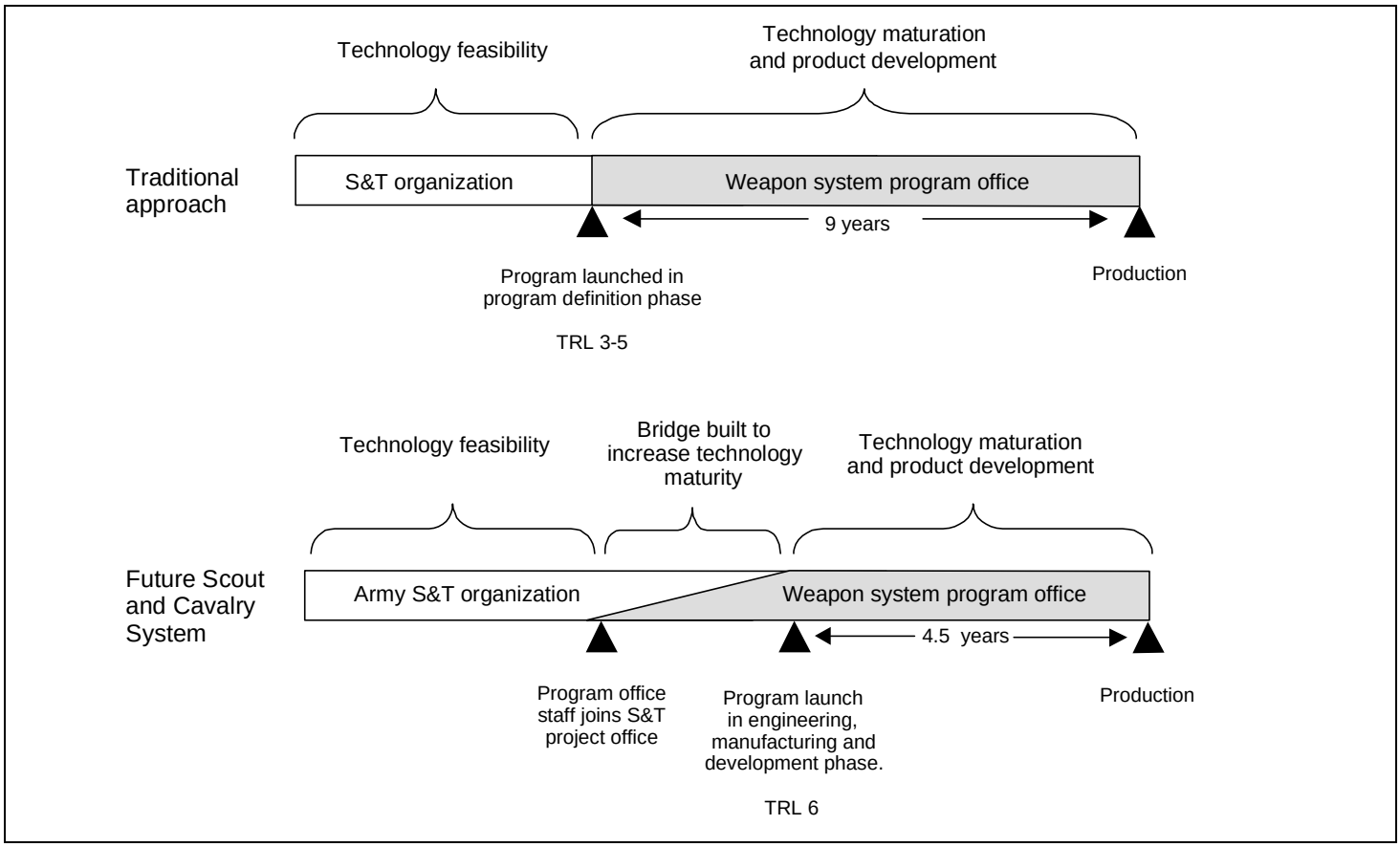
Future Scout and Cavalry System

In fiscal year 1997, the Army began piloting a variation of an ATD that is designed to help bridge the gap between technology development and product development by expanding the S&T community's role in managing technologies further into the development cycle. The Army's initiative, called Fast Track, is intended to reduce cost and cycle time by bypassing the program definition and risk reduction phase of the DOD acquisition process. The Army is testing this concept with its Future Scout and Cavalry System project. In this project, the Army will design, develop, and build a demonstrator vehicle to show the technical feasibility of the weapon. All of

