Planning for Department of Defense Investment in Technology Demonstrations

Timothy Webb, Richard Pei

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Timothy Webb, Richard Pei

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PREFACE

The purpose of this study is to support Department of Defense efforts to improve technology development planning. This report offers a number of recommendations for improving the development planning process. It focuses on the means by which the Office of the Secretary of Defense (OSD) evaluates the allocation of funding for development of key enabling technologies, particularly those to be embodied in weapon and support systems in the relatively long term.

The focus of the report is on that portion of the research, development, test, and evaluation (RDT&E) budget designated by the categories 6.2 (exploratory development) and 6.3a (advanced technology development). It also considers actions that can be taken by OSD, as distinct from the military departments, to identify key enabling technologies without which potentially interesting operational concepts would be rendered infeasible.

The study describes a hierarchical method for identifying key enabling technologies, and recommends a mechanism (the technology evaluation group) that OSD might employ to implement the method.

The project was sponsored by the Deputy for Research and Advanced Technology in the office of the Director, Defense Research and Engineering DR&E(R&AT), and was conducted in the Applied Science and Technology Program of RAND's National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense and the Joint Staff. This work will be of interest to participants in defense technology development, particularly those in OSD with responsibilities for oversight of the technology base and acquisition planning.

SUMMARY

The study team's review of various methods for mapping key enabling technologies for desired future military capabilities concluded that preferred methods

- Depend on a hierarchy of objectives and on concepts of operations for achieving those objectives, and
- Depend for success on reference to well-organized expert opinion.

These preferences have several roots. First, it is difficult for a small group of people to credibly set priorities for investment across the Department of Defense with its many subsidiary organizations and its "due process" culture. Planning methodologies advocated over the last several years failed to provide mechanisms for coordinating views across communities of policymakers, military operators, and technologists in the defining of key enabling technologies; such coordination is an important determinant of the credibility of any technology investment planning process. Finally, most attempts to create such methods have no means for explicitly linking the functions that military forces must perform to the need for enabling technologies.

We suggest that the Office of the Secretary of Defense (OSD) can address these shortcomings by more effectively harnessing expert judgment for evaluating military operational concepts, candidate military systems, and enabling technologies, in the context of establishing a coherent process for linking investments in technology with desired future military capabilities. By doing so, OSD can build greater consensus in the defense community about the allocation of resources for defense technology development.

To build such a consensus and facilitate its ability to oversee technology base planning, OSD can selectively convene technology evaluation groups (TEGs) to assess opportunities for developing and demonstrating technologies central to desired future military capabilities. These groups, composed of technologists, military operators, conceptual systems analysts, cost analysts, and policymakers, will define and evaluate technologies beyond the present state of the art. The outputs of these groups will be *options*: options for enabling technologies and options for advancing development of those technologies. The TEGs will not develop recommendations, but will instead generate information on the basis of which OSD can identify a handful of technologies

that might be highlighted for earlier demonstration than would otherwise occur. These demonstrations would build on generic efforts already under way, and would seek to develop technologies for particular types of application—using a concept-of-operations impetus.

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1. INTRODUCTION

At the outset of this research, the study team hoped to devise an analytic method for identifying key enabling technologies for future military systems, based on the goals stated in the 1990–1991 Department of Defense (DoD) Science and Technology Investment Strategy.[1] Specifically, the team hoped to devise an analytic methodology by which to identify so-called "go–no go" technologies necessary for achieving desired military capabilities over the long run.

The notion of "go–no go" technology presented in the investment strategy is a simple one: with such technology in hand, a particular operational or system concept is possible; without such technology, it is not. However, it is rare that future capabilities turn unambiguously on the availability of a particular aggregation of technology; more often, there are alternative aggregations that will suffice to bring such capabilities to fruition. For this reason, we use the term *key enabling technology* instead of "go–no go." This terminology admits the possibility that there are *options* for the technical approach used in most systems, and that there may be enabling technologies for a particular system that can serve as substitutes for one another.

The attempt to identify key enabling technologies prompted a broader look at the process of planning investment in technology, and at the relationship between technology development and defense planning more generally. As the study progressed, it seemed ever less desirable to create a "cookbook" method for identifying investment priorities—a method by which investment in particular technology areas could be determined centrally and relatively simply. We searched instead for a process that would engage those responsible for planning as principals in a structured evaluation of future needs and opportunities.

This report serves three purposes:

- It provides background on the DoD technology investment process, with reference to the ways in which technology investment decisions are made today.

[1] *DoD 1990–91 Science and Technology Program Investment Strategy, Our Mission and Vision,* pamphlet by Dr. George P. Millburn, Deputy Director, DR&E, Research and Advanced Technology (R&AT).

- It explains a way of organizing technology investments by reference to military functions. It describes ways in which technology evaluation groups can identify long-term enabling technologies by reference to those functions, and thereby better rationalize the entirety of DoD investments in technology development.
- It comments on the potential efficacy of a hierarchical approach in the context of the responsibilities of the Director, Defense Research and Engineering (DDR&E).

STATING THE PROBLEM

The Department of Defense wants to establish better links between military functions and the choice of technology projects:

- To help plan the allocation of resources,
- As a basis for justifying the budget, and
- As a basis for DoD oversight of service and agency technology investment activities.

The current allocation of resources across technology areas derives from the Program, Planning, and Budgeting System (PPBS), and is the product of incremental decisions aimed at allocating marginal dollars to best effect. This process has worked fairly well during times of stable or increasing budgets. But there is no adequate basis on which to evaluate the desirability of more fundamental shifts in resource allocation as the budget declines. As an example of the difficulty that lack of such a basis can cause, consider on what basis funds would be reallocated among technology development in aerospace propulsion and power, or materials and structures, or medical and life sciences. The existing defense planning process does not routinely generate information to support such broad allocation evaluations. Although it is beyond the scope of this research to address resource allocation for the entire defense technology base, this report outlines a hierarchical method for investment planning that might serve as a better analytic basis for broader resource allocations. The value of the hierarchical method is illustrated here by reference to a limited implementation by the Office of the Secretary of Defense (OSD).

Ultimately the ability to identify over- or underinvestment in technology development is determined by knowledge of the comparative returns on alternative investments—their comparative potential contribution to the conduct of military operations. Today's planning system makes such comparisons difficult, because it does not contain a

well-organized way of establishing links between technology investments and resultant future military capabilities.

Any method of establishing such links must account for the fact that there are several types of technology investments sustained by DoD:

- Investment to develop technology aggregates,[2]
- Investment to demonstrate technology aggregates, and
- Investment to assemble and test these aggregates in demonstration of proof-of-principle of operational concept.[3]

As with all investment in technology, DoD can expect that certain of its technology development activities will fail to achieve their goals; the planning process must allow for this, expecting progressively fewer "false starts" for investments of the third type than of the first. Of the three functional activities noted, we concentrate on the first two.

In our terminology, we forsake use of the terms "research," "exploratory development," and "advanced development," for several reasons:

- Individuals commonly use different points of demarcation between research, exploratory development, advanced technology development, and advanced development. This leads to confusion in discussions of technology base because these different points connote different aggregations of physical systems to different people. This confusion manifests itself in attempts to compare dissimilar aggregations of technology among which DoD might (re)allocate technology development resources. For an example of the resulting confusion, consider the variety of items called "technology" on the current DoD Critical Technologies list.
- Because imprecision in terminology contributes to individuals applying uncomparable standards for judging the appropriateness of

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[2]A technology aggregate is that element of a physical system that falls in scope and range of function between what are commonly called components and subsystems. It is not a piece part like a component, yet it has little functional capability outside the context of a larger subsystem. The Appendix has a number of examples.

