RAND

A Conceptual Framework and Preliminary Observations for Assessing Military Aerospace Design and Development Capability

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Project AIR FORCE

PREFACE

The purpose of this research is to provide a conceptual framework to analyze the future of Air Force Industrial Base R&D activities. Based on extensive interviews with major military contractors and independent historical analyses, it examines the resources (personnel, facilities, etc.) required to develop major military weapon systems. Estimates of required resources are used to assesses whether planned military aerospace budgets will support an industry capable of performing prospective major R&D projects. The consequences of not doing so are also examined. This draft presents initial observations. Subsequent reports will reflect more detailed data analyses.

Decision makers and budget/program planners who are concerned with the likelihood that industrial capability can support future programs based on military requirements will find this work helpful. A planning tool that takes budgets and future programs and assess industry's capability to perform the programs as planned can serve both program managers and budget planners. Such a tool is of interest not only to our sponsor, ASC, but to other government agencies that are responsible for supporting military R&D as well (Navy, Army, ARPA, and NASA).

This research project was sponsored by the Air Force Acqusition Headquarters and the Aeronautical Systems Center at Wright Patterson Air Force Base. It was performed within the Resource Management and System Acquisition Program of RAND's Project AIR FORCE Division, a federally funded research and development center.

PROJECT AIR FORCE

Project AIR FORCE, a division of RAND, is the Air Force federally funded research and development center (FFRDC) for studies and analyses. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is being performed in three programs: Strategy, Doctrine, and Force Structure; Force Modernization and Employment; and Resource Management and System Acquisition.

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PROJECT ORIGINS AND STRUCTURE

This project originated at the U.S. Air Force Materiel Command's Aeronautical Systems Center (ASC) Presidents' Day. ASC's Presidents' Day is an annual meeting of the ASC commander and his staff with the chief operating officers of ASC's largest contractors. During a discussion of ASC's planning process for future development activities the following issue arose: Would the level of future development activities be adequate to sustain a "viable" military aerospace industry? That is, one capable of meeting national security requirements? As a result RAND Project AIR FORCE (PAF) was asked to design and perform the analysis, which began in March 1994.

This analysis is limited to research and development activities of large contractors in the military fixed-wing aeronautical industry: the developers and producers of airframes and aircraft integration, avionics, propulsion, aircraft subsystems, and weapons. The initial project mandate was to determine whether current policies would lead to the survival of a "viable" industry, operationalized as: Would the future industry be capable of designing and developing sufficiently advanced military aircraft and weaponry at acceptable cost and schedule to meet national security objectives? The working hypothesis is that future capability is functionally dependent on the volume and nature of the historical R&D activities. These R&D activities are primarily determined by the programs, policies, and budgets of those parts of the U.S. government (USG), like ASC, that fund and administer military R&D. As a result, this is not simply an Air Force issue.

RESEARCH AND DEVELOPMENT INDUSTRIAL BASE

The Air Force industrial base is composed of the following component activities:

- Research and Development
  - Science and technology
  - Concept exploration and development
  - Demonstration and validation
  - Engineering and manufacturing development
    - New systems
    - Major modifications
  - Minor modifications
- Production
  - New systems
  - Modification kits
  - Spares
- Sustainment
  - Sustaining engineering
  - Modification installation
  - Overhaul (programmed depot maintenance)
  - Component repair

Since the private sector performs most of the R&D work, almost all of the production, and around half of the sustaining work, it is appropriate that our research methodology involved extensive interaction with industry.

There are many ways to disaggregate and analyze the varied activities that constitute "military aeronautical R&D." The three used in this analysis are: "Technological Improvement", "Incorporating Technology into Systems", and "Overhead". Roughly speaking, the first category, "Technological Improvement", includes all those activities that make it possible to develop new airplanes of improved technical quality. The second, "Incorporating Technology into Systems", is actually developing new airplanes (completely new or upgrades). If one did only the first and not the second, the technical quality of potential new airplanes would be high but never realized. If one did only the second but not the first, each successive generation of new aircraft would be technically about the same as the previous generation. A third category, "Overhead", includes mostly management activities and test and evaluation.

Why does the Air Force support research and development activities? Research and development activities influence both the technical frontier and the performance capability of the aircraft that are the best in fleet. The rate at which technology advances and is incorporated into new systems is a function of the research and development funding. The fleet average performance or technical capability is the average technical quality of the military aircraft fleet at any time. This rises as improved aircraft are introduced, which is a function of procurement spending. Keep in mind that technical improvement should be broadly interpreted. Advances that lower new systems' production cost or improve their maintainability should also be included.

One can now effectively characterize the process that generates work requirements for the R&D (and procurement) sector. Assessments of future military threats and uncertainties lead to requirements for fleet size, average fleet quality, and best in fleet levels. These requirements generate necessary rates of new system and upgrade introduction, which in turn lead to required rates of increase in the technical frontier line. The relationship between resources expended and R&D outcomes (technical quality improvement rate and number of new systems developed) determine required R&D budgets. A similar process leads to required procurement budgets.1

WHAT IS THE INDUSTRIAL BASE PROBLEM?

Two basic kinds of industrial base problems may exist. These are the "hiatus problem" and the "scale problem." The "hiatus," problem can occur in the following way. Dramatic changes in the national security environment may generate work requirements that fall, remain at low levels for some time, and then rise. The efficiency of work that is performed during the rise may suffer because new resources will have to be drawn into R&D. This affect may mean that more workers are needed to accomplish a specific job or more time is required to complete a given project. This would occur because during the rise period, new workers have to be hired as work requirements expand. They may be workers who have never done this kind of work, or they may be workers who had been

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[1] Translating the National Security Strategy into a work program for technical improvement involves many additional variables such as: number vs. quality, new system vs. upgrade efficiency, air vs. ground, "requirements" vs. affordability, etc., but the principles remain the same. A coherent national security strategy will imply a work program for technical improvement and new system/upgrade R&D through the steps outlined above. The Air Force Modernization Planning Process follows this model.

laid off and brought back, in either case there may be a learning period required to bring their efficiency up to the original level.

Industrial base policy may alleviate the problem by adjusting the spending. Much of this research investigates both (1) the cost penalty of a rise in work requirements and (2) the potential savings of appropriate policies during the down times.

A completely separate potential problem is the "scale" problem. In many kinds of economic activity there is a "minimum efficient scale," or a level of production below which average costs rise. It may be, as a result of the military requirements process characterized above, that the required level of work is too low to exploit all the economies of scale, and that unit costs rise.

Scale effects in military R&D can occur in two important ways. First, work requirements may make desirable levels of competition difficult. Whether the answer is to (1) simply suffer monopoly inefficiency, or (2) maintain competition and suffer the carrying costs of the other competitor during the times it has not won a project, is a matter for additional empirical analysis. Another potential R&D scale problem is due to specialization. In a world of reduced requirements, one team may have to be prepared to develop a wider range of aircraft. This may lead to some inefficiency as engineers find their experience diluted. However, it may be possible that some diversity of experience is beneficial.

Industrial capability

Our working definition of industrial capability to perform R&D is the following: R&D capability resides in development teams, which are operationally associated with divisions of companies. Each team's capability is defined in terms of the cost and time required to carry out specific development projects.

A typical R&D cost profile begins with some period of fairly low spending, which would be associated with a demonstration-validation phase. Then spending ramps up to about four times earlier levels, eventually tapering off to a relatively low level after production is well under way. Initial operational capability (IOC) is marked at a typical point, well after the spending peak but before all development spending is complete. A team is more capable if it can complete a given project more quickly or with less resources, or both. Several complicating issues regarding project-R&D profiles, R&D uncertainty, and cost-schedule trade-offs arise with this conceptualization. The overall capability of a team is simply the collection of R&D cost profiles associated with all potential projects. We have also assumed that a team cannot trade off between schedule and cost -- it does not have a choice between achieving an earlier IOC but at higher cost. Most industry people interviewed said that there was limited ability to buy time with money. Finally, characterizing development capability in terms of the cost and time required to develop a system of fixed technical performance is at odds with one of the primary aspects of R&D. That is, R&D outcomes are highly uncertain so part of the resulting product's quality can be attributed to the the team's capability, but part can also be due to the underlying characteristics of nature, and part to simple luck. This can be rectified by substituting "expected technical performance" for "technical performance".

Determinants of Industrial Capability

What determines whether a team is more or less capable? At any point in time a design team will be composed of a given number of technical personnel, appropriate facilities within which to construct test articles and perform tests, and support staff. In addition, the team will have a business infrastructure associated with it. Moreover, the design team will have a science and technology base to draw upon. This base will be partially embodied in the minds of the technical personnel, and partially accessible through documentary means.

In our conceptual model, development capability of a team depends on three factors: facilities available, science and technology base available, and experience level. As our questionnaire indicates, we elicited from the companies interviewed their judgment on how each of these factors affected their ability to complete both historical projects and prospective future projects. Due to the accumulation of experience, relatively high levels of R&D in any given period result in relatively high capability levels later, and vice versa.

INITIAL RESULTS FROM COMPANY INTERVIEWS

In terms of technical employment, the average estimate by airframe companies for the minimum size team that must be continuously doing development work (i.e., acquiring experience) to ensure that its current development capability is maintained was around 1,000. An interesting generalization is that this minimum team is close to the size required to complete a demonstration-validation type project. This implies that continuous employment on a series of demonstration-validation projects would maintain development capability.

The average for avionics companies and for the sum of propulsion plus a full set of subsystem companies was also about 500 each. Therefore, to maintain one minimum size team for each sector of the military aircraft business, approximately 2,000 technical personnel would have to be employed. The total cost of maintaining one full team (including one airframe team, and one avionics, propulsion, and set of subsystem teams) is about $500 million per year. Two important caveats must be noted. One, this team would not be capable of completing a full new system EMD. This is simply the team that maintains the capability to expand into a full EMD team. As stated above, it is best thought of as a prototype or demonstration-validation team. A full EMD team is about four times this size. Second, there is no allowance for competition. Depending on the number of competitors one wants to maintain, this number would have to be multiplied up. Moreover, one may want to have different competitive levels in different market sectors.

The Consequences of a Hiatus

The consequences of not maintaining continuous minimum experience levels and of reconstituting such a team were also postulated. The premise of this question is: the company would continue to exist with its expected production and sustainment programs but new development work would stop. This would not be comparable to new system development. This reconstitution question was meant to represent a "worst case" scenario of R&D experience loss.

What would happen if the company were asked to begin a new development project ten years after all new development had been stopped? What are the consequences in terms of program's schedule, cost and performance, of the no-development period for the company's ability to complete the project.

The companies focused on program schedule when responding. The reconstituted team would basically take longer in the program's pre-EMD phase. The extra time would be to identify and hire technical personnel (either experienced or not); for these new hires to learn or relearn system development techniques; and for them to acquire or reacquire experience through some trial and error episodes. The extra time in a pre-EMD phase was estimated to be between five and ten years. As a result, the new system's IOC would be delayed by that many years. If a nominal major program is now about 13 years from beginning of demonstration-validation to IOC, (about 5 for demonstration-validation and 8 for EMD), that would extend to about 20 or 21 years.

What would be the technical performance consequences of a hiatus in development activity? The consensus from our interviews was that the military aircraft developed after a hiatus would have about the same. Thus, the technical penalty to a first approximation would simply be the time lag and larger uncertainty bands.

There is a second potential problem with future development programs that could lead to loss of development capability. Even if a reasonable number of core teams are maintained, they do not in themselves have the capability to perform an EMD. They are simply the base from which an EMD team is built. The EMD team is about four times the size of the core team or about 8,000 engineers. We have been implicitly assuming that the additional 6,000 engineers are available to be hired whenever an EMD begins. Whether this is true depends on the timing of EMDs. It could be that even if core teams are maintained, program timing may lead to waves of layoffs and recalls as EMD programs ebb and flow. This will lead to some productivity penalties as EMD engineers must be found and hired. There are quantitative and qualitative aspects to the penalties.

Quantitatively, there are hiring and training costs, which can be of two types. One is the routine cost of hiring (or rehiring) and training a worker, perhaps an additional one or two year's pay depending on the training required. The second is the salary premium that the industry would have to pay for the uneven timing of the work. The premium's size will depend on the overall market strength and the intrinsic appeal of the military EMD work. A penalty in the 20% range is not unreasonable.

The qualitative penalty is similar to the second quantitative penalty. The "best and brightest" engineers may be unwilling to work in such a cyclical industry. This leaves the less qualified engineers to move between industries as demands change. We know of no attempts to measure this phenomenon for military aeronautical R&D. However, much anecdotal evidence exists of high quality personnel leaving the industry because of pessimism about future prospects.