[3] Defense Acquisition: Advanced Concept Technology Demonstration Program Can Be Improved (GAO/NSIAD-99-4, Oct. 15, 1998).

these tasks will be done under the management of the Army's S&T organization. The Army believes that a more extensive S&T project will make the program definition phase unnecessary and estimates that this concept will reduce the development process by as much as 4 years and save about $400 million. We did not review the Future Scout project in terms of its affordability, feasibility, or any impacts it may have on the Army's S&T budget. Figure 4.2 compares the Fast Track development process with the traditional approach.

Figure 4.2: Comparison of Traditional Technology Development Process With the Army's Fast Track Approach

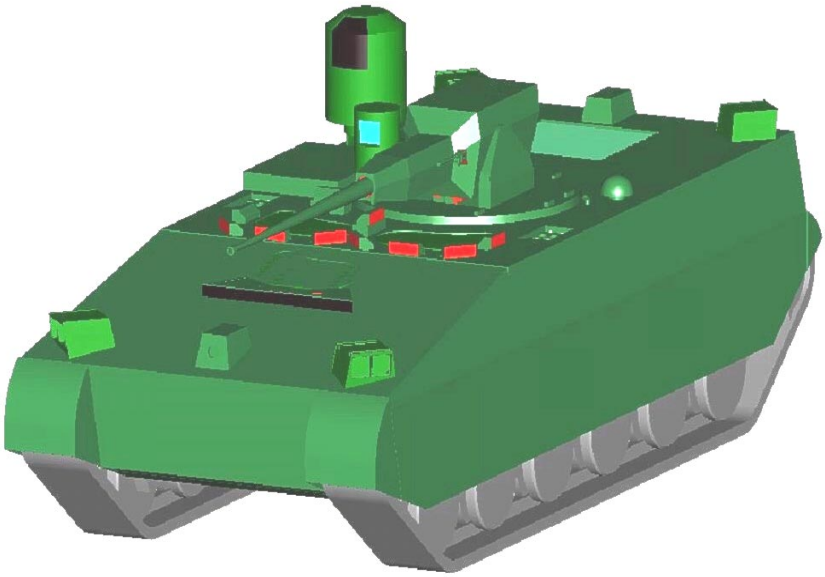


While we do not necessarily agree that the first phase of the acquisition cycle can be omitted, so far the Future Scout project is emulating technology development practices like those we observed in the successful cases. First, it has established demonstration criteria that must be met before the technology enters product development. Second, it has also

established forums that involve key players on the technology path to keep them informed of the technology's development progress. For example, the acquisition program manager will be integrated into the development project during the final 1.5 years of the S&T program. This should provide a good link between the technology development and product development, allowing the program manager to fully understand the technology before product development begins. Finally, by allowing an S&T organization the flexibility to manage technologies further into the development cycle, Army officials believe they will be able to make trade-offs among cost, schedule, and performance requirements before program launch, without raising concerns about the state of the project or breaching baselines that had been set without enough knowledge.

While this concept comes closer to the most successful technology development cases we reviewed, it still embodies greater technical risk. The Army expects to demonstrate some performance capabilities of the vehicle before the product development phase begins. However, the demonstrator vehicle will only be about 75 percent of a complete prototype, which means some key technologies will not be demonstrated to high readiness levels before that phase begins. Nonetheless, the project manager equated the expected overall technical maturity of the vehicle at transition to a TRL 6. The Army considers this a medium or acceptable level of risk, and it is willing to enter product development with some immature technologies. If, however, product development begins at engineering and manufacturing development, this risk could be assessed as high, based on TRLs. Figure 4.3 shows an artist's concept of the Future Scout and Cavalry System.