The distinction between development and demonstration is this: development is the painstaking work of building knowledge about the characteristics of a particular technology aggregate; demonstration is the conduct of a test or series of tests that will be published or otherwise vetted outside the immediate development community.

[3]An operational concept is a functional description of how a force element accomplishes specific tasks, describing the operating environment, the tactics, the people, and the systems that are necessary.

advancing from one stage of military system development (and acquisition) to another.

THE CURRENT APPROACH TO TECHNOLOGY INVESTMENT PLANNING

- Strong bottom-up character to planning of technology development projects.
- Military services submit plans for investment to the Deputy Director, DR&E (DDDR&E)(R&AT) for approval.
- DDDR&E(R&AT) monitors spending in 17 "technology areas" and generates issues for intervention based on the monitoring activity.
- The R&AT monitoring process does not organize information in a form useful for broad reassessment of investment priorities.

Although the military services make annual judgments about the appropriateness of technology development budget submissions, it has been many years since they have faced pressures to reallocate resources because of substantial changes in U.S. regional military objectives.[4] OSD-DR&E likewise rarely evaluates changes in long-term priorities. In fact, the categories of technological activity monitored by DR&E are not well suited to the evaluation of fundamental changes.[5] This concern was recognized in the 1989 Defense Management Report: "Under the pressures of the annual budget cycle, consideration of broad policies and development of guidance on high-priority objectives all too often [have] been neglected, and decisions made instead on a short-term, issue-by-issue basis not well-suited to optimizing the use of available defense resources."[6]

Over the past several years, it has become increasingly apparent that information on defense programs and budgets is not adequate for a

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[4]Changes relating to the demise of the Soviet Union, the change in relations between the Koreas, the increased importance of drug interdiction as a military activity, and so forth.

[5]These technology areas are chemical warfare and chemical and biological defense, environmental science and quality, materials and structures, personnel and training, ships and submarines, aerospace propulsion and power, tank/automotive technology, aerospace vehicle technology, weapons and munitions, medical and life sciences, logistics and civil engineering, surveillance reconnaissance and C3I, electronic devices, software and computers, electronic warfare, avionics and vetronics, research, and the national aerospace plane.

[6] Secretary of Defense Dick Cheney, *Defense Management Report to the President,* Office of the Secretary of Defense, July 1989.

fundamental reevaluation of technology investment priorities. The annual critical technologies report mandated by the Congress is a case in point. OSD has expended substantial effort to assemble this report, even though it encompasses roughly only one-third of the budget dedicated to technology development activities.[7] The report, rich though it is in technically useful information, does not give much attention to mapping critical technologies against desired future capabilities—though such mapping would provide a better basis on which to make resource allocation tradeoffs. Our own research is motivated in part by the desire to devise a framework for stating the merits of alternative investments in technology in terms of the military capability they ultimately support.

RECOMMENDATIONS

- R&AT should state long-term technology "goals" so that they imply desired future capabilities.
- R&AT should convene groups that will describe and evaluate technology to support such capabilities.
- These technology evaluation groups should be constituted to include military operators, development planners, and technologists. Their efforts should be sharply focused and of common format.
- R&AT can use the key enabling technologies identified by the groups as benchmarks for resource allocation.

Based on our examination, we offer a number of suggestions. First, we believe that any effort to formulate long-range goals for technology base activities should place high priority on expressing the goals as statements of desired future capabilities. For instance, we suggest that a statement such as *provide command and control of forces* is more appropriate and useful than *ensure the affordability of weapon systems*. This approach will facilitate disaggregation of higher-level objectives into notional systems implying specific technologies.

Second, R&AT should convene a technology evaluation group (TEG) for one or more of the long-range goals. The TEG will outline, as ex-

[7]*The Department of Defense Critical Technologies Plan,* prepared for the Committees on Armed Services, United States Congress, 1 May 1991 (AD-A234 900). For another application of the "critical technologies" approach, see *Report of the National Critical Technologies Panel,* Office of Science and Technology Policy, March 1991. For a skeptical view of the value of the critical technologies efforts, see Michael Schrage, "Making Laundry Lists of Crucial Technologies is a Futile Exercise," *Washington Post,* 10 May 1991.

plicitly as possible, concepts of operations, notional systems, and key enabling technologies for the long term. These groups will describe various approaches to achieving the desired capabilities, but will not attempt to reach closure on preferred concepts or technologies. They will be expected to identify key technologies that will enable competing concepts or alternative enabling technologies for a single concept.

These technology evaluation groups will serve two important purposes. First, the groups will bring together a range of policy, operational, and technological expertise that is rarely found in a single organization.[8] Second, by directly involving interested parties in the discussions, the groups will begin to build a valuable coalition of support for funding priorities. It is particularly important that these groups be well focused and generate information in a common format. In addressing each of the long-range goals, the technology evaluation groups will be generating a sharper sense of priorities for investment in technology, rehabilitating the efficacy of "expert" advice in support of such investment planning, and demonstrating a technique for identifying key enabling technologies that could profitably be adapted by the military departments and defense agencies for their own planning.

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[8]For more on the value of expert opinion in technology assessment, see (for example) Lawrence P. O'Keefe, *Technology Assessment for State and Local Government,* American Management Association, 1982, or Ben Martin and John Irvine, *Research Foresight, Priority-Setting in Science,* Pinter Publishers, New York, 1989.

2. THE DIFFICULTY OF LINKING THE NEED FOR FUTURE CAPABILITIES TO TECHNOLOGY: AN ILLUSTRATION

Several studies in recent years have attempted to categorize technology development efforts and to relate them to a higher set of national security objectives. One approach, depicted in Figure 1, called for a scenario-derived technology program, in which priorities for investment in technology development were to be identified by reference to operational capabilities that were consistent with plausible scenarios involving military force.

This hierarchy of tasks leaves a leap of reason to the reader—the translation of operational capabilities or cross-cutting capabilities (whether arrived at by scenario analysis or not) into statements about

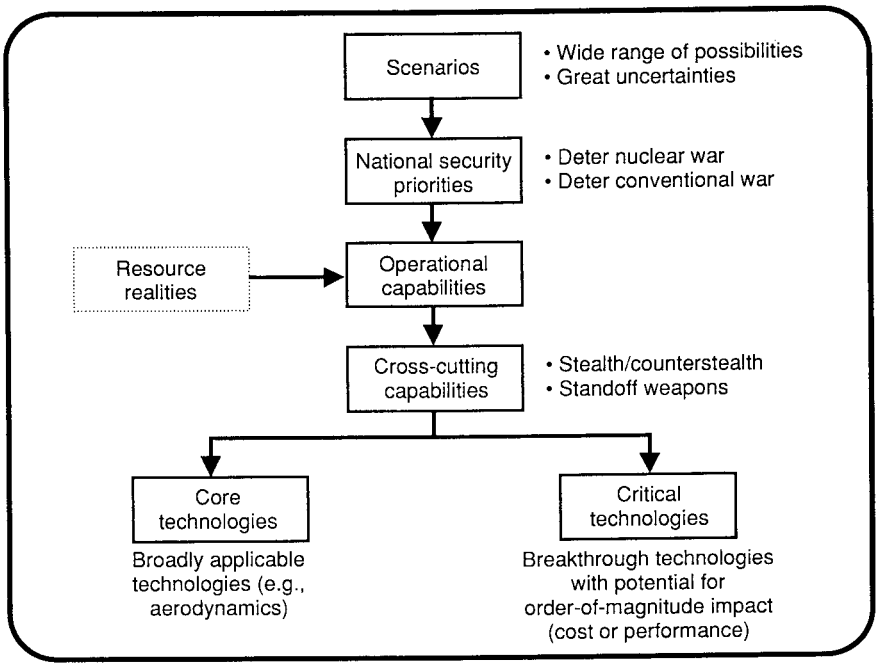

Figure 1—A Hierarchy with a Gap

enabling technologies. This is characteristic of the manner in which "critical technology" lists have recently been generated, and how the purpose for which the lists are intended—to inform funding tradeoffs among technology development activities—is undermined. This purpose would be better served by broadening "ownership" of the lists, by involving a larger community of interested parties in their creation, and by making the logic for their derivation more transparent.