Would there be a schedule delay if EMD engineers had to be hired from other industries? If it were known at the beginning of demonstration-validation that EMD would definitely occur there would not likely be a delay. In this case, planning for EMD hiring in about four years (one to train new workers) could be done, although the cost penalties for rehiring and training would occur. If hiring did not occur until EMD was about to begin, one would expect about a two year delay as engineers are found, recruited, hired, and trained.

Thus, our interviews identified two important ways that R&D capability in the future could be negatively affected by lack of experience. The first, and most drastic, is if development work stops and even core teams are not maintained. This would cause an estimated five to ten year delay for R&D capability to return to the present level, from the time work begins again. This is a very large national security penalty in an uncertain world.

The second is that lumpy timing of EMD programs could cause the industry's engineering employment levels to be unstable, even if core teams are continuously maintained. This would have cost penalties and would very likely lower the average quality of personnel.

Lastly, we are doing an overall historical analysis of the role of experience in military aircraft development from 1945 to the present, which is described in a companion report entitled, "The Role of Experience in U.S. Combat Aircraft Development Since WWII."

RESULTS OF BUDGET ANALYSIS

Between 1995 and 2001 the number of engineers associated with military aeronautical R&D falls from about 31,800 to about 14,300, which is a 55% decrease. The number working on operational systems falls from about 21,000 to about 7,000, a 67% decrease. Thus, there will be a substantial decrease in the number of engineers working on military aeronautical R&D projects. A large increase in engineering employment is required, from minimum levels of 14,300 in 2000-2001 to 22,400 by 2005. Given our assumptions on program timing, a similar decline and regrowth will occur between 2006 and 2010.

The first hiatus in employment is a serious problem that should be addressed now by military aeronautical R&D authorities. If our assumptions are correct, a large number of engineering personnel (approximately 8,000) will be laid off starting in 1997 but will have to be recalled in 2002-2004. This will lead to the problems associated with uneven timing of EMD programs: hiring and retraining costs, possible schedule slips, and possible difficulty attracting high quality personnel.

This leads us to consider an alternate approach to military aeronautical R&D planning. Avoiding drastic increases and decreases in technical engineering employment is a worthy independent goal in this sector because of the potential cost, schedule or quality-of-personnel penalties. However, as this analysis illustrates, planning solely within the FYDP horizon is insufficient given military aeronautical research and development time lines. Overall, military aeronautical R&D planning should be performed in a long-term fashion, with a view to the essential part of the associated industrial base: skilled engineering personnel. Plans should be made to avoid wasteful and risky disruptions in their employment. The appropriate way to do this would be to assess long-term requirements for improved military aeronautical technology (both technical base and systems) and then plan programs to stabilize (within reason) employment in the industry.

A TOOL FOR ANALYZING INDUSTRIAL R&D CAPABILITY

In order to more specifically assess the impact of alternate future R&D programs on future capability an analytic tool is necessary. This tool takes budgets and future programs and assess industry's capability to perform the programs as planned. Assuming a fixed top-line to the budget, the consequences of reduced capability on future programs is shown in terms of program delays and timing.

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We would like to recognize the efforts of the Industry/Government Process Action Team (PAT) (see below for participants) in supporting our research during the past year. These individuals not only provided invaluable insights contributing to the design of our research methodology but also obtained high-level support for our work within their own companies. During a two day interview process, the cooperation of PAT company representatives along with members of their staff enabled us to collect detailed information regarding the state of the military aerospace industry. Without such cooperation, we would have found it difficult to proceed.

Furthermore, Mr. John Griffin, Mr. Doug Taylor, and Mr. Tom Hogan of ASC/XR reviewed our progress throughout the year and offered both guidance and assistance. Of particular note, is the help we received in deciphering future R&D programs and their associated spending patterns.

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I. INTRODUCTION

How effective will the future military aerospace industry be in supporting U.S. national security policy? How is that effectiveness influenced by current and future U.S. military aerospace R&D programs and budgets? What is the appropriate present and future military aerospace R&D program structure and budget level, based on these and other considerations? This report documents some preliminary insights gained from a continuing research project.

I. PROJECT ORIGINS

The project originated at the U.S. Air Force Materiel Command's Aeronautical Systems Center (ASC) Presidents' Day held November 1993. ASC's Presidents' Day is an annual meeting of the ASC commander and his staff with the chief operating officers of ASC's largest contractors.

During a discussion of ASC's planning process for future development activities the following issue arose: Would the level of future development activities be adequate to sustain a viable military aerospace industry? That is, one capable of meeting national security requirements? Because the issue was important and the answer unclear, it was decided to study the issue. RAND Project AIR FORCE (PAF) was asked to design and carry out the analysis. As a result this study began in March 1994.

RAND Project AIR FORCE (PAF) was chosen for several reasons. First, as a federally funded research and development center (FFRDC) PAF is neither industry nor government. Consequently, it can serve as a neutral analyst and integrator of sensitive government and industry data. PAF regularly works with industry proprietary data that is not available to the government or other companies, and with government data that is not available to contractors. This precludes industry members from performing a comprehensive analysis. In order to assess the future viability of industrial structures both sensitive government budget data and proprietary industry project data must be simultaneously analyzed. As an integrator of highly sensitive data it is both challenging and crucial to report insightful results while preserving data sensitivities. In addition, RAND Project AIR FORCE (PAF) has done pioneering work in the area of industrial base capability preservation, as represented by R-4199, Maintaining Future Military Aircraft Design Capability, 1992, by Drezner et. al. and thus has a strong research experience base with which to begin.

II. PROJECT STRUCTURE

Working closely with U.S. Air Force and industry representatives, it was decided early-on to limit the project scope. Because of resource constraints, and a relative preference for depth over breadth, we limited the analysis to large contractors in the military fixed-wing aeronautical industry. This includes the developers and producers of airframes and aircraft integration, avionics, propulsion, aircraft subsystems, and weapons. It was also explicitly decided to focus on research and development activities excluding production and sustainment. Further work might expand the scope of this inquiry in both directions.

The initial project mandate was to determine whether current policies would lead to the survival of a "viable" industry. This mandate is operationalized in the following way: Would the future industry be capable of designing and developing sufficiently advanced military aircraft and weaponry at acceptable cost and schedule to meet national security objectives? The working hypothesis of the study is that future capability is functionally dependent on the volume and nature of historical R&D activities. These R&D activities are primarily determined by the programs, policies, and budgets of those parts of the U.S. government (USG), like ASC, that fund and administer military R&D. Thus, present and near-future USG military aeronautical R&D programs and budgets determine the longer-term future capability of the industry to complete R&D projects. Our research begins to: (a) quantify this relationship, and (b) assess whether any given present and near-future R&D plan is adequate to support longer-term national security goals. A more detailed description of how we conceptualize these relations is given in Chapter III.

The project team interviewed nineteen military aeronautical companies to gather relevant data. The companies are listed in Table 1.1 by sector. An extensive questionnaire, reproduced as Appendix A, was sent to each company before the interview.

Table 1.1

Companies Interviewed for this Project

- Aircraft
  - Boeing
  - Lockheed Fort Worth
  - Lockheed Georgia
  - McDonnell Douglas
  - Northrop-Grumman
  - Rockwell
  - Vought
- Propulsion
  - Allison
  - General Electric
  - United Technologies (Pratt & Whitney)
- Avionics
  - Hughes
  - Martin Marietta
  - Texas Instruments
  - TRW
- Other Systems
  - Allied Signal
  - CAE-Link
  - Raytheon
  - Textron
  - Tracor

The viability of aerospace design and development capability is not simply an Air Force issue. Other parts of the U.S. government, including the Navy, Army, ARPA, and NASA, support military aeronautical R&D. In addition, commercial aeronautical R&D, while not a perfect substitute, is also relevant for the military technical base. Moreover, certain kinds of military and commercial electronics R&D are relevant to both avionics and other applications. This analysis will take these factors into consideration.

II. AIR FORCE INDUSTRIAL BASE ISSUES: AN OVERVIEW

Before proceeding to the specific analysis of this project, we will discuss the following issues: What is the Air Force industrial base? What specific role does R&D play within this industrial base? What kinds of potential problems concerning the industrial base might the Air Force face in the future? Covering these basic issues ensures that the same terminology and definitions are used consistently throughout this report and among our readers.

I. THE AIR FORCE INDUSTRIAL BASE DEFINED

According to the US Industrial Outlook 1994 the aerospace industry[2] is a driver for advanced technologies and "accounts for more than 25 percent of all the nation's research and development expenditures, making it the country's leader in R&D spending on new technologies." Moreover, the aerospace industry utilizes "a number of the technologies identiifed as critical by OSTP, DoD, and Doc."[3]

Table 2.1 contains an inclusive list of what we consider to be components of the Air Force industrial base. As in any such list, the boundaries between categories can be fuzzy in practice. For instance, the distinction between "minor mod R&D" and "sustaining engineering" is often ambiguous.

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[2] SIC codes: 3721, 3724, 3728, 3761, 3764, and 3769. This is slightly different than our working definition because it includes space.

[3] Dept of Commerce, US Industrial Outlook 1994, p. 20-1.

Table 2.1

Air Force Industrial Base Components

- Research and Development
  - Science and technology
  - Concept exploration and development
  - Demonstration and validation
  - Engineering and manufacturing development
    - New systems
    - Major modifications
  - Minor modifications

- Production
  - New systems
  - Modification kits
  - Spares

- Sustainment
  - Sustaining engineering
  - Modification installation
  - Overhaul (programmed depot maintenance)
  - Component repair

This study only considers issues pertaining to the R&D components of the military aerospace industrial base. Since the private sector does most of the R&D work, almost all of the production, and around half of the sustaining work, it is appropriate that our research methodology involved extensive interaction with industry. Furthermore, we recognize that such s methodology could be applied to the other components of the military aerospace industrial base (production and sustainment) as well.

II. A VIEW OF R&D

There are many ways to disaggregate and analyze the varied activities that constitute military aeronautical R&D. Table 2.2 contains the taxonomy most useful for this analysis. This disaggregation is not pure or unique, only workable leading to helpful analytical results.

Table 2.2

A Categorization of Military Aeronautical R&D Activities

Technological Improvement
  - Basic and applied research
  - Exploratory and advanced development
  - Subsystem improvement

Incorporating Technology into Systems
  - New systems: Dem-Val and EMD
  - Upgrades

Overhead
  - Management
  - Test and evaluation

Roughly speaking, the first category, "Technological Improvement", includes all those activities that make it *possible* to develop new airplanes of improved technical quality. The second, "Incorporating Technology into Systems", is *actually developing* new airplanes (completely new or upgrades); i.e., incorporating the technical improvements from the first category into actual flying systems. If one did only the first and not the second, the technical quality of potential new airplanes would be high but never realized. If one did only the second but not the first, each successive generation of new aircraft would be technically about the same as the previous generation.

The biggest difficulty with this taxonomy is that it assumes no pure technical improvements occur in system development by themselves; i.e., no "learning-by-doing" occurs during system development. This distinction literally assumes that system development is the process of incorporating and integrating technical improvements derived from the first set of activities into flying systems. In reality, some pure technical improvement does occur. Therefore, if no activity takes place in the "Technological Improvement" category, it is still possible to have some improvement in new generations of aircraft due to technical improvements obtained during system development. However, our goal is to analyze the balance between different R&D activities so this taxonomy is useful. Such an analysis provides insights into preferred policy options that may influence distinct types of R&D activity. The budget analysis in Chapter 4 uses this distinction. A third category that we call overhead includes mostly management and test and evaluation.

Table 2.3 shows the USAF program elements (PEs) distributed into these military aeronautical R&D activity categories. This set comprises the USAF's white world contribution and is used in Chapter 4's budget analysis. A number of R&D related PEs have been excluded for the reasons described below. Weapons R&D will be analyzed separately for a subsequent report. Also excluded are some aeronautical related R&D PEs that do not primarily concern aircraft, such as air base survivability. Furthermore, this PE list is based on the 96 Budget Estimate Submittal (BES), which does not include a PE for NGAF EMD (Next Generation Attack Fighter, the aircraft that is expected evolve from the JAST demonstration program). However, we include an estimate of NGAF EMD in the budget analysis presented in Chapter 4. Ultimately, the PE list will be updated to the 96 PB and will include NGAF EMD information.