Figure 4.3: Future Scout and Cavalry System



An Army S&T organization is maturing technologies and proposing performance trade-offs for the Future Scout and Cavalry System before program launch

Source: DOD.

Integrated High Performance Turbine Engine Technology Program

The Integrated High Performance Turbine Engine Technology program—a joint government and industry effort—is focused on developing technologies for more affordable and higher performance turbine engines for both missiles and aircraft. It is a technology validation program and is managed by an S&T organization to perform demonstrations of various engine technologies to higher readiness levels than most S&T projects. After the demonstrations, the technologies enter a product development program. The program takes the technology through a series of tests that range from individual component tests to full-scale engine demonstrations. The program has established strong links with the acquisition programs for which the technologies are intended. For example, Air Force Research Laboratory officials informed us that they established formal technology transition plans with the F-22 and Joint Strike Fighter programs that document agreements on what technology development activities will be performed to support the programs. Representatives from each program office are invited to all technology demonstrations and are kept informed about demonstrated progress.

As part of the program, the Air Force developed a set of standards to assess the readiness levels of technologies similar to NASA's TRLs. According to the Air Force, the S&T organization uses these standards to determine when the project has been completed. These standards were the first application of readiness levels by the Air Force Research Laboratory. There are five technology readiness levels ranging from component-level tests in a laboratory to the highest level involving actual flight tests of engines. The program typically does not take technologies to the highest readiness level (flight test) because of the high cost. The program stops when it has been determined the technology is well defined within acceptable boundaries and a good correlation exists between test results and engineering predictions. This readiness level would translate to a TRL of 5 or 6, as used in this report. The final step of the technology development is left to the product developer who determines if the technology can be packaged and integrated into the final product.

Conclusions and Recommendations

Conclusions

Clearly, DOD's continued advancement of new technologies is essential to the continued superiority of its weaponry. The leading edge military capabilities the United States possesses today, such as stealth aircraft, precision munitions, and intelligence-gathering satellites, bear witness to the effects of such technical advances. At the same time, the incorporation of advanced technologies before they are mature has been a major source of cost increases, schedule delays, and performance problems on weapon systems. As DOD contemplates increasing its annual investment in new weapons to $60 billion, the expectations on program managers are great: they must develop and field weapons of superior capability more quickly and less expensively than in the past. The way advanced technologies are matured and included in weapon systems will play a central role in meeting these expectations. Although different ways to better assimilate new technologies into weapons are legitimate topics for debate, that it has to be done better is not.

The leading commercial firms' practices have produced results that resemble those sought by DOD: more technically advanced, higher quality products, developed in significantly less time, and less expensively than their predecessors. Managing the development of advanced technology differently--and separately--from the development of a product has been key to these results. The firms insist that advanced technology reach a high level of maturity, the point at which the knowledge about that technology is essentially complete, before allowing it into a product development. By separating the two, the firms lessen the product manager's burden and place that person in a better position to succeed in delivering the product. These practices may not necessarily accelerate the pace at which technology matures. In fact, several of the commercial technologies we reviewed took 10 years or more to get to market. The clear beneficiaries of the practices are the product developments, for which the investments are much larger, and time translates into significantly more resources than in a technology project. Adapting these practices on its weapon system programs can help DOD to reduce costs and the time from product launch to fielding, and use technology advances as they become available more frequently.