In this study, we take two tacks to improve upon the process depicted in Figure 1; first we articulate a more complete hierarchy from national objectives through technologies; second, we suggest a way in which DDR&E might profitably adapt part of this hierarchy to clarify the science and technology (S&T) investment strategy.

RESEARCH, DEVELOPMENT, TEST, AND EVALUATION FUNDING BREAKDOWN

Our discussion of the hierarchical planning process centers on activities that are commonly described as exploratory and advanced technology development (6.2 and 6.3a budget categories). This allows us to highlight development activities pertaining to nascent systems, rather than systems that are already the subject of an acquisition program. We do not discuss the planning of research, even though research outputs are important antecedents to investments in technology development. Where research is concerned, OSD's principal responsibility is to ensure that there is a reasonable balance of funding across the range of disciplines that are germane to defense purposes.

As Figure 2 shows, our discussion covers about 20 percent of the money spent on defense RDT&E activities. However, the importance of these expenditures is out of proportion to the fraction of total funding they consume. Without a well-organized process for investing in development of generic technologies and the demonstration of concept-enabling technologies, the down-side risks associated with later acquisition would typically be increased.

One of the principal motivations behind the hierarchical planning approach is to relate technology base activities more carefully to decisions to initiate acquisition programs. Although various studies have touted the virtues of demonstrating technologies, components, subsystems, and systems before making commitments to programs, the existing directives and regulations governing the acquisition of

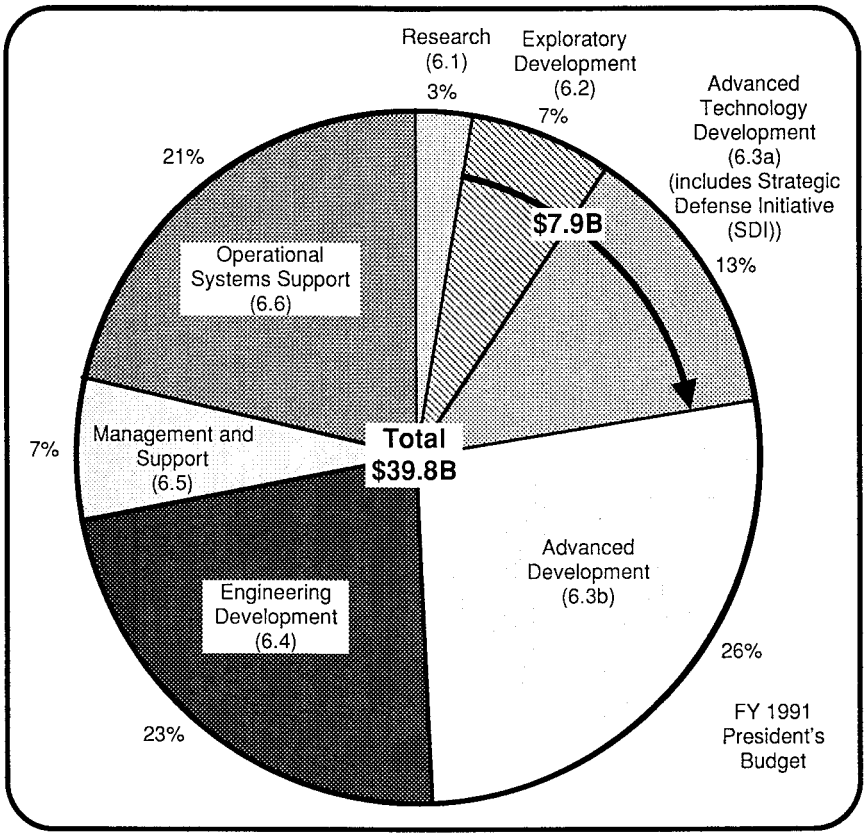

Figure 2—RDT&E Breakdown for 1991

weapon systems (5000.1 and 5000.2) do not provide clear guidance. It is difficult without such guidance to routinely relate technology base activities to decisions about acquisition programs.

An impediment to providing such guidance is that the terminology used to classify various technology development activities is ambiguous. What is the functional distinction between advanced development and advanced technology development? Between advanced technology development and exploratory development? Because there are no clear answers to these questions, we have chosen to avoid this language, and to use instead descriptors that connote more directly the development functions that are performed as any aggregation of technology finds its way into a weapon or combat support system.

The following description of a hierarchy therefore breaks not only with the conventions of Directive 5000.1 and Instruction 5000.2, but also with the language typically used to describe the budget categories used for defense technology development. This framework is offered in the context of finding a better way for R&AT to identify key enabling technologies for military systems that may appear a decade from now, but it also applies to planning for acquisitions in the nearer term.

EXPRESSING THE NEED FOR MILITARY FORCES

Rather than pursue a "scenario-based" approach to planning, we have chosen to apply the hierarchical-objectives approach depicted in Figure 3. This logic structure allows for systematically articulating our forces' military functions. Although the stating of regional military objectives is parallel to working out scenarios for conflicts in those regions, scenario analysis alone often fails to focus attention

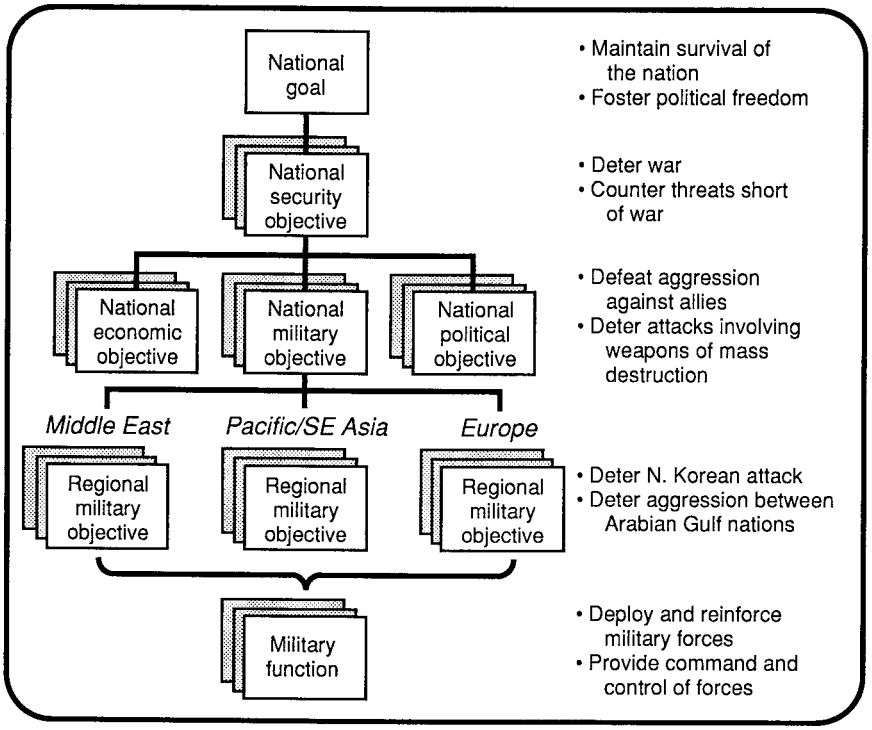

Figure 3—Planning Hierarchy, Part 1

on whether and how responses to the chosen scenarios serve overarching national security objectives.