Table 2.3

USAF PE's Included in Military Aeronautical R&D Activities (RDT&E appropriation only)

Technological Improvement

61101	In-House Lab Independent Research
62102	Materials
62201	Aerospace Flight Dynamics
62203	Aerospace Propulsion
62204	Aerospace Avionics
62269	Hypersonic Technology Program
63112	Advanced Materials for Weapon Systems
63202	Aerospace Propulsion Subsystems Integration
63203	Advanced Avionics for Aerospace Vehicles
63205	Aerospace Vehicle Technology
63211	Aerospace Structures
63216	Aerospace Propulsion and Power Technology
63245	Advanced Fighter Technology Integration
63253	Advanced Avionics Integration
63269	National Aerospace Plane Technology Program
63270	Electronic Warfare Technology
63742	Combat Identification Technology
64201	Aircraft Avionics Equipment Development
64218	Engine Model Derivative Program
64227	Flight Simulator Development
64242	Advanced Interdiction Aircraft (AX) Study
64268	Aircraft Engine Component Improvement Program
64270	Electronic Warfare Development
64609	R&M Maturation/Technology Insertion

Table 2.3 (continued)
USAF PE's Included in Military Aeronautical R&D Activities (RDT&E appropriation only)

Incorporating Technology into Systems	
11113	B-52 Squadrons
11120	Advanced Cruise Missile
27129	F-111 Squadrons
27131	A-10 Squadrons
27133	F-16 Squadrons
27134	F-15E Squadrons
27136	Manned Destructive Suppression
27141	F-117A Squadrons
27160	Tri-Service Standoff Attack Missile (TSSAM)
27217	Follow-On Tactical Air Reconnaissance System
27417	Airborne Warning and Control System
27590	Seek Eagle
31317	Senior Year Operations
41119	C-5 Airlift Squadrons
41218	KC-135
63800	JAST Demonstration
64226	B-1B
64231	C-17 Program
64233	Specialized Undergraduate Pilot Training
64237	Variable In-Flight Test Aircraft (VISTA)
64239	F-22 EMD
64240	B-2 Advanced Technology Bomber
64249	Night Precision Attack
64770	Joint Surveillance/Target Attack Radar System (JSTARS)
Overhead	
64735	Combat Training Ranges
65807	Test and Evaluation Support
65808	Development Planning
65863	RDT&E Aircraft Support
78026	Productivity, Reliability, Availability, Maintainability Program Office (PRAMPO)
A1004	International Activities

Note, activity devoted purely to improving subsystems, particularly avionics and engines, is included in "Technological Improvement"; i.e., it makes it possible to develop a better (especially upgraded) aircraft in the future. However, much actual avionics and engine development is included in the "Incorporating Technology" category -- the EMD categories for new systems. As an example, much of the F-22 EMD expenditure is for avionics and engine development.

Figure 2.1 illustrates how these R&D activities affect military capability over time. The horizontal axis represents time, and the vertical axis is an index of the technical quality of military aircraft. (For ease of exposition, we are representing the technical quality of military aircraft as unidimensional. In reality it is multidimensional, but the concept is the same. Similarly, it is best to consider new systems only. Upgrades will be introduced later.)

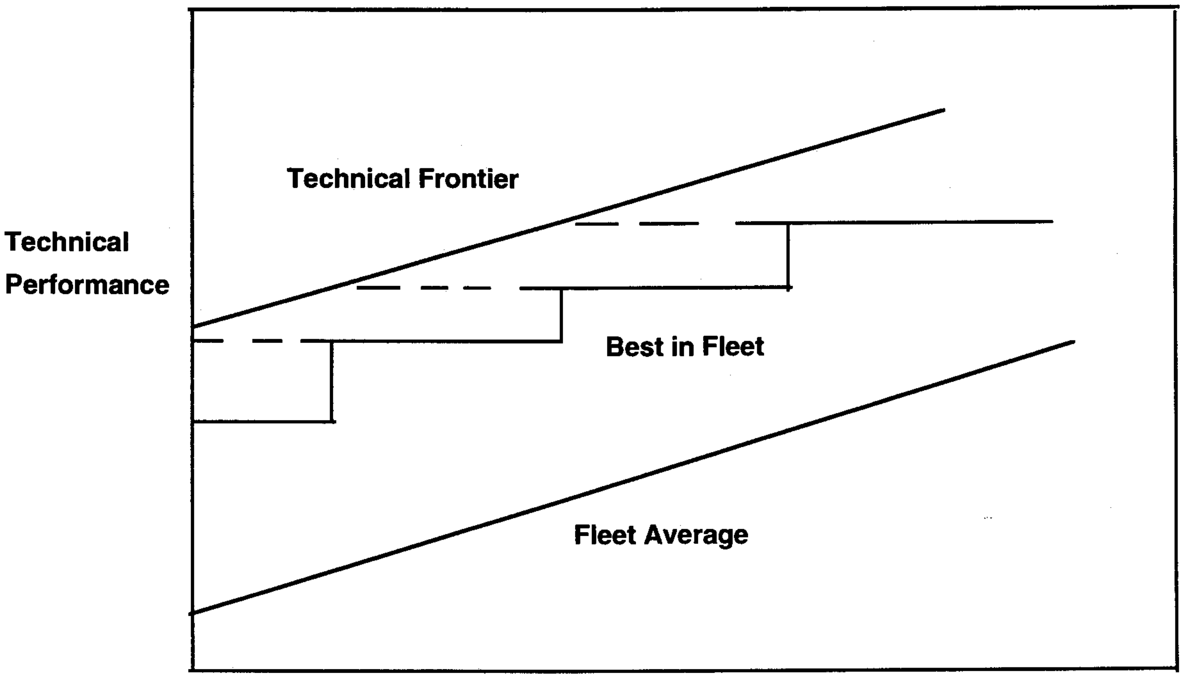

Fig. 2.1-Evolution of Fleet Technical Performance

The top line, called "technical frontier," shows the highest technical quality aircraft that could be designed and developed starting at that time. It is assumed to rise based on the resources devoted to the R&D activities classified as "technical improvement". I.e., if no technical improvement R&D was done, the line would be flat. As the resources devoted to technical improvement R&D activities increase, the line rises at a faster rate.

The second line, called "Best in Fleet," shows the technical quality of the highest quality aircraft in the fleet. It rises in a step-like fashion to show the discrete timing of new system developments. Each upturn is the IOC date of a new aircraft. It does not rise to the "Technical Frontier" line when a new aircraft is introduced because of the time required for system development. Indeed, the dashed line backward from "Best in Fleet" to "Technical Frontier" represents system development time; it is the time lag between when a new technical quality was possible and when it was introduced. This time varies depending on the nature of the new system and resources available.

The rate at which the "Best in Fleet" line rises depends on the resources devoted to "Incorporating technology into systems", much as the rate at which the "Technical Frontier" line rises depends on the resources devoted to technical improvement. More specifically, each new system development will lead to the introduction of a new "best in fleet" aircraft, so as more resources are devoted to new system development projects, the faster (more frequently) the "Best in Fleet" line will rise.

The bottom line is called "Fleet Average," and is the average technical quality of the military aircraft fleet at any time. It rises as improved aircraft are introduced, and as older aircraft of lower technical quality are retired. It rises as a function of procurement spending.

Upgrade programs presumably seldom affect the "Best in Fleet" line, but the development resources, together with procurement resources spent, make it possible for the "Fleet Average" line to rise more quickly as the technical quality of existing aircraft is improved.

Using Figure 2.1 one can now effectively characterize the process that generates work requirements for the R&D (and procurement) sector. Assessments of future military threats and uncertainties lead to requirements for fleet size, average fleet quality, and best in fleet levels. (The last two parameters are distinct because a fleet composed of half aircraft of quality 100 and half of quality 200 may have substantially different military utility than the same size fleet composed entirely of aircraft of quality 150. Arguments for "hi-lo" fleet mixes are often based on such a notion.) These requirements generate required rates of new system and upgrade introduction, which in turn lead to required rates of increase in the technical frontier line. The relationship between resources expended and R&D outcomes (technical quality improvement rate and number of new systems developed) determine required R&D budgets. A similar process leads to required procurement budgets.[4]

Keep in mind that should be broadly interpreted. Advances that lowers new systems' production cost or improves their maintainability should also be included. By decreasing the cost of military capability technical improvements either allow an increase in overall level or a decrease in the taxes used to pay for it. This stylized view of military aeronautical R&D will be pursued further later in this report.

III. WHAT IS THE INDUSTRIAL BASE PROBLEM?

Why does the Air Force, and the military in general, have to be specifically concerned with the industrial base? Why must it adopt an "Industrial Base Policy?" This discussion will be generally applicable to all three components of the industrial base (R&D, procurement, and sustainment) but in keeping with the focus of this project, most of the issues described below will deal with the R&D component.

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[4] Translating the National Security Strategy into a work program for technical improvement involves many additional variables such as: number vs. quality, new system vs. upgrade efficiency, air vs. ground, "requirements" vs. affordability, etc., but the principles remain the same. A coherent strategy will imply a work program for technical improvement and new system/upgrade R&D through the steps outlined above. The Air Force Modernization Planning Process follows this model.

There are two basic kinds of industrial base problems that may exist: the "hiatus problem" and the "scale problem." We define them both in terms of the basic R&D and procurement work requirements. To briefly summarize, R&D work requirements are derived in the following way. Military planners determine the technical quality of aircraft required to meet national security objectives. From this, they determine the number and size of system development activities (new and upgrade) and the rate of technical improvement required. We call these the "work requirement" of the R&D component of the industrial base. Then there are presumably relations that give the resources required to bring about both the system developments, and the rate of technical increase. [In economics terminology, such relations are called "production functions." They functionally relate inputs (e.g., number and skill of engineers employed) to R&D outputs (like number of new systems developed).] The resource requirements derived from these relationships then determine required procurement budgets.

The "hiatus," problem can occur in the following way. Dramatic changes in the national security environment may generate work requirements that fall, remain at low levels for some time, and then rise. The efficiency of work that is performed during the rise may suffer because new resources will have to be drawn into R&D. The lowered efficiency might be realized as an increased number of workers needed to do a given job, or a longer time required to carry out a given project. This efficiency loss would occur because during the rise period new workers have to be hired as work requirements expand. They may be workers who have never done this kind of work or they may be workers who had been laid off and brought back, but in either case there may be a learning period needed to bring their efficiency up to the original level.

Figure 2.2.A illustrates this concept. Time is on the horizontal axis and resources devoted to R&D on the vertical. The solid line shows the R&D sector work requirement derived from military force requirements. It assumes that the R&D resource efficiency in terms of producing technical improvement is constant at the pre-fall (pre-T_0) level. Thus, work requirement and resources used can be represented by

the same index. The decrease in work requirement at T_0, and subsequent rise at T_1, can be rationalized in a familiar end-of-the-Cold-War story. Because of the fall of the Warsaw Pact, relatively modest improvements in technical capability are needed in the T_0-T_1 period. But after that, improvements in our systems may be needed due to technical advances in other countries (either in aircraft or anti-aircraft systems).

If the resources brought into the R&D sector in the post-T_1 period have the same efficiency as those already in the sector, the solid line represents both resources and requirements, and there is no problem. But if these new resource have lowered efficiency because they are inexperienced, then higher expenditure is needed to achieve the same result. The dashed line in Figure 2.2.B might represent such a situation. Not only are more resources needed, but they must be hired *before* T_1, in order to achieve the same result. Because of their inexperience, the new resources require a learning period before they can carry out the R&D projects. This is a problem not only because it takes more resources to carry out projects, but also because it requires careful planning to anticipate (by increasing spending before T_1) that the required new R&D projects simply can't be carried out in the time frame called for by military requirements.