Separating technology development from product development calls for a new approach to managing technology development. Two conditions are essential to such an approach. First, the right environment for maturing technologies must exist. A practice that is instrumental in providing this environment is maturing technology to achieve product readiness before it

is constrained by the rules of an acquisition program. In the successful DOD cases we reviewed, this environment was provided by S&T organizations or a team of S&T and product developers who managed technologies to high readiness levels before they were included in an acquisition program. These organizations provided an environment more conducive to the ups and downs normally associated with the discovery process. A corollary practice is agreeing on what level of knowledge is needed about a new technology before it is considered for inclusion in a product design. When that knowledge level does not exist, the flexibility for S&T organizations and product managers to either take the time to mature the technology or trade off product requirements until they can be met with mature technology is essential. It is a rare program that can proceed with a gap between product requirements and maturity of key technologies and still be delivered on time and within costs. Second, S&T and product managers must be provided with the disciplined processes, information, standards, and authority to make good handoffs of technology to product. Prepared with the tools and authority to make sound handoff decisions, both S&T and product managers can function as gatekeepers to safeguard the product development from undue technology risks.

Leading commercial firms have adopted this approach as a matter of necessity and have used the organizations, tools, and other practices to foster technology development and improve the outcomes of product developments. The high stakes stemming from the large investment required for a new product and the risks if the product does not meet customer needs reinforce this approach in leading commercial firms. The DOD cases that followed a similar approach were realizing better program outcomes, at least in the sense that the programs avoided key technology development problems. Yet, these cases are not the norm for DOD programs for several reasons.

- More typically, the commitment to develop and produce a weapon system is made before a match between technology and weapon system requirements exists.
- DOD programs operate under different conditions that make it more difficult—and less rewarding—to separate technology development from product development.
- Budget realities make it more difficult for S&T organizations to carry technologies to the high readiness levels needed to meet product requirements; such resources are more available within product developments.

- The pressures to show the unequalled performance necessary to win funding encourage including promising, but immature, technologies in weapon system designs.

It will take procedural, organizational, and cultural changes within DOD's acquisition process to foster an environment in which (1) technologies can be successfully matured outside the purview of weapon system programs, (2) programs can be relieved of the pressures to include immature technologies and the unrealistic expectations that the technologies will conform to tight cost and schedule projections, and (3) technology advances will not stall due to inadequate funding or lack of identification with a product in the later, more expensive stages of demonstration.

Experience has shown that such an approach can work within DOD on individual cases. DARPA played a primary role in managing the transition of the nonpenetrating photonics mast technology to the Virginia class attack submarine. The Integrated High Performance Turbine Engine Technology program has carried advanced jet engine technologies to TRLs of between 5 and 6 for successful inclusion into programs. In the Future Scout program, an Army S&T organization, augmented by product development staff, is managing an ATD to lower the risk of key technologies before a product development program is launched. However, it remains to be seen whether the Army will be successful in using large and expensive S&T projects, such as the Future Scout program, without affecting other Army S&T projects. A challenge for DOD will be whether the lessons learned from these individual cases offer an approach that has DOD-wide application. Meeting this challenge is essential to fielding technologically superior weapons more quickly and within predicted costs.

Recommendations

We have previously recommended that DOD separate technology development from weapon system programs. That recommendation was made without prejudice toward the necessity of technology development but rather with the intent that programs could be better managed if such development was conducted outside of a program manager's purview. Similarly, the recommendations that follow are made without prejudice toward—or the intention of compromising—the basic research and other activities that S&T organizations perform. We recognize that implementation of these recommendations will have organizational, funding, and process implications and will require the cooperation of the Congress.

To help ensure that new technologies are vigorously pursued and successfully moved into weapon system programs, we recommend that the Secretary of Defense adopt a disciplined and knowledge-based method for assessing technology maturity, such as TRLs, DOD-wide. This practice should employ standards for assessing risks of handoff to program managers that are based on a technology's level of demonstration and its criticality to meeting the weapon system's requirements.

With these tools in hand, we recommend that the Secretary (1) establish the place at which a match is achieved between key technologies and weapon system requirements as the proper time for committing to the cost, schedule, and performance baseline for developing and producing that weapon system and (2) require that key technologies reach a high maturity level—analogous to TRL 7—before making that commitment. This would approximate the launch point for product development as practiced by leading commercial firms.