The last step in Figure 3—the statement of *military function*—is crucial to the further identification and evaluation of enabling technologies. We must be careful that our statements of military function are at an appropriate level of aggregation, otherwise they may prematurely constrain the operational concepts and systems that might be appropriate to achieving regional military objectives, or the statements may be so broad as to be practically useless. As an example of a military function stated at an appropriate level of aggregation, we suggest the need to *deploy and reinforce military forces*.

Military functions are perennial—they are ideas around which military forces have been organized for decades, if not centuries. Although they can be accomplished in some measure today, there is an enduring wish to accomplish them more completely and more skillfully. At the next lower level of aggregation are *military tasks*, which are subordinate to military function, being more specific about the characteristics of the forces to be deployed and hence more variable over time.

The distinction between functions and tasks is more than academic. One of the pervasive problems associated with choosing among technology projects is that competing investments are often difficult to compare because they are organized to address objectives at different levels of generality. This problem has its parallel in the imprecision with which military functions and associated tasks are described. The authors consequently emphasize the importance of the careful use of language in describing the hierarchy.

3. HIERARCHY FOR RELATING MILITARY FUNCTIONS TO TECHNOLOGY DEVELOPMENT[1]

Military functions are usually satisfied by achieving several military tasks (see Figure 4). These tasks are the true *requirements* of the defense planning process, although the technical specifications for systems are often mistakenly described as requirements. An example of a military task is to *move light armored forces rapidly to the theater.* The appropriate weight of effort among tasks to achieve the function of deploying and sustaining military forces is described in an overall concept of employment.

It is important to remember that there are various factors that determine whether and to what extent we wish to improve our capabilites to accomplish military functions and tasks. Consider, for example, the general decline in the forward presence of U.S. military forces overseas, often under circumstances beyond our control. This factor heightens the need to develop forces that are useful in a broader range of contingencies than might have seemed important during the Cold War. We expect to see new, lighter armored forces appropriate for rapid deployment to potential trouble spots. The fact that a number of changing exogenous factors condition our priorities also provides impetus for changes to existing forces and places a premium on generating options, not just for technology aggregates, but for system concepts in which these aggregates might appear.

Just as there are a number of military tasks subordinate to each function, so *there are operational concepts subordinate to each task;* in this example, operational concepts have as candidate ingredients the air and sea lift of military forces, prepositioning, and the like.[2] An operational concept is a functional description of how a force element

[1]This hierarchical approach is derivative of work in the same vein by Glenn Kent, Ted Warner, and others at RAND. For more depth on the subject, see Glenn A. Kent and William E. Simons, *A Framework for Enhancing Operational Capabilities,* RAND, R-4043-AF, January 1991. This hierarchical approach to planning, and particularly its reference to tasks and concepts, has strong parallels in the German defense planning process (*Bundeswehrplanung*).

[2]For example, with the decline in overseas basing of U.S. forces, we might imagine a mix of tasks to support the deployment of forces that relies more heavily than do present concepts on long-range transport of U.S.-based systems. This has direct implications for investment in technology—perhaps the technology of long-range transport aircraft.

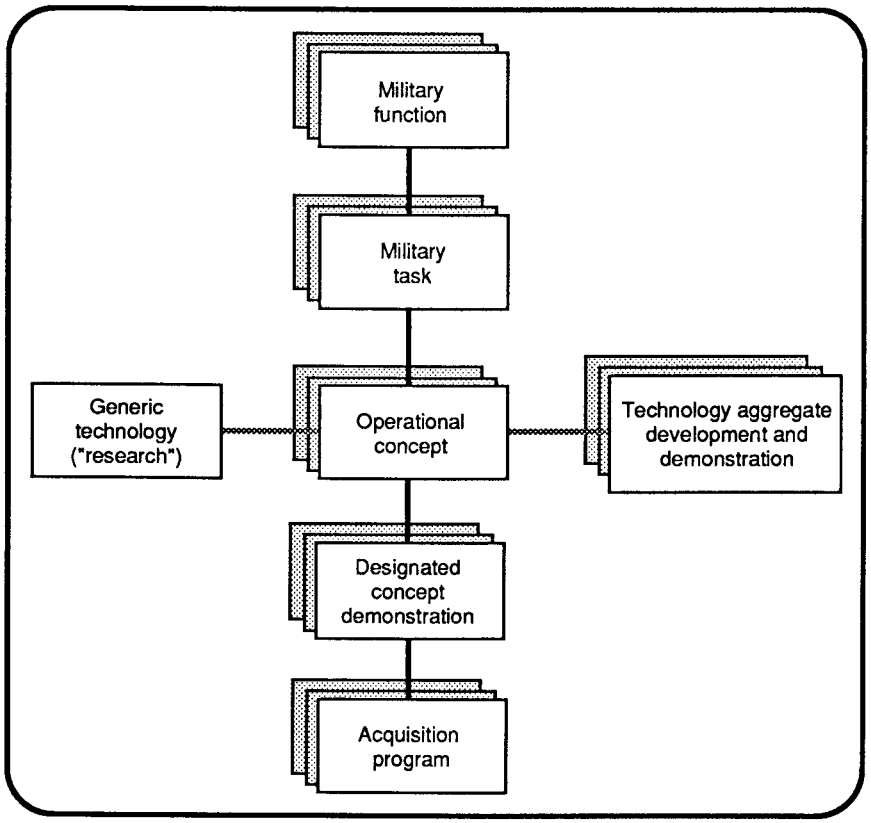

Figure 4—Planning Hierarchy, Part 2

accomplishes specific tasks, describing the operating environment, the tactics, the people, and the systems that are necessary.

In the process of formulating and assessing operational concepts, it is important to review the resources and constraints that condition desired approaches. Those who evaluate concepts must be mindful of two sets of factors: those that most directly affect tradeoffs by high-level policymakers:

- Need for U.S. military forces to respond quickly to any geographic point,
- Decreasing forward presence of U.S. forces,
- Diminishing defense budget,

- Planned reduction in manpower and materiel,
- International proliferation of technological know-how for development of military systems, and
- Other factors,

and those that most directly affect tradeoffs by senior managers of technology base resources:

- Increasing information intensiveness of all systems, military and nonmilitary,
- Greater availability of technology aggregates outside the defense economy and outside the country,
- Increasing importance of system integration engineering as a proportion of engineering effort,
- Increasing reliance on simulation of designs rather than on prototype physical systems, and
- Other factors.