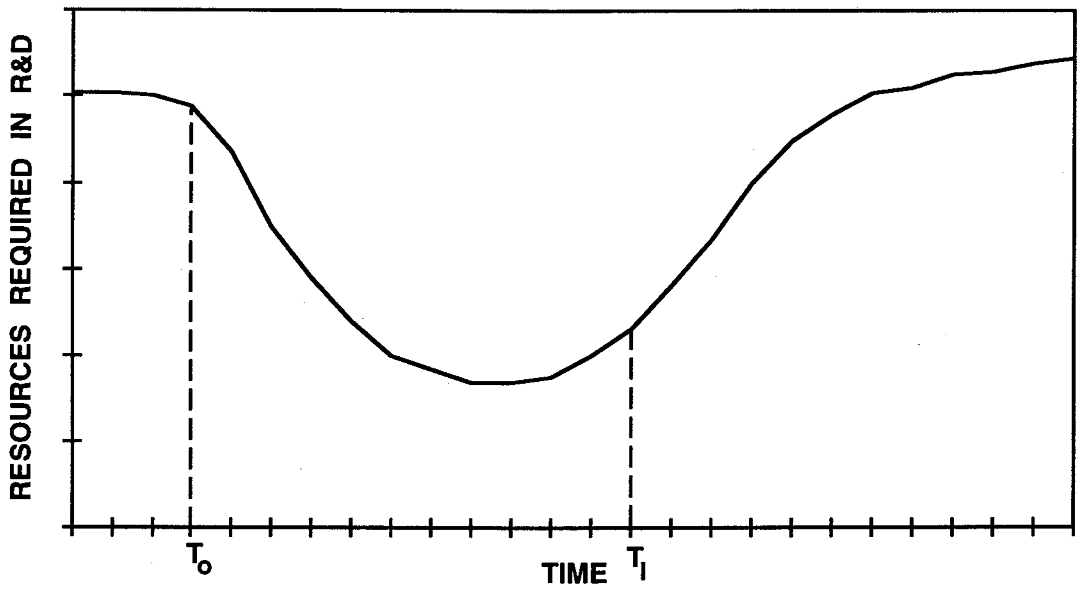

Fig. 2.2.A-The Hiatus Scenario: Work Requirements Fall and then Rise. If Productivity Does Not Decrease During the Rise, Resources Required are Proportional to Work Requirement.

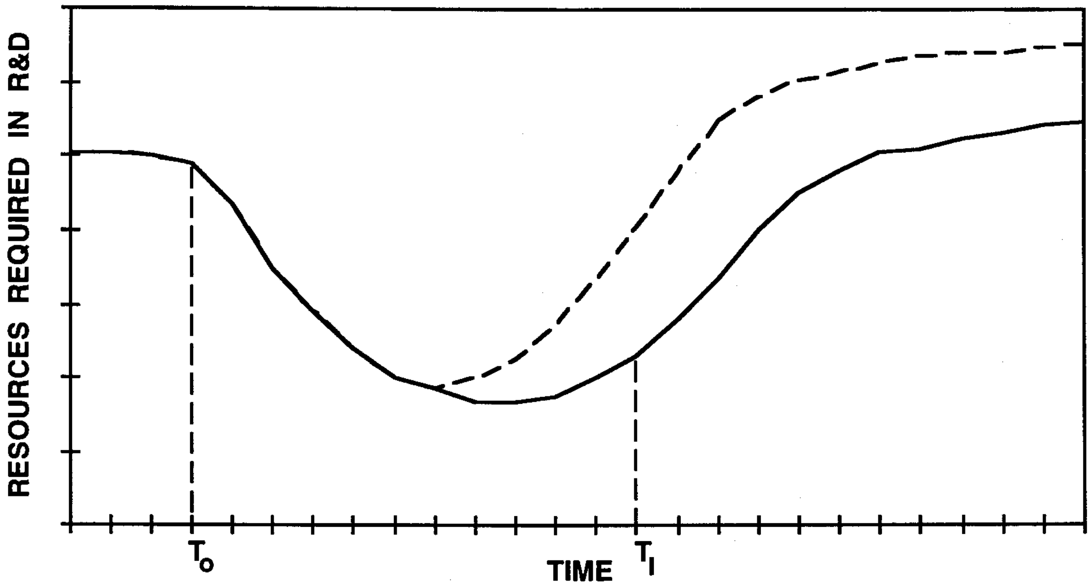

Fig. 2.2.B-The Hiatus Problem: If Productivity Falls During the Rise, The Dashed Line Represents Resources Needed to Carry Out the Solid Line Work Program.

Industrial base policy may alleviate the problem by adjusting spending to the dotted line in Figure 2.2.C. One may be able to avoid some of the increased cost of the "rise", and indeed save money in the long run, by not letting spending fall as much as possible if dictated by current requirements. The resources represented by the difference between the dotted line and the solid line immediately after T_0 would be those employed by the "industrial base" policy, and they would be maintaining skills needed for a smooth transition to the increase in R&D work expected after T_1. The difference between the dashed and dotted curve after they cross would be avoided "waste" due to the sudden ramp-up of work later in the period. Of course, whether the dotted or dashed line is ultimately less costly is an empirical matter. Much of this research investigates both (1) the cost penalty of a rise in work requirements and (2) the potential savings of appropriate policies during the down times.

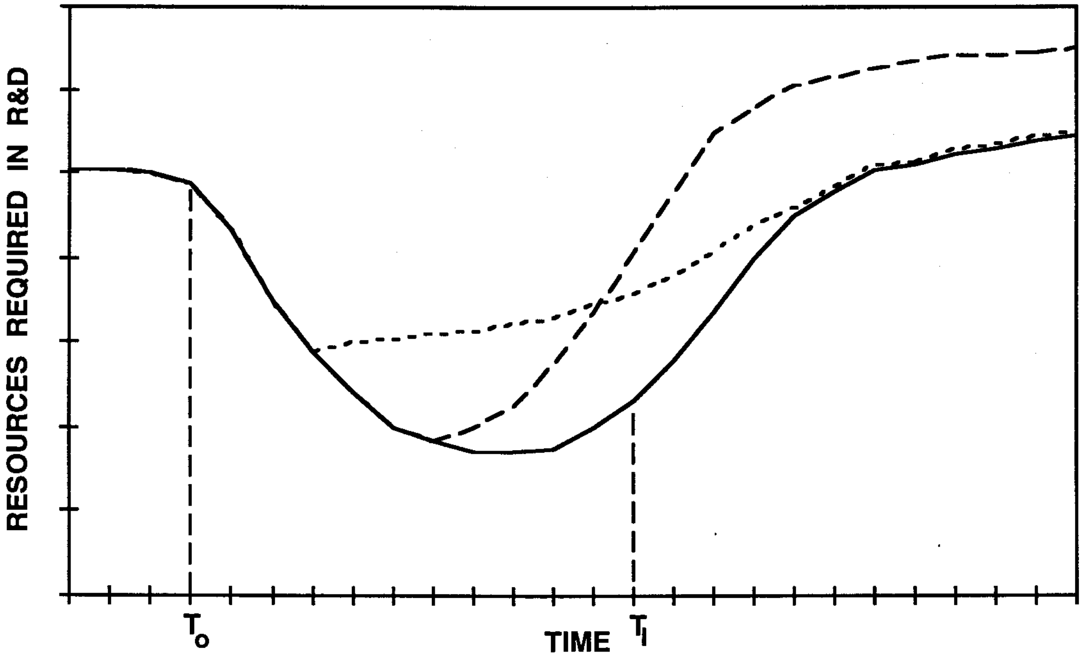

Fig. 2.2.C-A Policy Solution: Maintaining R&D Resources Early in the Fall Can Save Resources later. The Dotted Line Represents Resource Use Under this Policy. (R&D carried out is the same as with dashed line resource use.)

A completely separate potential problem is what we call the "scale" problem. It is well known that in many kinds of economic activity there is a "minimum efficient scale," or a level of production below which average costs rise. As a result of the military requirements process characterized above, the required level of work may be too low to exploit all the economies of scale, and unit costs may rise as a result. This phenomenon is most easily seen in production today; as budgets fall many aircraft are being produced at very low levels relative to planned levels and unit costs are higher as a result.

Scale effects in military R&D can occur in two important ways. First, some level of competition is desirable. However, the requirements for work may make this difficult as the following examples illustrate. In a world in which several projects occur simultaneously, several companies may exist. These companies can be expected to compete to win the projects. This competition should lead to efficiency as each company tries to lower costs to make more attractive bids. However, in a world of reduced arms races, there may be a new, lower R&D requirement, which makes it more difficult to maintain competition. In the extreme, say only one project is performed at a time. The seemingly best policy might be to have a de facto monopoly that does each project sequentially. However, this may lead to monopoly inefficiencies causing the cost of this project to be higher than the average cost of similar projects completed in a competitive environment. This is an example of scale economies, and thus of the "scale problem." Whether the answer is (1) to simply suffer monopoly inefficiency, or (2) to maintain competition and suffer the cost of maintaining the other competitor during the times it has not won a project, is a matter for analysis. At any rate, this example shows how unit costs can rise as the level of R&D work falls.

Another potential R&D scale problem is due to specialization. In a world of abundant activity, development teams may be able to specialize, e.g.. develop fighters or bombers. In a world of reduced requirements, one team may have to be prepared to develop a wider range of aircraft. This may lead to some inefficiencies as engineers find their experience diluted. They may find a need to learn or re-learn certain aspects of particular aircraft development as they move between types of aircraft. However, the magnitude of this effect is uncertain at the present and it may be possible that some diversity of experience is beneficial.

We are pursuing empirical estimates of the magnitude of both the hiatus and scale problems. Our results to date are in the next chapters.

III. APPROACHES TO ANALYZING R&D CAPABILITY

This chapter begins with our conceptual approach to analyzing industrial capability necessary to effectively perform R&D, its determinants, and how U.S. Air Force and other government agencies' policies affect it. Then we discuss some empirical insights into these issues resulting from our company interviews. We are still discussing many of these issues with the companies while we do comparative analyses of their responses. Therefore, this section should be considered preliminary as interaction with the companies continues. Finally, we describe the analytic tool developed for quantitative assessments of industrial viability issues. The ultimate users of this tool, U.S. government decision makers, will have to add data from their own sources to get maximum utility out of it.

I. CONCEPTUAL APPROACH TO THE ISSUES

This section describes the analytic framework within which we assess industrial R&D capability and the various policies that affect it.

Industrial capability defined

We begin with a definition of "industrial capability to perform R&D." Intuitively it is clear that some groups, companies, or countries are better at performing military aeronautical R&D than others. Our working definition is the following: R&D capability resides in *development teams*, which are operationally associated with divisions of companies. Each team's capability is defined in terms of the cost and time required to carry out specific development projects.

To clarify this point begin with a reference project, the Next Generation Attack Fighter (NGAF) and hold the technical characteristics constant. Each potential *development team* will have a R&D cost profile to complete the project. A typical R&D cost profile, based on the company interview data, is shown in Figure 3.1. It begins with some period of fairly low spending, generally associated with a demonstration-validation phase. Then spending ramps up to about four times earlier levels, eventually tapering off to a relatively low level after production is well under way. Initial operational capability (IOC) is marked at a typical point, well after the spending peak but before all development spending is complete. A second R&D cost profile, associated with a less capable team, is overlaid on the first in Figure 3.2. It takes longer to complete the development project and incurs higher cost as well.