We recommend that the Secretary find ways to ensure that the managers responsible for maturing the technologies and designing weapon systems before product development are provided the more flexible environment that is suitable for the discovery of knowledge, as distinct from the delivery of a product. Providing more flexibility will require the cooperation of requirements managers and resource managers so that rigid requirements or the threat of jeopardizing the funding planned to start product development will not put pressure on program managers to accept immature technologies. Such an environment may not be feasible if the program definition and risk reduction phase remains the effective launch point for an entire weapon system program.

An implication of these recommendations is that S&T organizations will have to play a greater role in maturing technologies to higher levels and should be funded accordingly. Therefore, we recommend that the Secretary of Defense evaluate the different ways S&T organizations can play a greater role in helping technologies reach high levels of maturity before product development begins. For example, given that a technology has sufficient potential for application to a weapon system, at a minimum, an S&T organization should be responsible for taking a technology to TRL 6 before it is handed off to a program office at the program definition and risk reduction phase. During this phase, the program manager would be responsible for maturing the technology to TRL 7 before it is included in an engineering and manufacturing development program. In a situation where a single, design-pacing technology is to be developed for a known

application—like the nonpenetrating periscope—an S&T organization should be required to mature that technology to TRL 7 before it is turned over to a product development manager. S&T organizations could play a similar role when a significant new technology is being prepared for insertion into an existing weapon system. Finally, when multiple new technologies are to be merged to create a weapon system, S&T organizations should be required to bring key technologies to TRL 6 and then become part of a hybrid organization with product developers to integrate the technologies and bring them to TRL 7 before handing full responsibility to a product development manager.

To help guard against the possibility that the more basic research and technology development activities would be compromised by having S&T organizations routinely take key technologies to TRL 6 or higher, we recommend that the Secretary extract lessons from the nonpenetrating periscope, the AAAV, and the Army's Future Scout programs, and other ATD and ACTD programs. Specifically, the Secretary should assess whether the resources needed to enable S&T organizations to play a leading role in the development of technologies and, in some cases, preliminary system design, detracted from or displaced more basic research and technology development programs.

Finally, we recommend that the Secretary empower managers of product development programs to refuse to accept key technologies with low levels of demonstrated maturity. The Secretary can encourage this behavior through supportive decisions on individual programs, such as by denying proposals to defer the development of key technologies and by favoring proposals to lengthen schedules or lessen requirements to reduce technological risk early.

Agency Comments and Our Evaluation

DOD generally concurred with a draft of this report and its recommendations, noting that the traditional path to new weapon system development is no longer affordable or necessary (see app. I). DOD stated that it has embarked upon a "Revolution in Business Affairs" that will enable new technologies to be developed more efficiently and effectively. It believes that the first steps in this direction have already been taken but agrees that more progress needs to be made. DOD agreed that TRLs are necessary in assisting decisionmakers in deciding on when and where to insert new technologies into weapon system programs and that weapon system managers should ensure that technology is matured to a TRL 7 before insertion occurs. DOD concurred that S&T organizations should be

involved in maturing technologies to high levels, such as TRL 6, before transitioning to the engineering and manufacturing development phase and agreed to assess the impact of this involvement on other S&T resources. We note that the best practice is to mature technology to at least a TRL 7 before starting the engineering and manufacturing development phase, whether the technology is managed by an S&T organization, a weapon system program manager, or a hybrid of the two organizations.

DOD noted that while TRLs are important and necessary, the increasing projected life for new weapon systems, total ownership costs, and urgency based upon threat assessments are also important considerations for system development decisions. We agree and note that our recommendations are not intended to cover all aspects of weapon system development decisions or to suggest that technology maturity is the only factor in such decisions. Rather, the recommendations are in keeping with the purpose of the report, "to determine whether best practices offer methods to improve the way DOD matures new technology so that it can be assimilated into weapon system programs with less disruption." We believe that a knowledge-based approach to maturing technology, such as TRLs, can benefit other considerations as well. For example, decisions on what technologies to include in a weapon system and when to include them can have a significant bearing on its total ownership costs.