The following example lays out how the technical community, by beginning with statements of military function, can identify key enabling technologies. The example focuses on the function of providing command and control of forces, a function that is addressed jointly by the military services. This is the sort of function that can form a basis for demonstrating a technology evaluation group under DDR&E.

IDENTIFY MILITARY FUNCTIONS

This is a sample list of military functions:

- Deploy and reinforce military forces
- *Provide command and control of forces*
- Suppress generation of enemy air sorties
- Defeat attacks by enemy aircraft
- Disrupt enemy command and control
- Clear enemy obstacles
- Damage, disrupt, demoralize enemy troops
- Defeat enemy troops at close quarters
- Delay/damage enemy follow-on forces

- Suppress enemy surface-to-surface weapons
- Redeploy forces within theater

For our example, we will discuss the functional objective to achieve worldwide, instantaneous, secure, survivable, and robust command, control, communications, and intelligence capabilities. This objective appeared among the DoD science and technology strategic goals for 1990.

To create a long-term focus on technologies to contribute to this objective, DDR&E might convene a technology evaluation group (TEG) to marry the talents of technologist, operator, development planner, and cost analyst. In contrast to the service concept evaluation groups, the TEGs would turn their attention to technology aggregates for far-term operational concepts. The TEGs would be charged with thinking about selected future possibilities for DoD investment in technology. Later figures will expand the command and control example, and simultaneously illustrate the sorts of output a DoD technology evaluation group might generate.[3]

IDENTIFY MILITARY TASKS

- Direct forces to engage or disengage,
- *Coordinate data exchange among friendly forces*,
- Order changes to geographical disposition of units,
- Convey rules of engagement, and
- Prevent inadvertent conflict among friendly forces.

To accomplish the command and control of forces, it is necessary to have capabilities to accomplish military tasks such as those shown here. Again, the list is representative, not exhaustive. Again, it is a

[3]An organization of comparable intent was established by the Congress in 1986 to assess new technologies and their potential for achieving significant improvements in U.S. conventional war-fighting capabilities. The Interagency Technology Assessment Group (ITAG) was to compare emerging technologies with intelligence/threats and develop new ways to enhance deterrence, improve crisis stability, and increase conventional war-fighting capabilities. The ITAG is an Executive Branch organization, but is explicitly sponsored by the Under Secretary of Defense for Acquisition (USD/A). Its membership goes well beyond DoD, to include representation from the National Aeronautics and Space Administration, Department of Energy, Office of Science and Technology Policy, and the National Security Agency. The ITAG conducts a few ad hoc studies each year, the product of which are short technical reports to the USD/A. Recently, the budget for the ITAG has been sharply reduced. Unpublished RAND work by B. Augenstein and G. Sears recommends remedial action to strengthen the ITAG.

list of things we can do today, but that we wish to do better in the context of changing international circumstances. The TEG would be charged with defining and planning for the development and demonstration of technology aggregates to enable hypothetical forces to accomplish these tasks. In the process, the group would state as clearly as possible the shortcomings of current forces in the light of changing international circumstances. It is important (as it was in connection with statements of military function) to state these tasks at an appropriate level of aggregation.

This list of tasks does not spring into being any more easily than does the list of military functions. But it is advantageous that the technology evaluation groups be presented with such a list to help them organize their work. Without the discipline imposed by some organization of tasks, the TEG might get bogged down arguing the validity and importance of objectives, rather than expending effort discussing means of accomplishing them. This necessitates that tasks be delineated in an authoritative manner, so that they do not themselves become a matter for dispute.

To carry the example further, we consider the task to *coordinate data exchange among friendly forces*. Below we articulate some competing concepts of operations for such data exchange, and explore ways in which a TEG might identify key enabling technologies for far-term systems to serve this task.

It is important to note that the TEG gives attention to *alternative* concepts of operations. The TEG is not in the business of searching for *the correct* solution, but for *alternatives*. It must be able to develop a sense for why the alternative operational concepts are timely, both in light of the technological state of the art and of the sorts of constraints mentioned above (decreasing forward presence, declining budget).

FORMULATE AND EVALUATE OPERATIONAL CONCEPTS

Figure 5 states several options for the coordination of data exchange among friendly forces—options of the kind that technology evaluation groups would be developing and assessing. The options in Figure 5 are quite simple: Option A corresponds to our present approach and supposes that we continue to improve our data exchange methods and systems along known lines; Option B describes an alternative, in which we move toward a distributed network with a common time

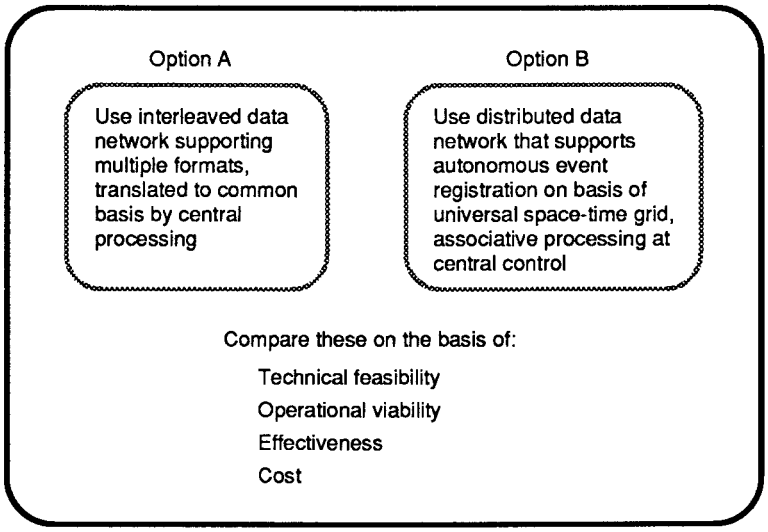

Figure 5—Options for the Coordination of Data Exchange Among Friendly Forces

standard, message protocols, and other characteristics that would make event registration and other data exchange activities more transparent among command elements. Such an approach would be advantageous for creating event-reporting structures in fast-developing contingencies, for rapid changing of strike priorities based on all-source battle damage assessment, and for similar purposes.

The first question to be addressed by the evaluation group is: Can Option B be considered preferable to Option A, and under what circumstances? Option A is a refinement of business as conducted today, whereas Option B is a qualitatively new approach. Option B will perhaps cost more than the next increments of improvement under Option A. The TEG must make a clear statement of what drives them to consider Option B, whether the advantages it offers are likely to be worth the cost.

The technology evaluation group will be responsible not only for the comparison of concepts across various criteria, but for the initial articulation of those concepts as well. In fact, this exposition of concepts is a most important part of the process, since outcomes in terms of systems fielded can only be as good as the concepts articulated. Because the TEG will be focusing more on longer-term concepts than on those for which near-term demonstrations are feasible, the group

should be able to avoid some of the advocacy that almost naturally accompanies proposals for near-term "concept-derived" demonstrations.

The formulation of operational concepts relies both on information about generic work on technology ("curiosity-oriented" work that is not tied to particular operational concepts) and on information derived directly from technology aggregate demonstrations conducted in association with proof of principle of nearer-term operational concepts. The TEG must include participants knowledgeable about both of these bodies of work; in our example, such understanding is requisite to identifying the enabling technologies for Option B, and for understanding the degree of advance from the existing state of the art these prospective technologies represent.