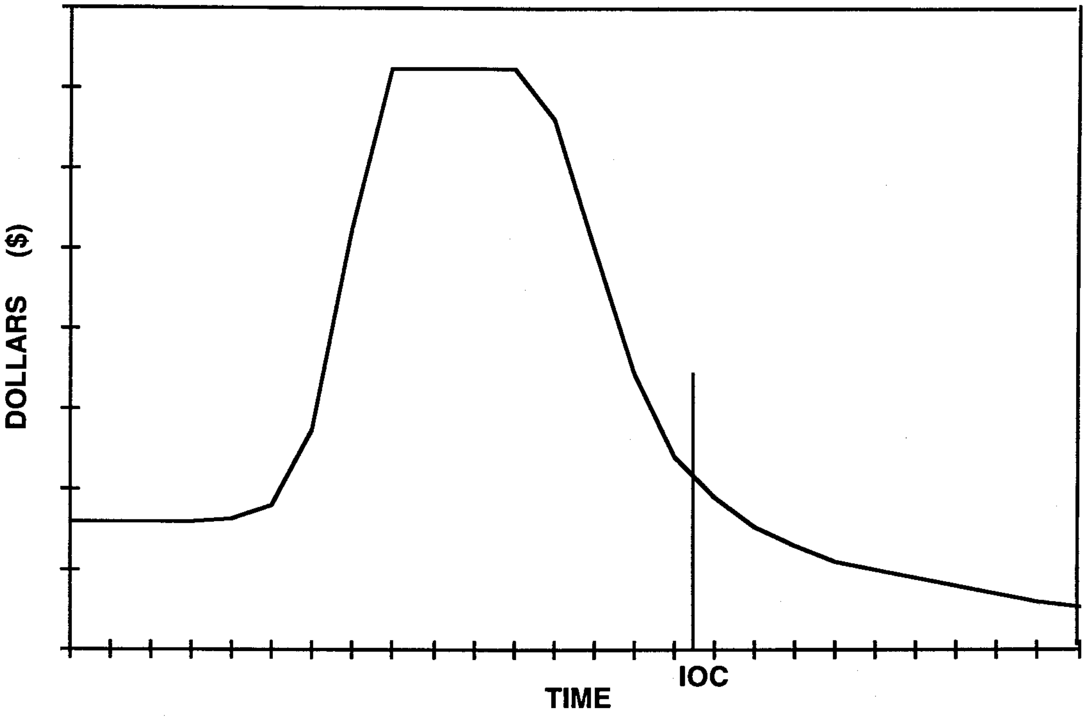

Fig. 3.1-Illustrative Development Project Cost Time Line

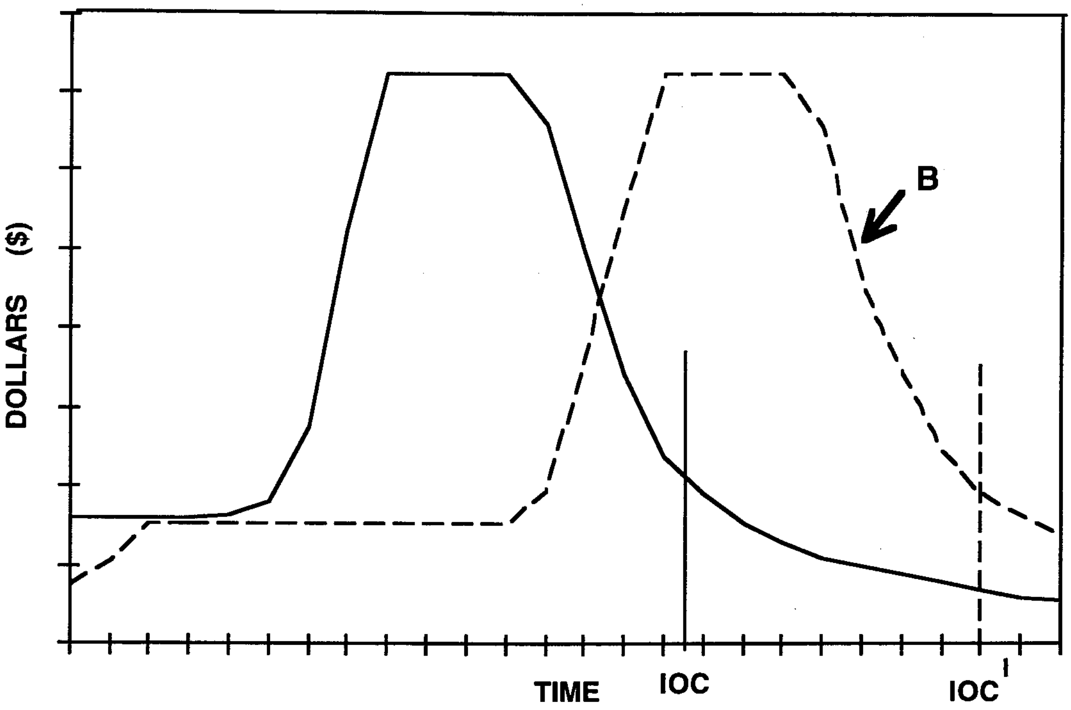

Fig. 3.2-Two Development Cost Time Lines. Line B Represents Lower Capability.

This quite simple idea captures our characterization of R&D capability. That is, a team is more capable if it can complete a given project more quickly or with less resources, or both. The shapes of the possible R&D profiles are bound by best case and worst case scenarios. The best possible outcome would be a team that could complete a project in no time at no cost, obviously a silly postulate, but a natural limiting definition of "best possible" capability. Recall that in this definition technical quality is fixed; what if a team simply cannot do the project? That would be represented by a cost profile that continues forever with no IOC -- an infinite time and cost.[5]

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[5] In reality, if any team can complete a project, one would probably assume that all teams could with sufficient time and money. At the worst case, they could hire the first team to show them how

Several complicating issues regarding project-R&D profiles, R&D uncertainty, and cost-schedule trade-offs arise with this conceptualization. First, at any given time, there can be many different candidate R&D projects. Some teams may be better at some projects than others. The overall capability of a team is simply the *collection* of R&D cost profiles associated with all potential projects. Since we cannot enumerate *all* potential project-team R&D profiles at any time, we will technically not be able to wholly characterize the overall development capability of any team, or the industry as a whole. However, in practical terms, the ability to analyze the several of the most important and relevant projects at any given time makes this definition workable. We can usefully think about an industry that would be relatively good or bad, in terms of schedule and total cost, at developing an NGAF. Similarly we can assess what would cause individual teams to be good or bad in these terms. The same is true for other important potential military aeronautical development projects.

Another issue is our implicit assumption that capability is unidimensional; i.e., a team with a worse schedule will also have a higher cost. We have also assumed that a team cannot trade-off between schedule and cost. In other words, it does not have a choice between two R&D cost profiles of the sort shown in Figure 3.3 when planning a development program. In that diagram, profile "A" can achieve an earlier IOC but at higher cost. In our analysis, we will generally hold to these two simplifying assumptions. Most industry people interviewed said that there was limited ability to buy time with money. Indeed, most said that stretching a program generally made it cost more because certain fixed factors (management, facilities, other overhead) had to be employed over a longer period of time.[6]

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[6] It may be useful in future work to extend these assumptions of capability beyond its current unidimensional characterization.

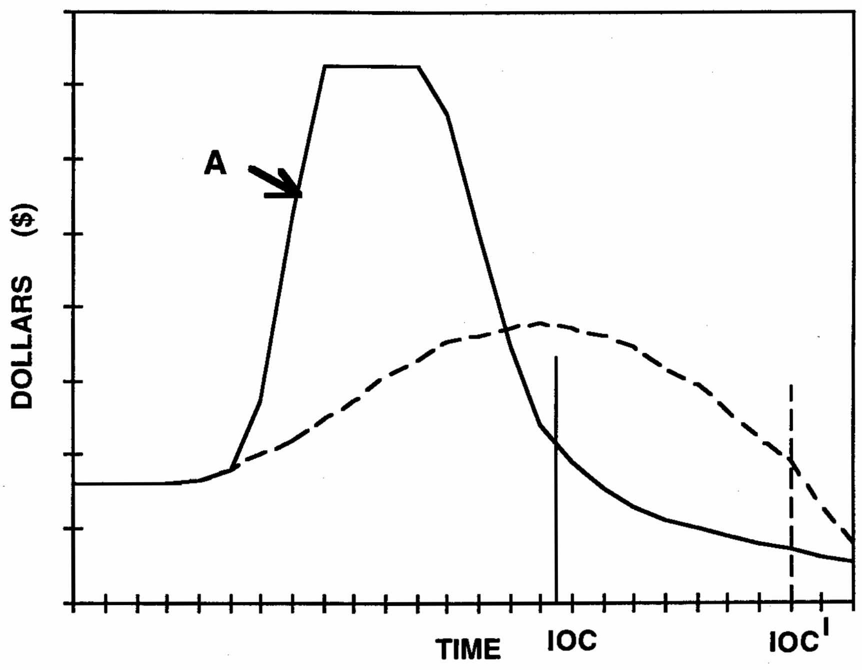

Fig. 3.3-Two Development Cost Time Lines. Line A Shows Higher Cost and Earlier IOC

Characterizing development capability in terms of the cost and time required to develop a system of fixed technical performance is at odds with one of the primary aspects of R&D. That is, R&D outcomes are highly uncertain. In reality, an R&D program generates a product with technical characteristics (speed, range-payload, observability, ...) that cannot be truly known until the program is complete. Therefore, part of the resulting product's quality can be attributed to the the team's capability, but part can also be due to the underlying characteristics of nature (unknown before the project was undertaken), and part to simple luck. In a nutshell, when an R&D project has disappointing results, we can never be *certain* whether it was because the problem was too hard, or the team was not very good. Equivalently, when a development project has spectacular success, we can never be exactly sure whether it was because the problem was easier than we thought, or because the development team was better than we thought.

For this analysis, we will formally resolve this problem by substituting "*expected* technical performance" for "technical performance". This adds another dimension of unobservability to the issue. Knowing that it is reality that adds this complication, we believe the concept is still useful for policy analysis.

In summary, for any development team, capability is defined by the time and cost required to complete specific development projects. In practice, we will consider the most important development projects at any given time. These include development of new aircraft, and major upgrades; as well as development of avionics, propulsion systems, subsystems, and weapons for the relevant companies.

Determinants of industrial capability

What determines whether a team is more or less capable? At any point in time a design team will be composed of a given number of technical personnel, appropriate facilities within which to construct test articles and perform tests, and support staff. In addition, the team will have a business infrastructure associated with it. Moreover, the design team will have a science and technology base to draw upon. This base will be partially embodied in the minds of the technical personnel, and partially accessible through documentary means. Some of these may be public and some proprietary to the specific organization. Finally, the team will have both individually and collectively an experience base. This base is the collection of military aeronautical (or related) development projects performed in the past. Finally, a team may have to bring on new members with varying degrees of experience for large projects. We are considering how all of the above factors: size, facilities, S&T base, individual and collective experience, affect capability.

There is a distinction between "scientists, engineers, and technical managers" on a team and support personnel. We will often use the shorthand term "technical employment" for the first group. As a practical matter, we often use the category "degreed engineers and scientists"[7] for this category since many companies keep records this way. We define teams by the number of technical employees and adjust our cost per technical employee to account for support personnel. Support personnel include financial, accounting, legal, clerical and administrative, security, and so on. We have not investigated whether varying the ratio of support to technical personnel is an important phenomenon.

In our conceptual model, a team's development capability depends on three factors: facilities available, science and technology base available, and experience level. As our questionnaire indicates, we elicited from the companies interviewed their judgment on how each of these factors affected their ability to complete both historical projects and prospective future projects. In the next section those judgments are synthesized, along with historical evidence collected from the literature, to assess how future levels of these three factors will affect development capability: the cost and time required to complete future development projects.

First, we complete our conceptual model of the overall relation of R&D policies, programs, and budgets to R&D capability. In any given time period (say Period 1), development teams will have some level of capability. Also in Period 1, there will be an overall military aeronautical R&D budget level that will be distributed among the existing teams (or possibly to new ones). Given the teams' capability and the distribution of the resources, this will lead to a certain number of development projects being performed. Furthermore, it will lead to a certain amount of experience accrual, facility development, and S&T work. This in turn, will generate a new level of team capability in Period 2 and the cycle continues. Due to the accumulation of experience, relatively high levels of R&D in any given period result in relatively high capability levels later, and vice versa.

The basic premise of our analysis is that history matters. In other words, today's activities will influence the future capability of

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[7] A limited number of production workers who specialize in building test articles and prototypes are included as well. Many indicated that they are highly skilled artisans.

industry. The experience of scientists and engineers is one measure of a design team's quality and is perhaps the best measure. Important advancements in information technology, education and training, and business organization may mitigate the detrimental effects reduced experience has on team capability. A few companies interviewed indicated that they are attempting to compensate for inexperience through better documentation of lessons learned. Because of reduced workload, some are cross-training individuals so they become generalists rather than specialists. This will give the engineers a broader base from which to gain experience. Recent advances in simulation and modeling techniques have reduced the number of test articles that have to be produced. These analytic tools have reduced the need for trial-and-error by synthesizing the knowledge of many experts. However, there is probably a limit to the substitution for experience. Movements in the technical frontier may require new analytic techniques, for example the analytical tools for advanced material systems had to be developed when advanced composites began to be incorporated into aircraft structure. These changes may reduce the number of engineers required for EMD, since they perform alot of the number crunching and calculating but may not help conceptual designers, who rely much more on their experience to formulate a concept for a new airplane. The historical analyses accompanying this report will assess the role of experience in successful aircraft design.

The third section of this chapter will describe an analytic tool that traces the path of capability over time as a function of R&D spending levels. The tool can evaluate alternate R&D paths in terms of future capabilities. But first we turn to the information gathered in our company visits.

II. INITIAL RESULTS FROM COMPANY INTERVIEWS

We are using the results of our company interviews to characterize the impact of size, experience, facility availability, and S&T base on R&D capability. As our questionnaire shows, companies were asked to describe both historical and prospective future R&D projects and estimate how each of the above factors affects their ability to perform these projects. The historical programs discussed are identified in Table 3.1.