DOD stated that there should be an established point for the transition of technologies and that it plans to supplement its milestone review process with additional guidance in the next revisions to DOD Directive 5000.2R. It also stated that its policy on the evolutionary approach to weapon acquisitions should be developed in consonance with the technology transition strategy. We cannot comment on the revisions to the directive or the evolutionary acquisition policy because they have yet to be published. However, under the current milestone review process, the pressures placed on a program during the program definition and risk reduction phase—when much technology development occurs—can operate against the flexibility and judgments that are needed to mature technologies. If the revisions to the directive supplement the current milestones without relieving the pressures brought to bear on programs as they are launched in the program definition and risk reduction phase, it will remain difficult to discourage the acceptance of immature technologies in the design of new weapon systems. To relieve these pressures, we encourage DOD, as it develops the directive and the evolutionary acquisition policy, to separate technology development from product development and to redefine the launch point for a program as the point at which enough knowledge has

been gained to ensure that a match is reached between the maturity of key technologies and weapon system requirements.

DOD also stated that program managers already have the ability to reject inappropriately mature technologies, and to the extent technology immaturity affects acquisition baselines, to advise acquisition executives of feasible alternatives. We did not find this to be the case in our review. Rather, we found that the program managers' ability to reject immature technologies is hampered by (1) untradable requirements that force acceptance of technologies despite their immaturity and (2) reliance on tools for judging technology maturity that fail to alert the managers of the high risks that would prompt such a rejection. As noted in the report, once a weapon system program begins, the environment becomes inflexible and deviations to program baselines can attract unwanted attention. This reality limits the program managers' ability to reject immature technologies.

Technology Readiness Levels and Their Definitions

Technology readiness level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system "flight proven" through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

Comments From the Department of Defense

THE UNDER SECRETARY OF DEFENSE

3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

ACQUISITION AND TECHNOLOGY

JUL 16 1999

Mr. Louis J. Rodrigues
Director, Defense Acquisition Issues
National Security and International
Affairs Division
U.S. General Accounting Office
Washington, D.C. 20548

Dear Mr. Rodrigues:

This is the Department of Defense response to the General Accounting Office (GAO) draft report, "BEST PRACTICES: Managing Advanced Technology Development Can Improve Weapon System Outcomes," dated June 7, 1999 (GAO Code 707336/OSD Case 1836). The Department concurs with the GAO draft report.

The Department agrees with the GAO that much of the traditional path to new weapon system development is no longer affordable or necessary. Following the lead of commercial best practices, the Department has embarked upon a Revolution in Business Affairs that will enable the acquisition of new technologies more efficiently and effectively. The first steps in this new direction have already been taken, but, as GAO points out, more progress needs to be made. The Department welcomes the GAO's recommendations, and our specific responses to these recommendations are included herein as an attachment.

Thank you for the opportunity to review and comment on the report. Technical corrections to the report were separately provided. The professionalism and the level of cooperation between my staff and yours are greatly appreciated, and we look forward to working with your staff again in the future.

Sincerely,

Dave Oliver

Attachment:
As stated

GENERAL ACCOUNTING OFFICE DRAFT REPORT - DATED JUNE 7, 1999 (GAO CODE 707336) OSD CASE 1836

"BEST PRACTICES: MANAGING ADVANCED TECHNOLOGY DEVELOPMENT CAN IMPROVE WEAPON SYSTEM OUTCOMES"

DOD RESPONSE

Now on pp. 7 and 63-64.