IDENTIFY CONCEPT-ENABLING TECHNOLOGY AGGREGATES

Figure 6 shows examples of the sorts of systems that will be necessary to support the concept of a distributed data network—event relays and recording systems, central processing capabilities, guidance systems, and the like. The network calls for a guidance system on host nodes (fighters, tanks, ships). One way to provide common guidance to these nodes is to equip each with some form of global positioning system (GPS) receiver. This does not imply that all receivers be identical, but rather that they all be based on a system that provides a high-quality time/frequency standard. There are a number of aggregations of enabling technology for multi-channel GPS receivers: antennas, circuitry to translate the broadcast radio-frequency signal into a digital form, circuitry to interpret the pseudo-random noise signal structure of GPS, and a number of other separable items.

Most of these are fairly mature aggregations of technology, and so are not the subject of TEG attention. One possible exception is the RF/IF/AD (radio-frequency/intermediate frequency/analog-to-digital) "front end" of a GPS receiver. This is a "key enabling technology": it enables a smaller, more rugged, cheaper receiver, without which the distributed data network concept might never be realized. Over the last few years emphasis has been placed on building monolithic gallium-arsenide hybrid devices to serve the RF/IF/AD function—a challenging technical effort given the existing state of GaAs device design and manufacture.

This is the sort of technology aggregate that the TEG might evaluate in depth because of its potential importance to systems that enable a

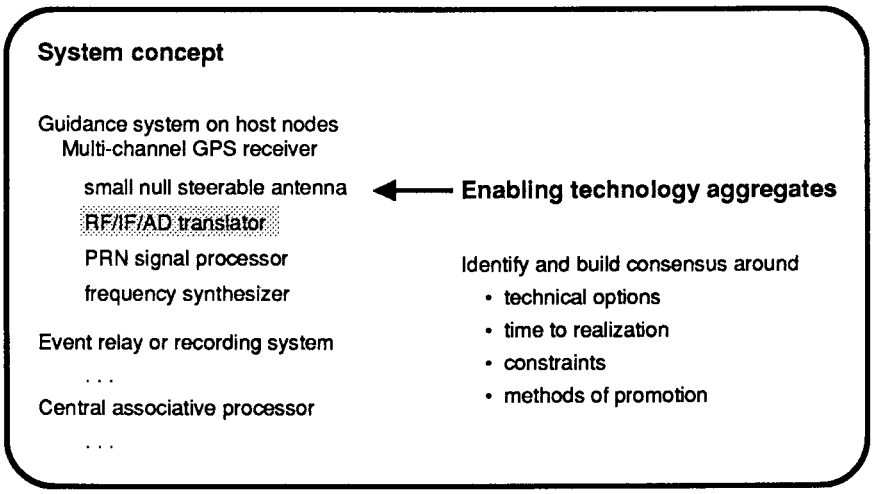

Figure 6—Identifying Technology Aggregates to Support a Distributed Data Network

fundamentally different way of coordinating data exchange among friendly forces. The purpose of such evaluation would be to suggest that adequate funding be made available for development of GaAs devices for this application. The technology would be identified as "critical" in that it is one of the principal technological options for future achievement of the military function of commanding and controlling forces. The current DoD list of critical technologies lacks such explicit ties to potential future concepts of operations, so that the degree to which various technology aggregates are "critical" cannot be determined. It is expected that different TEGs will identify key enabling technologies that are similar to one another. In general, an aggregation of technology that enables multiple functions and tasks will seem to deserve higher funding priority than one that does not.[4]

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[4]Those readers who are familiar with defense technology base issues might wonder what relationship technology aggregate demonstrations have to the Advanced Technology Transition Demonstrations (ATTDs) now pursued by each of the services. Although there is some overlap in the concepts, ATTDs concentrate more than technology aggregate demonstrations on near-term prospective development programs. Furthermore, the language developed here to describe technology aggregates avoids the technology-centric basis for organizing new development programs, using instead the more appropriate concept-of-operation basis. In truth, technologies do not transition; rather concepts of operations evolve as aggregations of technology are assembled into nascent systems that will better accomplish operational objectives. It is conceptually and rhetorically important to separate technology demonstration from the proof of

The TEG will employ a variety of analytic tools in identifying concepts and evaluating candidate technologies: concept and systems analysis, cost analysis, technology assessment, theater and campaign analysis, and the like. However, it is important to remember that the TEG is not expected to conduct analysis to the level of detail expected in cost and operational effectiveness analysis (COEA)—which is used to make decisions about starting new system development programs. The TEG is not in the business of laying out options for *system* development, but rather for laying out options for the development and demonstration of *technology aggregates*. For example, although the TEG cannot proceed in complete ignorance of the expected costs of hypothetical systems embodying particular technology aggregates, neither is the group responsible for refining cost estimates to the standards necessary to support proposals for formal system development.

The TEG may find it especially helpful to employ modeling and simulation to help compare proposals for technology aggregate demonstration. In fact, it may well be worth using the TEG as an impetus for developing targeted simulation capabilities, which would help to answer questions like: "Is this concept worth pursuing?" and "What is the likelihood that technology aggregate X will prove as valuable to develop and demonstrate as technology aggregate Y?" Modeling and simulation may prove particularly valuable as aids to system analysis of largely hypothetical concepts, evaluation of which is often difficult to organize.

CONDUCT DEMONSTRATIONS OF ENABLING TECHNOLOGY AGGREGATES

Figure 7 summarizes an evaluation of an objective statement for a technology aggregate; such a statement can ultimately be used to organize a demonstration project for this aggregate. The greater the proposed advance in the state of the art, the less certain will be the suitability of the specifications in the objective statement—suitable in the sense of addressing a particular function or task, without asking too much or too little. In the case of far-term technology aggregates, such a statement of objective will usually be fairly broad, and its ac-

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principle of operational concept. Otherwise a bias may grow toward treating each technology that is the subject of an ATTD as though it should rightfully be associated with a development program.

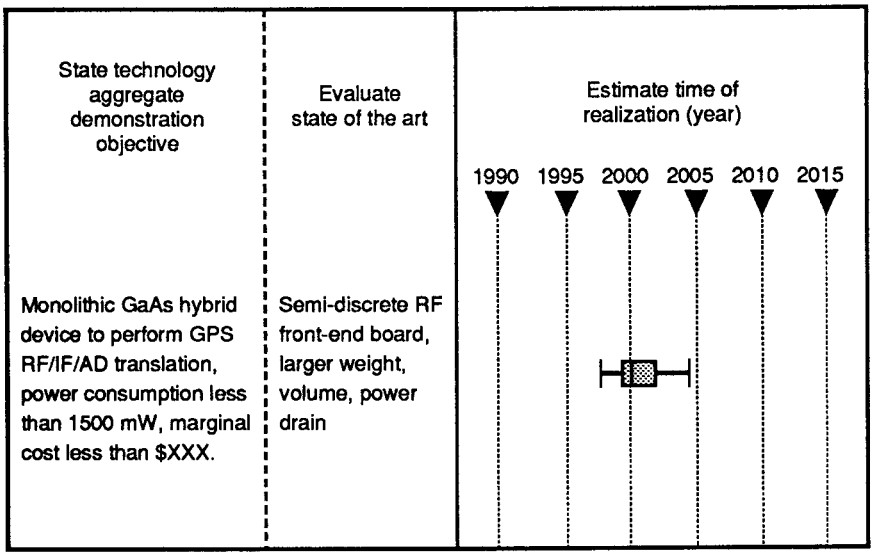


Figure 7—Summary Evaluation of a Technology Aggregate

complishment will not be demonstrated in the near term. Such a statement of objective may instead suggest generic, level-of-effort work in a particular technological discipline.