Table 3.1

Historical Programs

COMPANY	HISTORICAL PROGRAM
Allied Signal	F-22 ECS, T-800 Engine, F-16 EPU, V-22 IR Suppressor
Allison	T406-AD-400 Engine (V-22)
Boeing	A-6 rewing, B-1B offensive avionics
CAE-Link	B-2 Simulator
General Electric	YF120, F-110-GE-100
Hughes	APG-73
Lockheed, FW	F-16
Lockheed, GA	F-22
Martin Marietta	LANTIRN
McDonnell Douglas	AFX, ATF, F-18E/F, F-15
Northrop Grumman, CA	B-2
Pratt and Whitney	F-119 Engine (F-22)
Raytheon	Patriot Missile
Rockwell	B-1B
Texas Instruments	LANTIRN Navigation Pod
Textron	Sensor Fuzed Weapon
Tracor	AN/ALE-47 Countermeasures Dispensing System
TRW	F-22 CNI
Vought	B-2

Scale issues: maintaining capability

We begin by exploring the low extremes of possible experience levels. We asked each company to characterize, in terms of technical employment, the minimum size team that must be continuously doing development work (i.e., acquiring experience) in order for it to maintain its current development capability.

The average figure given by airframe companies was around 1,000. Most answers were near 1,000, but there were both high (around 2,000) and low (around 500) outliers. Since this is a judgmental question, we are not too surprised at the distribution. We are pursuing additional explanations for these differences now. An interesting generalization is that this minimum team is close to size required to complete a demonstration-validation type project, so that continuous employment on a series of demonstration-validation projects would maintain development capability.

Avionics, propulsion, and other companies also responded. The average for avionics companies was around 500 while the average for the sum of propulsion plus a full set of subsystem companies was also about 500. The variation around these rough averages was comparable to the airframe companies. Most answers were near the average with outliers going from about half to about twice the average. Note, that with only nineteen companies total, we are obviously into rather low sample sizes.

In summary, to maintain one minimum size team for each sector of the military aircraft business, approximately 2,000 technical personnel would have to be employed. The total cost of maintaining one technical employee is estimated at about $250,000 per year.[8] This includes the salary and benefits of the employee, plus an allowance for facility construction and maintenance, fabrication of prototype and test articles, all associated overhead personnel, and profit. In other words, it is the complete cost to the government for maintaining the team per team member. This number was relatively constant across company types. (The total number of employees on a team, including the technical personnel AND all the other associated workers, including test article production workers, was estimated at about twice the number of technical workers. That is, all other workers were about the same number as "scientists, engineers, and technical managers.")

Thus, the total cost of maintaining one full team (including one airframe team, and one avionics, propulsion, and set of subsystem teams) is about $500 million per year. Two important caveats must be noted. One, this team would not be capable of completing a full new system EMD. This is simply the team that maintains the capability to expand into a full EMD team. As stated above, it is best thought of as a prototype or demonstration-validation team. A full EMD team is about four times the size of this "minimum capability" team. (We will refer to the "minimum-size team" as a "core team" in the rest of the paper.) Second, there is

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[8] As we refine the numbers this factor may increase for EMD because of the additional material and manufacturing costs for prototypes.

no allowance for competition. Depending on the number of competitors one wants to maintain, this number would have to be multiplied up. Of course, one may want to have different competitive levels in different market sectors. This issue will be discussed in more detail in Chapter 4.

The consequences of a hiatus

The consequences of not maintaining continuous minimum experience levels and of reconstituting such a team were also postulated. The premise of this question is: the company would continue to exist with its expected production and sustainment programs but new development work would stop.[9] Of course, this would not be comparable to new system development. This reconstitution question was meant to represent a "worst case" scenario of R&D experience loss.

What would happen if the company were asked to begin a new development project (basically a new system) ten years after all new development had been stopped? Generally, the first response was that the company would no longer be competitive with the other companies that had been continuing development activities, so it would lose in any proposal process. The question was then modified. In this case the company is given the new project. In other words, one might interpret the question as assuming that all companies had stopped new development and were therefore similarly handicapped in any proposal process. The question then becomes what are the consequences of the no-development period for the company's ability to complete the project. The consequences of this hiatus would possibly affect a program's schedule, cost and performance.

The companies focused on program schedule when responding. Responses turned out to be much like the two R&D cost-profiles in Figure 3.2. The solid line represents the costs incurred by a team that had maintained its minimum or core size (thus its capability); while the dashed line represents the costs incurred by a reconstituted team. The

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[9] The gray area between sustaining engineering and minor modification R&D means that even in this case there may be some development-like work going on.

reconstituted team would basically take longer in the program's pre-EMD phase. The extra time would be to identify and hire technical personnel (either experienced or not); for these new hires to learn or relearn system development techniques; and for them to acquire or reacquire experience through some trial and error episodes. The extra time in a pre-EMD phase was estimated to be between five and ten years. As a result, the new system's IOC would be delayed by that many years. If a nominal major program is now about 13 years from beginning of demonstration-validation to IOC, (about 5 for demonstration-validation and 8 for EMD), that would extend to about 20 or 21 years.[10]

If a minimum size, or core team, was continuously employed performing dem-val programs rather than enduring a period of no development, the effect of the schedule penalty described above could be reduced. In a no development situation, 20-21 years are needed from program start to IOC. However, if a dem-val was being performed with this core team, a new system EMD could be completed in another 8 years. During those years (whether it is 20-21 or 8) the US is vulnerable to surprize breakthroughs in military capability by potential enemies. This penalty should primarily be thought of as a national security penalty, since it would make the U.S. vulnerable. This is because it would take us a long time to respond. If the intelligence lead time for breakthrough developments is between eight and twenty years, maintaining the teams would be the difference between meeting or failing to meet the new threat.

What would be the *technical performance* consequences of a hiatus in development activity? Specifically, let us consider the technical performance of a new fighter-attack aircraft under two possible scenarios. One is that demonstration-validation begins about 1997, it takes 13 years for dem-val and EMD so that IOC occurs around 2010. The second is that new development activity stops for ten years, and then a new development program begins in 2005. As argued above, in this case

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[10] For simplicity, we are equating IOC with the end of EMD. In reality, as Figures 3.1 and 3.2 show, EMD falls off before IOC, during initial production and operational conversion training. EMD continues beyond IOC as operational experience is acquired. We are using this convention simply as shorthand.

IOC would be about 20 years after program start -- 2025 - to account for the time lag required to reconstitute development teams. How would the technical performance of the aircraft developed by 2025 (call this aircraft F2) compare to the technical performance of the 2010 aircraft (aircraft F1) developed without the hiatus?

One might argue that F2 would be inferior to F1 because the inexperienced development team designing F2 would essentially have "forgotten" some of today's state-of-the-art. This is particularly valid since much of this state-of-the-art is embodied in the minds of experienced aircraft developers. As a result it would not have been passed down to others during the hiatus and would have to be relearned through the difficult trial and error process. To the extent the state-of-the-art can be (and would have been) documented, this is less important. On the other hand, there would have been advances in commercial technology during the hiatus that may contribute to a better F2 (spin-on). Advances in electronics power and miniaturization, materials technology, commercial aircraft all are possible examples. However, so much military technology is unique one should not expect too much from potential spin-on. The consensus from our interviews was that these two influences would roughly offset each other. Therefore, the military aircraft developed by 2025 (F2) would have about the same technical performance as the aircraft developed by 2010 (F1). A few respondants felt that the same technical performance could be achieved for F2, but because of the many unknowns associated with the hiatus they felt that the expected performance would have greater uncertainty. Thus, the technical penalty to a first approximation would simply be the time lag and larger uncertainty bands.

So far we have been considering the consequences of drastic reductions in military aeronautical R&D; namely, going to essentially a zero level of new development and then reconstituting. This generates an extreme point for assessing the role of experience: If we stop accumulating experience today and try to resume in about ten years, it will take between five and ten years to simply get back to where we are today.

There is a second potential problem that could lead to loss of development capability with future development programs. Even if a reasonable number of core teams are maintained, they do not in themselves have the capability to perform an EMD. They are simply the base from which an EMD team is built, as shown in Figure 3.1. The EMD team is about four times the size of the core team or about 8,000 engineers.[11] We have been implicitly assuming that the additional 6,000 engineers are available to be hired whenever an EMD begins. Whether this is true depends on the timing of EMDs. It could be that even if core teams are maintained, program timing may lead to waves of layoffs and recalls as EMD programs ebb and flow. This will lead to some productivity penalties as EMD engineers must be found and hired. There are quantitative and qualitative aspects to the penalties.

Quantitatively, there are hiring and training costs, which can be of two types. One is the routine cost of hiring (or rehiring) and training a worker, perhaps an additional one or two year's pay depending on the training required. The second is the salary premium that the industry would have to pay for the uneven timing of the work. That is, if an engineer knows that EMD programs, hence their jobs, are likely to end in five or ten years, they will only join such a program if offered additional pay over jobs with steadier outlooks. The premium's size will depend on the overall market strength and the intrinsic appeal of the military EMD work. A penalty in the 20% range is not unreasonable.

The qualitative penalty is similar to the second quantitative penalty. The "best and brightest" engineers may be unwilling to work in such a cyclical industry. This leaves the less qualified engineers to move between industries as demands change. We know of no attempts to measure this phenomenon for military aeronautical R&D. However, much anecdotal evidence of high quality personnel leaving the industry exists because pessimism about future prospects.

Would there be a schedule delay if EMD engineers had to be hired from other industries? If it were known at the beginning of demonstration-validation that EMD would definitely occur there would not

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[11] The F-22 project, larger than average, currently employs about 10,000 engineers.

likely be a delay. In this case, planning for EMD hiring in about four years (one to train new workers) could be done. Although the cost penalties for rehiring and training, identified above, would occur. If hiring did not occur until EMD was about to begin, one would expect about a two year delay as engineers are found, recruited, hired, and trained.

Thus, our interviews identified two important ways that R&D capability in the future could be negatively affected by lack of experience. The first, and most drastic, is if development work stops and even core teams are not maintained. This would cause an estimated five to ten year delay for R&D capability to return to the present level, from the time work begins again. This is a very large national security penalty in an uncertain world.

The second is that lumpy timing of EMD programs could cause the industry's engineering employment levels to be unstable, even if core teams are continuously maintained. This would have cost penalties and would very likely lower the average quality of personnel.

We are continuing our interactive research with industry to refine our estimates of the above phenomena. Additionally, we have gathered extensive information from individual companies about how experience affected the outcomes of specific projects. Subsequent reports will detail these areas. Finally, we are doing an overall historical analysis of the role of experience in military aircraft development from 1945 to the present, which is described in a companion report entitled, "The Role of Experience in U.S. Combat Aircraft Development Since WWII."

III. A TOOL FOR ANALYZING INDUSTRIAL R&D CAPABILITY

The conceptual framework and associated observations presented in earlier sections can lead to improved insight into the issues. In order to more specifically assess the impact of alternate future R&D programs on future capability an analytic tool is necessary. This section describes the model being developed.

The purpose of this model is to take budgets and future programs and assess industry's capability to perform the programs as planned. Assuming a fixed top-line to the budget, the consequences of reduced capability on future programs is shown in terms of program delays and timing.

Inputs

Its input structure is fairly straightforward. Inputs are the future military aeronautical R&D program defined as a time path of projects and their budgeted dollars. Each project has an associated funding distribution by industry sector and company (or division, if appropriate) and a distribution into spending categories (technical employment, overhead personnel, prototype building and testing, facility building and maintenance, miscellaneous, profit/fee). These factors along with deflators are used to calculate each company or division's technical employment levels.

Mechanics

The experience level of each company/division is based on calculated technical employment and estimated factors for retirement, attrition, etc. Future layoffs or hiring by company/division or industry required to perform anticipated programs is also estimated. Finally, experience/capability ratings can be made to depend on the kind of development projects, as well as the level of funding. Based on this, one can identify specifically where experience levels are falling so low that capability is lost. Indeed, if experience levels fall below those specified as adequate, a company/division is assessed a cost and schedule penalty for completing projects.

The simultaneity of experience levels and R&D capability now comes into play. The calculations are performed as follows:

- Future postulated programs are prioritized.
- If there is too low a level of experience (due, say, to layoffs and rehiring because of EMD lumpiness) to complete programs at baseline cost and schedule (i.e., baseline development capability) programs will be stretched and cost increased.
- If so specified, lower priority programs will be delayed further to keep R&D budgets at original levels.

Therefore, using this model an analyst can explore the consequences of inadequate R&D capability on delaying the introduction of new systems and increasing overall R&D costs.