RECOMMENDATION 1: To help ensure that new technologies are vigorously pursued yet successfully moved into weapon system programs, the GAO recommended that the Secretary of Defense adopt a disciplined and knowledge-based practice for assessing technology maturity, such as technology readiness levels (TRLS), DOD-wide. The GAO asserted that this practice should employ standards that are based on a technology's level of demonstration and its criticality to meeting the weapon's requirements. (p. 5, p.45/GAO Draft Report)

DOD RESPONSE: Partially concur. The Department agrees that TRLS are an important input and are necessary, but adds that they are not sufficient alone to decide when and where to insert new technologies into weapon system programs. Military system development decisions require a total ownership cost approach through the entire life cycle of a system, not just an assessment of technology maturity. Given the increasing projected life for new military systems, additional considerations also present include the training and logistics costs over time, coupled with urgency based upon threat assessments.

Now on pp. 7 and 63-64.

RECOMMENDATION 2: With those tools in hand, the GAO recommends that the Secretary of Defense (1) establish the point at which a match is achieved between key technologies and weapon system requirements as the proper point for committing to the cost, schedule, and performance baseline for developing and producing that weapon system, and (2) require that key technologies reach a maturity level—analogous to TRL 7—before making that commitment. The GAO indicated that this would be analogous to the launch point for product development as practiced by leading firms. (p. 5, p.45/GAO Draft Report)

DOD RESPONSE: Concur. The Department agrees with the GAO that there should be an established point for transition and that decision points as currently identified in the Milestone review process will be supplemented with additional guidance in the next revisions to the DoDD 5000.2R. The Department believes that the evolutionary acquisition strategy for new weapons systems should be developed in consonance with the technology transition or insertion strategy and additional guidance will be developed for the next revisions to the DoDD 5000.2R.

Now on pp. 7 and 63-64.

RECOMMENDATION 3: The GAO also recommended that the Secretary find ways to ensure that the managers responsible for maturing the technologies and designing weapons systems before product development begins are provided the more flexible environment that is suitable for the discovery of knowledge, as distinct from the delivery of product. The GAO suggested that providing more flexibility will take the cooperation of requirements managers and resource managers so that rigid requirements or the threat of jeopardizing the funding planned to start product development would not put pressure on managers to accept immature technologies. According to the GAO, such an environment may not be feasible if the program definition and risk reduction phase remains the effective launch point for an entire weapon system program. (p. 5, p.45/GAO Draft Report)

DOD RESPONSE: Partially Concur. DoD assigns responsibility to different individuals for research projects related to technology and to major systems development, and the individuals are frequently in different organizations, such as DARPA or a laboratory for research programs, and a systems command for an acquisition program. Managers of research projects generally enjoy a more flexible environment than program managers do who are charged with developing systems to meet operational capability dates within constrained budgets as well as within constraints such as interoperability and logistics compatibility. The Department's technology managers already promote and offer technology opportunities to their warfighting and weapon system program managers by delivering products to meet Warfighter needs within life cycle cost, program schedule and performance constraints. We agree that the Department must caution against the singular notion that technology opportunity, or advance, is more important than these last factors. The S&T community is closely coupled with the Department's program managers to offer enhanced capability options—throughout the life cycle—from the DOD's Advanced Technology Demonstrations (6.3) and supporting Applied Research (6.2) programs. Constraints on technology often must be applied so we can develop the truly essential and militarily relevant technologies within our budget.

Now on pp. 7 and 63-64.