Figure 7 is a notional summary of deliberations among a group of technical experts with knowledge pertinent to the stated objective; this group may be a subset of the TEG, or it may be a subpanel called by the group to make such evaluations. Once having agreed on the objective, the evaluation entails several kinds of judgments:

- Judgments regarding the time by which operational realization of the objective is likely, given resources necessary to sustain a technology-limited schedule (i.e., no limit on resources). In this example, the mean response is around the year 2000, the middle two quartiles are between the years 1999 and 2002, and so on.
- Judgments about constraints on realization and on the most appropriate methods of promoting the stated objective.
  - — Basic research advances needed
  - — Process technology advances needed

  - — Integration advances needed
  - — Highly dependent on other advances?
  - — Lack of laboratory constituency?
  - — Lack of knowledge of concepts of operations?
  - — Insufficient industrial base?

- Judgments about the balance among candidate methods of promoting accomplishment of the particular objective—an investment strategy.

  - — In-house or industry
  - — Form of contract
  - — Competition or sole source

It is possible to imagine a number of examples similar to this one for nascent technology aggregates (for example, the Defense Advanced Research Projects Agency (DARPA)-sponsored work on hybrid IMU-GPS guidance packages, or the Air Force work on scene-matchers for bomb kits), or for aggregations of technology that are already well along in development and demonstration [the Integrated High-Performance Turbine Engine Technology (IHPTET) program], or for technology aggregates that have already found their way into military systems (the DARPA-Lincoln Lab Multiple Antenna Surveillance Radar antecedent to Joint STARS, and the TIMATION antecedents to the GPS satellites).

The purpose described for technology evaluation groups is not new; it has occasionally been addressed by the services or DARPA to organize technology investment planning. But it has never been systematically employed by the services or agencies, let alone by OSD.

This hierarchical exposition does not involve a numerical ranking scheme. Such schemes are sometimes used to tally judgments about the relative importance of subordinated objectives in order to "derive" priorities for detailed projects. But such schemes usually undervalue dialogue between technologists, military operators, and those responsible for stating higher levels of political and military objectives; the TEG is explicitly intended to facilitate this interaction.

CONDUCT DESIGNATED CONCEPT DEMONSTRATION—DECIDE ABOUT PROGRAM

- For concepts that meet evaluation criteria, conduct designated concept demonstration to demonstrate proof of principle of operational concept (minimum hardware configuration, field demonstration).
- Initiate an acquisition program only after successful proof of principle.

Work on far-term technology aggregates will eventually provide the basis for evaluation of what will become near-term concepts and systems. It is important that technology aggregates be sufficiently well demonstrated and that the proof of principle of operational concept be demonstrated before a decision is made to start a full-scale development program. This proof of principle will take a variety of forms—brass-board PAVE MOVER radars on F-111s proving the concept of long-range airborne detection of moving armored targets, early F-117 airframes proving the concept of small stealthy fighter aircraft, and so forth. Only after successful proof of principle should an acquisition plan be initiated.

SUMMARY OF THE HIERARCHY

The hierarchy we have presented (summarized in Figure 8) is applicable across the military departments, agencies, and OSD. We have used it here to highlight a near-term contribution that DDR&E can make: organizing technology evaluation groups to identify key enabling technologies for far-term systems. The fruit of such work will be statements of objectives for key enabling technologies and plans for achieving these objectives. In the terms of Figure 8, the OSD technology evaluation groups can also better rationalize the generic technology investigations that are the basis for tomorrow's enabling technology demonstrations.

In the process of conducting concept evaluations, OSD would become a more discriminating consumer of technology investment plans originating with the services and agencies. Over time, OSD's method of monitoring technology base activities would increasingly reflect the logic of this hierarchy. This would create some tension, since in some respects the hierarchy is not consistent with the governing documents for defense acquisition: DoD Directive 5000.1 and DoD Instruction 5000.2. Specifically, the hierarchy suggests a much sharper separation between proof of principle of operational concept and

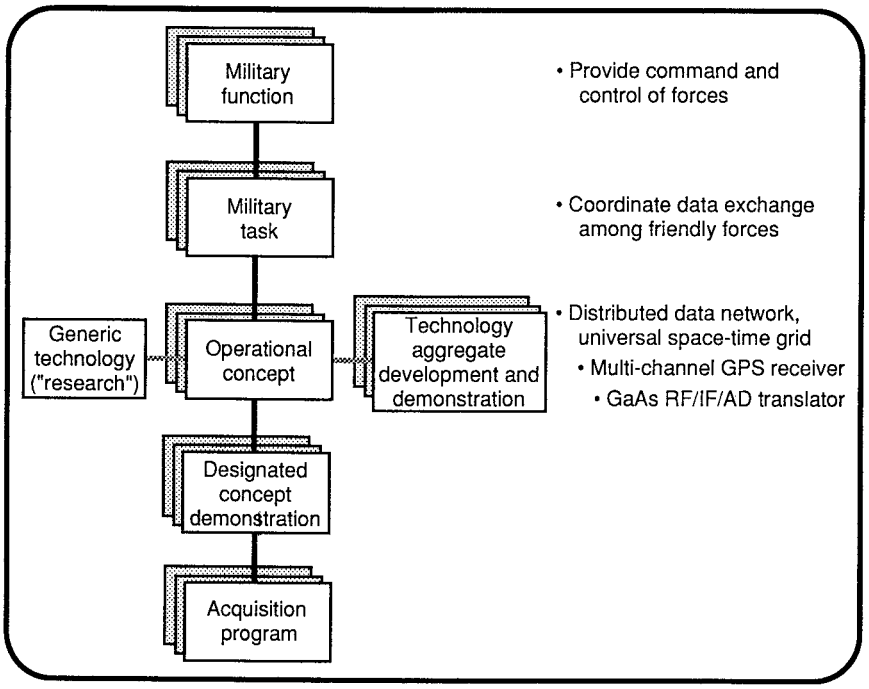


Figure 8—Summary of the Hierarchy as Developed in Example

system development and acquisition. In this respect, the hierarchy reflects lessons from other RAND work on management of risk in acquisition programs—particularly the value of good understanding of technological uncertainty before committing to full-scale development—and does more to capture the 1986 recommendations of the Packard Commission.[5]

To review: we do not propose a deterministic method by which to identify key enabling technologies for future military systems. Rather, we believe it is important to more effectively harness expert judgments in the context of a comprehensive process for defense

[5]*A Quest for Excellence, Final Report to the President by the President's Blue Ribbon Commission on Defense Management,* Office of the Secretary of Defense, June 1986. Particularly note David Packard's statement in the foreword of the report (page xii): "If DoD truly is to fly and know the cost before it buys, the early phase of research and development must be one of surpassing quality, following procedures and meeting timetables distinct from those of approved production programs." The hierarchy of subordinated objectives provides such a clean distinction, yet allows for the explicit linking of technology base activities to military operational objectives.

planning. Most direct management of technology base activities will remain with the military services, with OSD serving an oversight function. Part of this oversight, particularly that which ensures that the services and agencies are giving adequate attention to key enabling technologies for next-generation weapon systems, can be facilitated by OSD conducting its own evaluation of future concepts for accomplishing military functions and tasks. DDR&E can serve as a focal point for the demonstration of the technology evaluation groups. This approach will also lend more coherence to planning for development of generic technologies, and in the process build greater consensus in the defense community about suitable levels of effort for such work.