The model also allows a factor to be introduced for inadequacy of competition. (See the next section for a discussion of this.) Inadequate competition will also increase the cost of programs and cause program schedules to be stretched. In this way, the user can explore the trade-offs between maintaining fewer competitors, each with high experience but little pressure from potential rivals, and vice versa.

Some initial results from early model applications are described in the next chapter.

IV. INITIAL RESULTS AND OBSERVATIONS

Contains PPBS Information
Do Not Distribute Outside of DoD

This chapter presents two kinds of results from the analysis to date. The first is an examination of future military aeronautical R&D budgets, which give rise to a number of industrial base concerns. The second is a discussion of the role of competition in military aerospace R&D.

I. BUDGET ANALYSIS

The US government budgetary elements that fund aeronautical research and development are primarily found in the Air Force, Navy, ARPA, and NASA. The current Air Force aeronautical R&D FYDP is graphically displayed in Figure 4.1 using the aggregate budget categories defined earlier.[12] These categories, used to simplify the analysis, include "Overhead", "Technological Improvement", and "Incorporating Technology into Systems". They are defined in Tables 2.2 and 2.3. Because of its significance, the F-22 is identified separately in these figures. Thus, the category "Other EMD, Upgrades, JAST" includes the PEs in "Incorporating Technology into Systems" from Table 2.3, less the F-22.

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[12] A note on our budget data. Right now we are working with the 96 BES, modified in two elements in anticipation of the 96PB. These are removing PE 64242 (AX), and adding an NGAF EMD PE. These two changes have a net effect of adding $80 million to the 2001 budget total and no net effect in other years. We will update the analysis as soon as we get the 96 PB.

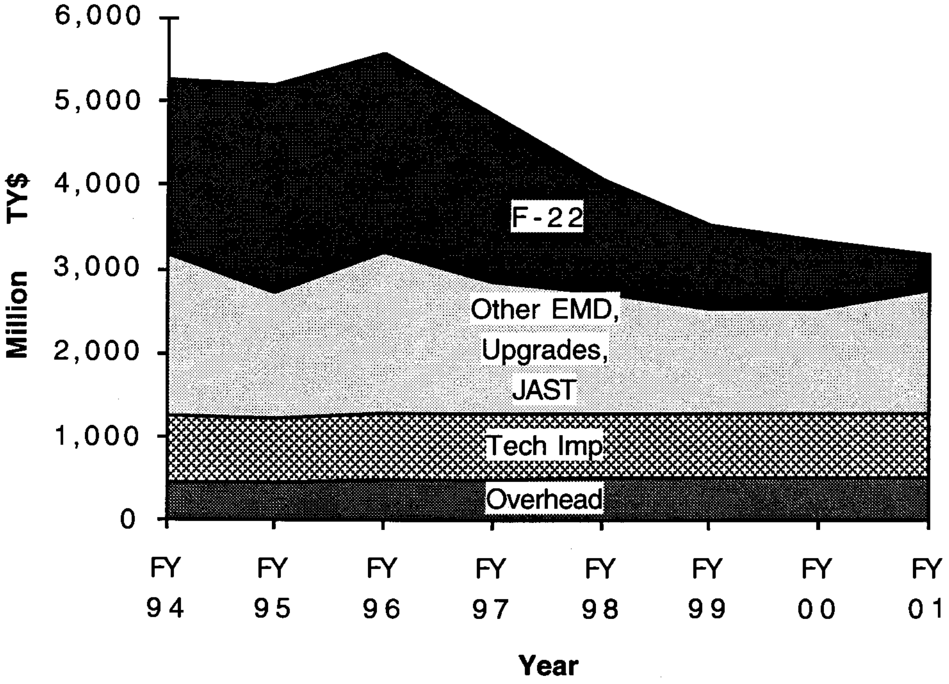

Fig. 4.1—USAF Aeronautical R&D Budget

As Figure 4.1 shows, overall spending in then year dollars will fall by roughly two billion dollars between 1995 and 2001. This reflects EMD completion for several systems: the F-22, B-2 and C-17. This decline is counterbalanced with only modest budget amounts for the next generation attack fighter (NGAF) and upgrades of existing systems.

Figure 4.2 shows technical employment in industry associated with this spending program. These numbers are derived from the analysis tool described in Chapter 3. They are derived by applying industrial-technical-employee-per-program-dollar factors for the various programs using the data collected at company interviews.[13] In addition, ASC estimates of each program's monetary distribution between performers,

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[13] Recall that "industrial technical employment" means "scientists, engineers, and technical managers". Aeronautical development team members, including airframe, avionics, propulsion, and other systems.

contractor and organic, were used. As illustrated in Figure 4.2, there is a dramatic decline in industrial technical employment supported by Air Force aeronautical R&D beginning in 1997. The decrease is from about 17,800 to about 7,200 personnel, a 60% decrease.[14]

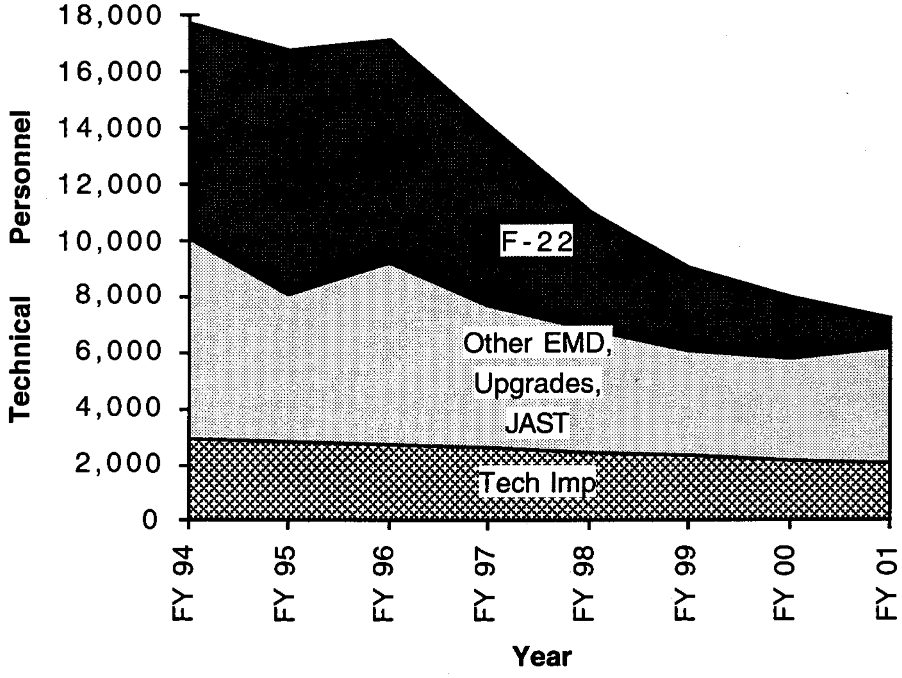

Fig. 4.2—USAF Aeronautical R&D Technical Employment

Figure 4.3 shows a similar estimate for technical employment supported by Navy aeronautical R&D. The pattern is comparable to the Air Force. Engineering employment falls about 63%, largely due to the decline of major EMD programs that are not offset elsewhere. In the

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[14] Engineering employment declines at a faster rate than the FYDP primarily because inflation has been removed. (We will use the terms "technical employment" and "engineering employment" synonomously. The former is formally more correct, but the connotation of the latter is appropriate, since most of the employees we are including are in fact engineers.

case of the Navy, there are two major programs shown in the figure: the F/A-18E/F, and the V-22.[15]

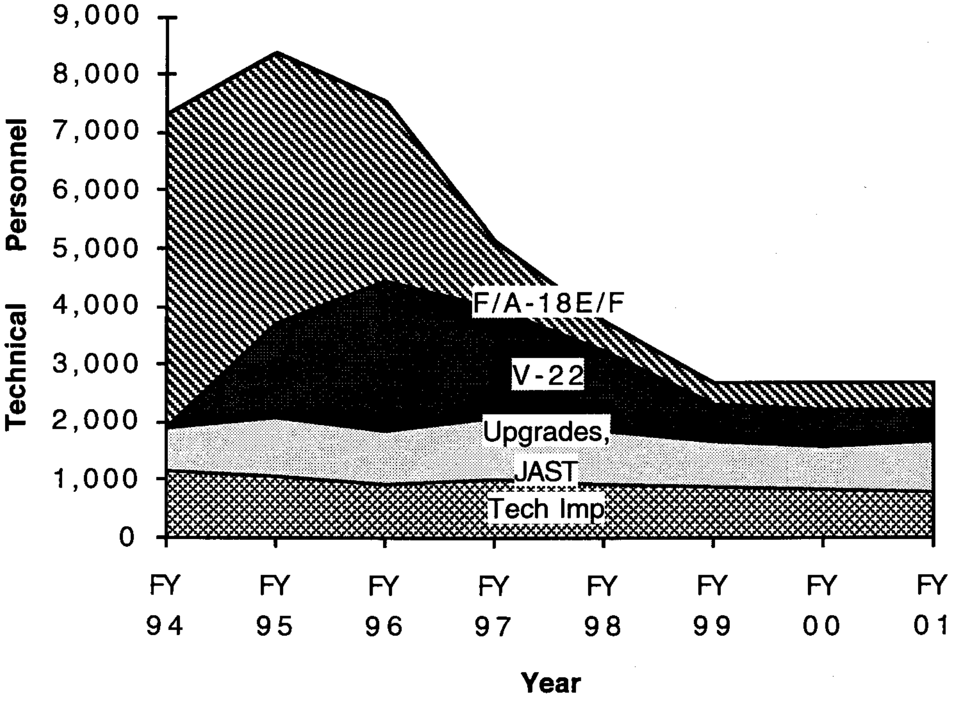

Fig. 4.3—USN Aeronautical R&D Technical Employment

An overall estimate of engineering employment associated with all U.S. military aeronautical R&D is presented in Figure 4.4. It includes the data in Figures 4.1 and 4.2 as well as estimates of NASA, ARPA, and production related IR&D/B&P. (These estimates are currently rather rough, and will be refined.) The three latter categories add about

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[15] For the Navy, we are using the 1994-1997 data from *Inside the Navy* 13 February 1995. F/A-18E/F 1998-2001 data is from the SAR, as is 1998-1999 V-22 data. V-22 spending in 2000 and 2001 is assumed to be equal to 1999 in then-year dollars. Technical employment for the Navy in 1998-2001 for the other categories is assumed to be in the same proportion to the Air Force's as it is in 1997. This last is the weakest assumption. We will update this with the Navy 96 PB when we obtain it.

5,000 engineers, and are projected to be roughly constant over the FYDP period. This is probably an optimistic assumption.

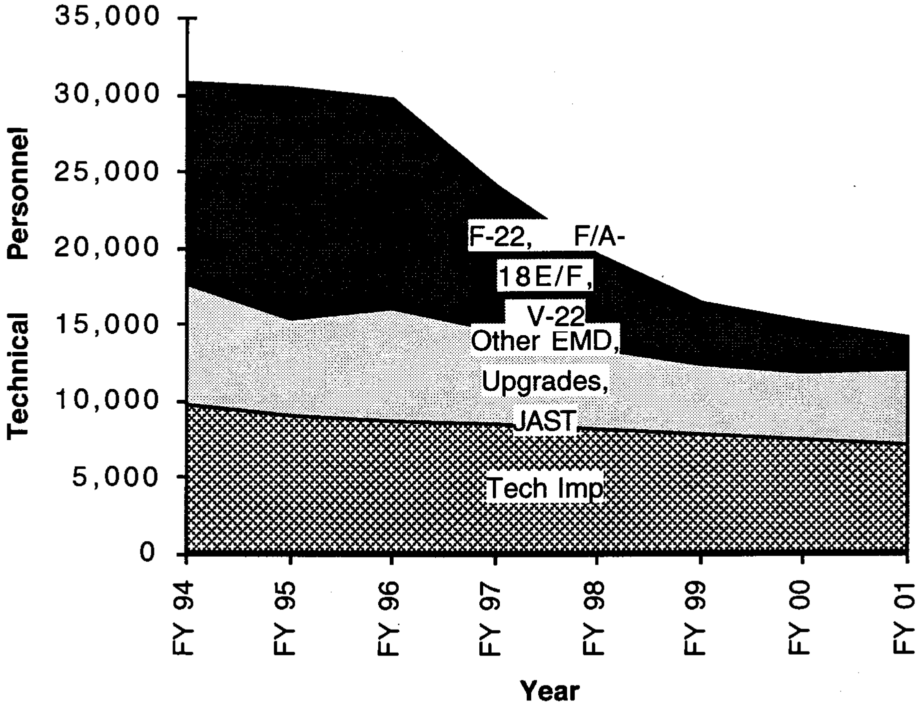

Fig. 4.4—Overall Aeronautical R&D Technical Employment

In summary, between 1995 and 2001 the number of engineers associated with military aeronautical R&D falls from about 31,800 to about 14,300, which is a 55% decrease. The number working on operational systems falls from about 21,000 to about 7,000, a 67% decrease. Thus, there will be a substantial decrease in the number of engineers working on military aeronautical R&D projects, which is the best measure of the size of the R&D industrial base.