RECOMMENDATION 4: The GAO indicated that an implication of these recommendations is that Science and Technology (S&T) organizations will have to play an greater role in maturing technologies to that level and should be funded accordingly. Therefore, the GAO recommended that the Secretary of Defense evaluate the different ways S&T organizations can play a greater role in helping technologies reach high levels of maturity before product development begins. For example, given that a technology has sufficient potential for application to a weapon system, the GAO suggested that, at a minimum, an S&T organization should be responsible for taking a technology to TRL 6 before it is handed off to a program office at the program definition and risk reduction phase. Further, the GAO indicated that during this phase, the weapon system program manager would be responsible for maturing the technology to TRL 7 before the technology can be included in engineering and manufacturing development programs. The GAO asserted that, in a situation where a single, design-pacing technology is to be developed for a known application—like the non-penetrating periscope—an S&T organization should be required to mature the technology to TRL 7 before it is turned over to a product development manager. The GAO also asserted that S&T organization could play a similar role when a significant new technology is being readied for insertion into an existing weapon system. Finally, when multiple new technologies are to be brought together to create a weapon system, the GAO indicated that S&T organizations should be required to bring key technologies to TRL 6 and then become part of a hybrid organization with product developers to integrate the technologies and bring them to TRL 7 before handing full responsibilities off to a product develop manager.

DOD RESPONSE: Concur. The DoD S&T organizations should be involved in maturing technologies to high levels of maturity like TRL 6 before transitioning to EMD. The Department concurs with the GAO that the weapon system program manager should assure that technology is matured to TRL 7 before insertion into a new system. (Maturing a technology to Technology Readiness Level 6, however, may be sufficient for the purposes of a preplanned product improvement program or block upgrade program for a system which has already been deployed.) DoD also concurs that the relevant S&T organizations must continue to support system managers in all phases of development. This is done in the DOD today, typically through the Integrated Product Development Process. Integrated Product Teams are employed in the Services today for life-cycle system development and acquisition.

Now on pp. 7 and 65.

RECOMMENDATION 5: To help guard against the possibility that the more basic research and technology development activities would be compromised by having S&T organizations routinely take key technologies to TRL 6 or higher, the GAO recommended that the Secretary of Defense extract lessons learned from the non-penetrating periscope, the Advanced Amphibious Assault Vehicle (AAAV) program, the Army's Future Scout Program, and other Advanced Technology Demonstration (ATD) programs and Advanced Concept and Technology Demonstration (ACTD) programs. Specifically, the GAO asserted that the Secretary should assess whether the resources needed in these efforts to enable S&T organizations to play a leading role in the development of technologies and, in some cases, preliminary system design, detracted from or displaced more basic research and technology developments efforts.

DOD RESPONSE: Concur. The recommendation that the Department assess the impact upon other S&T resources is appropriate.

Now on pp. 7 and 65.

RECOMMENDATION 6: The GAO further recommended that the Secretary of Defense empower managers of product development programs to refuse to accept key technologies with low levels of demonstrated maturity. The GAO indicated that the Secretary can encourage this behavior through supportive decisions on individual programs, such as by denying proposals to defer the development of key technologies and by favoring proposals to lengthen schedules or lessen requirements to reduce technological risk early.

DOD RESPONSE: Concur. Program managers are responsible for balancing the many different requirements for a system, including cost, schedule and performance. In their on-going assessment and management of programs, managers continually re-evaluate the maturity, projected schedule and risk associated with relevant technologies. Decisions by the acquisition executive are made with input from the program managers. Thus program managers already have the ability to reject inappropriately mature technologies, and, to the extent technology immaturity impacts acquisition baselines, to advise the acquisition executive of feasible alternatives and make recommendations.

GAO Contacts and Staff Acknowledgments

GAO Contacts

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Acknowledgments

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Related GAO Products

Best Practices: Commercial Quality Assurance Practices Offer Improvements for DOD (GAO/NSIAD-96-162, Aug. 26,1996).

Major Acquisitions: Significant Changes Underway in DOD's Earned Value Management Process (GAO/NSIAD-97-108, May 5, 1997).

Best Practices: Successful Application to Weapon Acquisitions Requires Changes in DOD's Environment (GAO/NSIAD-98-56, Feb. 24, 1998).

Best Practices: DOD Can Help Suppliers Contribute More to Weapon System Programs (GAO/NSIAD-98-87, Mar. 17, 1998).

Defense Acquisition: Improved Program Outcomes Are Possible (GAO/T-NSIAD-98-123, Mar. 18, 1998).

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