4. MORE ON TECHNOLOGY EVALUATION GROUPS

Once technology objective statements, assessments, and investment strategies are in hand, work will remain to adjudicate among competing demands for funding. The TEGs do not serve this purpose, except to the extent that they provide information on the potential fruits of investment in various kinds of technology development. The work of the TEGs can subsequently be incorporated into more quantitative methods for making resource allocation tradeoffs, strengthening the basis of such techniques.

The TEGs are not intended to be one-shot affairs, generating documents to lie on a shelf and gather dust. Instead, they are intended to generate strategies for pursuing demonstration of technology aggregates that will be acted upon by the military services and that will periodically be updated as circumstances warrant. The early work of the TEGs is intended to begin a more systematic process of evaluating the adequacy of technology base activities for meeting future needs for military capability. The evaluation of concepts by technology evaluation groups could become a focal point for top-down and bottom-up planning concerns—where the views of policymakers, military operators, and technologists are made to converge.

A common criticism of hierarchical methods as the basis for such planning is that they generate too many branches to be practicable for outlining a broad range of investments. But the authors do not envision the method being implemented simultaneously, once-and-for-all across the breadth of defense technology base activities. Rather, they envision the method being applied to several military tasks of particular importance—tasks for which political-military and technology changes have rendered existing capabilities dangerously inadequate. OSD would have only a handful of TEG efforts under way at any time.

OSD cannot practically conduct technology evaluations whose purpose is to justify near-term proof-of-principle demonstrations. This is a service responsibility, although OSD plays a role when the objectives to be addressed cross service lines, or when the services cannot reconcile their own competing interests. But OSD *can* conduct a limited number of evaluations whose aim is to identify technologies—the lack of which render interesting far-term operational concepts infeasible. In conducting these evaluations, the technology evaluation

groups will delineate innovative approaches for satisfying operational requirements. In doing this, the groups will also address OSD's interest to become more proactive in technology investment planning while:

- Taking advantage of not having so strong an institutional interest as the services in initiating new development programs. (An inevitable and expected outcome of an emphasis on proof-of-principle demonstrations is a set of preferences for new system development programs.)
- Exploiting OSD's broad view of progress in defense technology, spanning the services.
- Dampening expectations that OSD can pick technological winners. (A TEG may find the "next Stealth," but is even more than usually likely to identify blind-alley demonstrations, particularly since it is examining technologies further from the state of the art than are development planners in the military services.)

Although technology evaluation group findings will be used to make decisions to fund technology aggregate demonstrations, these decisions will not automatically ratify the systems the technologies may enable. Rather, the technology aggregate demonstrations lay the groundwork for more thoroughgoing cost and operational effectiveness analyses, on the basis of which decisions can be made to embark on proof-of-principle demonstrations. The analysis conducted by the TEG will resemble the COEA in some respects, but will be embryonic by comparison. The COEA is associated with prospective systems that are on the cusp of a development program decision; the TEG is investigating enabling technologies for system concepts that are relatively far term.

5. APPLYING THE HIERARCHY TO THE PRESENT PROCESS (OR VICE VERSA)

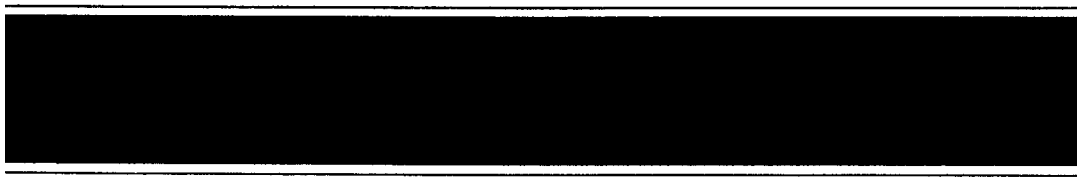
The process used by DoD to oversee investments in technology development has typically been an ad hoc element of the PPBS process. Departments and agencies responsible for executing technology base programs conduct annual planning exercises for technology investment based on language in the OSD Defense Planning Guidance (DPG). The DPG offers only the broadest of guidance in a number of technology areas (see list in footnote 5 in Section 1), with some specifics for science and technology based on a variety of factors, including current policy, knowledge of technological capabilities, and preferences for OSD-originated technical thrusts. Although the technology areas capture a wide range of service programs and form the basis for DDR&E review of service budget submissions, they are primarily organized by technical discipline rather than by reference to military functions served. Once the services and agencies have formulated their plans, the plans are reviewed by the cognizant authority in OSD; in the case of the services, R&AT staff specialists review budgets for compliance with guidance, inadequate progress, duplication of effort, and so on.

There has been substantial debate on whether this is the best way to plan and oversee defense technology investment. Our study was initiated to help inform this debate, with a view to more practical and functionally oriented implementation of the science and technology planning process. There are two approaches by which a more systematic approach could serve OSD technology base oversight: (1) In one approach, the strategic plan is drawn broadly enough to cover all technology base activities, and OSD uses the plan as an umbrella under which to describe all relevant spending by the services and agencies. Management initiatives are identified on an ad hoc basis. This resembles the approach used today, but the organizing principle would no longer be the aforementioned technology areas, but rather a set of military-functional areas. (2) In a second approach, the strategic plan is drawn in two parts: one broadly, along the lines of the existing technology areas, and another more narrowly, intended for use in identifying *special* opportunities for OSD to develop key enabling technologies for far-term systems. Either approach is consistent with

the method presented in this report—neither obviously requires more OSD staff resources than are now engaged in the oversight process, with the exception of additions for periodic meetings of technology evaluation groups.

Appendix
EXAMPLES OF TECHNOLOGY AGGREGATES

Subject military task:	Deep strike of enemy armored vehicles
Candidate system:	Cruise missiles with individually guided submunitions
For submunitions subsystem:	Hybrid electro-mechanical inertial reference unit
Technology aggregate:	**Silicon open-loop accelerometer**
Technology:	Method for fabricating silicon captured mass structures
For cruise missile subsystem:	Fiber optic gyro-based inertial measurement unit
Technology aggregate:	**Fiber optic gyroscope**
Technology:	High purity/tensile strength fiber optic cable
Subject military task:	Precision conventional bombing from large bombers
Candidate system:	Kit for existing conventional bomb
Subsystem:	Scene-matcher
Technology aggregate:	**Infrared scene-matching sensor**
Technology:	GaAs focal plane array for IR sensing
Subject military task:	Destroy theater ballistic missiles (TBMs) in the final stages of their flight
Candidate system:	Patriot with substantially upgraded radar
Subsystem:	Conformal phased-array skin-mounted antenna
Technology aggregate:	**GaAs wafer with 16 integral antenna modules**
Technology:	Techniques for wafer-scale miniaturization in GaAs
Subject military task:	Episodic long-range atmospheric reconnaissance

Candidate system:	Atmospheric/low earth orbit (LEO) hypersonic vehicle
Subsystem:	Titanium metal matrix composite structures for particular airframe
Technology aggregate:	**Titanium metal-matrix composite stabilator**
Technology:	Small-scale fiber/matrix bonding methods
Subject military task:	Precision bombing of enemy Command and Control
Candidate system:	Advanced tactical bomber
Subsystem:	New core engine demonstrator
Technology aggregate:	**3-D swept aero fan from ceramic/metal matrix**
Technology:	New metal matrix material

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