Is this a problem? Figure 4.5 illustrates one way in which it might. It appends to Figure 4.4 a projection of technical employment requirements in military aeronautical R&D based on the following assumptions:

(1) "Technical Improvement" employment remains constant at 2001 levels. I.e, the level of effort devoted to increasing the potential technical capability of new systems stays at about 7,200 engineers and scientists per year.

(2) It is a fact that the "Other EMD, Upgrade" employment is essentially all upgrades by 1999 and employs about 4,500 engineers. This is projected to stay constant at this level over the period (2002-2015). This is most likely a very optimistic, or low, assessment of upgrade requirements, since the fleet will be aging dramatically.

(3) The engineering work force on the three major EMDs (F-22, F/A-18E/F, and V-22) will fall from about 15,000 to 2,100 by 2001. It is assumed that 2,100 engineers and scientists will be required for dem-val of three new notional systems that will begin full EMD by the year 2010. At that time, required employment will be around 11,000 engineers and scientists. These are notional systems and represent a tactical airlifter, a medium bomber, and an electronic warfare aircraft. (This is a relatively low number for these kinds of programs, so is optimistic.) Employment for these three new systems stays constant at about 2,100 through 2007, when EMD begins.

(4) The Next Generation Attack Fighter (NGAF) is developed with an IOC of 2010 (years 2000 and 2001 funding is in the FYDP now). Its total EMD cost is equivalent to the F-22 ($15.8 billion in dollars of 1995 purchasing power).

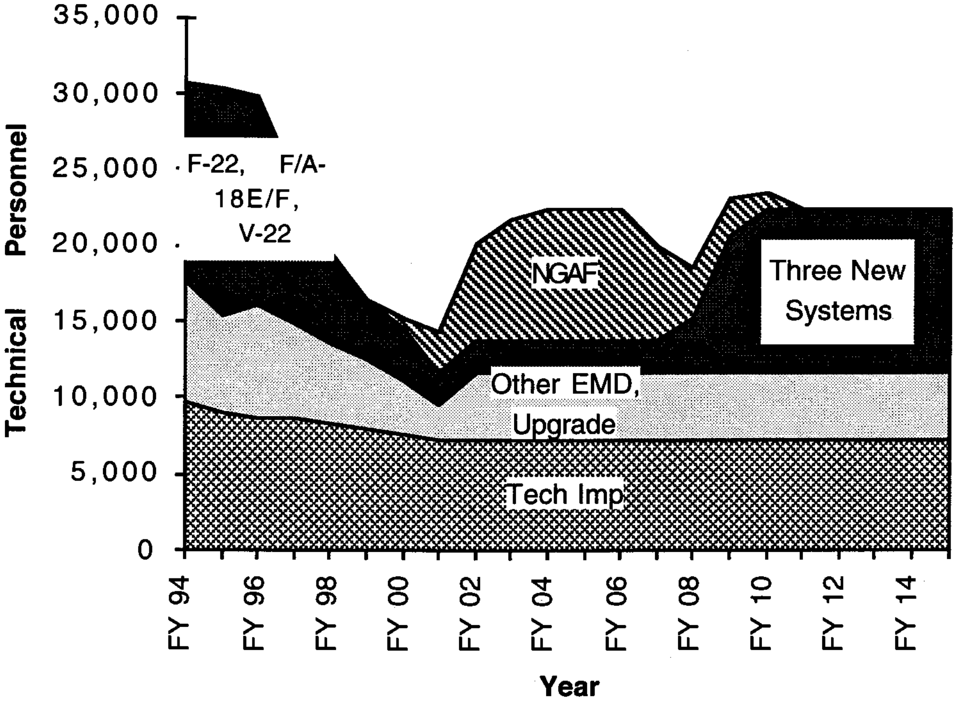

Fig. 4.5—Aeronautical R&D Employment Projections

The employment picture shown in Figure 4.5 results from these assumptions. A large increase in engineering employment is required, from minimum levels of 14,300 in 2000-2001 to 22,400 by 2005. Given our assumptions on program timing, a similar decline and regrowth will occur between 2006 and 2010.

The first hiatus in employment is a serious problem that should be addressed now by military aeronautical R&D authorities. If our assumptions are correct, a large number of engineering personnel (approximately 8,000) will be laid off starting in 1997 but will have to be recalled in 2002-2004. This will lead to the problems associated with uneven timing of EMD programs: hiring and retraining costs, possible schedule slips, and possible difficulty attracting high quality personnel (identified in Chapter 3 of this report).

Sensitivity analysis

The following discussion addresses possible alternatives to the assumptions made for the analysis presented above. These alternative assumptions may reduce the overall number of engineers recalled after a hiatus.

(1) NGAF EMD may be less than F-22 EMD costs. By assuming equivalent EMD costs, in effect this assumes substantial avionics suite and engine development. To the extent existing equipment is used (holding other costs constant), there will be a decrease in engineering personnel recalled -- primarily at electronics and propulsion companies. However, the proportionate recall at airframe companies would be the same in either case.

It is also possible that the NGAF will be less costly to develop particularly since affordability is an important element of the program. However, based on our industry discussions, it is possible that R&D cost will not be significantly lower than the F-22 and may even be higher, as developers strive for the lowest possible production costs. Emerging evidence on new business practices indicates that modern development methods are in fact more expensive than older ones, with the payoff coming in lower production costs. Even at relatively low production runs, these higher development costs are economically justified.

(2) Another possibility is to substitute other engineering workforces for the EMD workforce. In particular, the EMD workforce could be augmented with the "Technical Improvement" work force. There are two potential problems with this. First, the technical personnel who perform "Technical Improvement" kind of work tend not to be the same kind of personnel who perform EMD. They also tend to be more senior and more expensive. If NGAF EMD were financed by cutting "Technical Improvement" it would likely still be necessary to rehire many engineers laid off from the F-22, F/A-18E/F, and V-

22 programs. They would simply be paid for by laying off scientists and engineers currently in "Technical Improvement." Thus the EMD-hiatus-rehiring problem is not necessarily solved. The other problem with this solution is that the national security consequences of cutting "Technical Improvement" work may be very undesirable. Particularly in light of the fact that this work enables the U.S. to stay on the cutting edge of technology and makes it possible to develop new aircraft with very high effectiveness.

(3) Cutting other system development is not likely to be a solution, since, as noted above, the Upgrade budget in this analysis is very modest for the aging force expected in 2000-2010.

(4) NGAF IOC could be delayed. However, there are limits to this possibility because the aircraft it is replacing are reaching the end of their service lives.

(5) NGAF EMD could be begun earlier, and performed at a lower rate. This may be a solution. It would save money in the long run because it would not require rehiring and retraining costs. Moreover, it would probably lead to retention of higher quality personnel for the project. Finally, it would alleviate the rather tight schedule needed to achieve IOC in 2010 given that substantial spending does not begin until 2001 in the current plan.

We are proceeding with additional analyses of potentially mitigating factors for the hiatus issue. Among important issues to be considered are the role of production and sustaining engineering in maintaining the development industrial base, and how military aeronautical R&D hiring and spending fits in with civilian counterparts, especially commercial airlines. The production factors actually probably exacerbate the situation as production lines close down. Sustainment could be a help to the extent that work is done in the private sector.

The hiatus shown in Figure 4.5 for the 2006-2010 period should not be viewed as a forecast with any great point accuracy. However, the dem-val and EMD time scales for the "three new systems" are not unreasonable. The interesting point of this hiatus is that it illustrates how employment cycles can easily occur if planning processes do not explicitly control for them.

Indeed, that is a reason for the potentially very difficult employment cycle we are facing as NGAF winds up. Although the rehiring of 8,000 or so engineers on a base of 14,000 is not what we would consider "non-viable," it is certainly not easy, and introduces substantial risk that the hiring will not be smooth, leading to delays in NGAF IOC anyway.

This leads us to consider an alternate approach to military aeronautical R&D planning. Avoiding drastic increases and decreases in technical engineering employment is a worthy independent goal in this sector because of the potential cost, schedule or quality-of-personnel penalties. However, as this analysis illustrates, planning solely within the FYDP horizon is insufficient given military aeronautical research and development time lines. Therefore, longer term planning is warranted. It could easily lead to a conclusion that NGAF EMD be begun earlier and at a lower overall pace. There is a potential budgetary problem with this, due to year-to-year budget constraints. That is, even though an earlier NGAF EMD program would save money in the long run, by avoiding rehiring and retraining costs, it would move budget authority earlier in time and violate some annual ceilings. (The fact that earlier expenditure has a real cost in terms of the time value of money is already included in our assessment that an earlier program would save money.) Creative solutions can be found for this, such as long-term contracts, but they would require some changes in current acquisition procedures.

In summary, our budget analysis shows an industrial base problem in military aeronautical R&D. The current program appears to require firing and then rehiring of about 8,000 technical personnel between 1998 and 2005. This is an inherently wasteful procedure. A much better spending program that both saves money and lowers risk on the NGAF can be devised, moving the NGAF earlier in time without changing total program cost.

Overall, military aeronautical R&D planning should be performed in a long-term fashion, with a view to the essential part of the associated industrial base: skilled engineering personnel. Plans should be made to avoid wasteful and risky disruptions in their employment. The appropriate way to do this would be to assess long-term requirements for improved military aeronautical technology (both technical base and systems) and then plan programs to stabilize (within reason) employment in the industry. Subsequent reports from this project will expand on this proposal.

II. COMPETITION IN MILITARY AERONAUTICAL R&D

In the last section, we argued that long term planning in military aeronautical R&D should have reasonably stable employment as a goal. This did not address the scale issue: what employment level should be stabilized. In Section 2 of Chapter 2, we outlined a procedure for determining the appropriate rate of advance in military aeronautical technology. We then argued that one should work backwards from that through an assessment of productivity in the sector, to determine the appropriate input level (i.e., employment). This section addresses one part of that process: what is the appropriate level of competition in military aeronautical R&D?

First let us ask, what is wrong with monopoly in this sector? After all, the companies are fully audited on all their government contracts so that they can only be reimbursed for legitimate costs of performing system R&D. Since a monopoly supplier can not pocket any excess revenue (unlike a firm in the commercial market), what is the role of competition? Intuitively, we all know the problem: a monopolist does not have the incentive (fear) of potential loss of business to spur it to maximum performance. With a guaranteed market, there are no economic incentives to do other than a satisfactory status quo job. Departures from the status quo, which always entail cost and risk, have no reward to a monopolist, who already has the market and has nothing to gain from improved performance.

For this reason, one wants competition. Is two competitors a reasonable outcome? If each competitor knows that the customer (in this case the government) wants two competitors, it may not. This situation may become a de facto monopoly, if each firm believes that the government will not deny it business for fear of then facing a true monopoly.

Therefore, three competitors may be required for workable competition. No firm can feel invulnerable in its market position because the customer could drop it, bring up another, and never face a monopoly.

We are doing some formal economic analysis on these issues in the project. The analysis takes into account: the role of entry barriers, information asymmetries, and other factors to determine how market performance depends on the number of competitors. A separate project report will describe that analysis and give more definitive assessments of what a desirable competition policy would be.

APPENDIX A. - QUESTIONNAIRE

APPENDIX A - QUESTIONNAIRE FOR ASC/INDUSTRY/RAND MILITARY AIRCRAFT INDUSTRY VIABILITY STUDY

INTRODUCTION

We are gathering data for a research project on the future economic viability of the military aircraft industry. This study was requested by Lieutenant General Fain, Commander of the Air Force Aeronautical Systems Center. There is concern that the next decade's military aircraft development and production budgets, programs, and policies may not be sufficient to sustain a viable military aircraft industry into the next century. As a result, the Air Force may find itself without an adequate industrial base for sustaining required new aircraft development and production in the future. This study was commissioned to determine (a) if that indeed is a problem; and (b) if so, what should the Air Force do about it now?

This questionnaire collects information on the next decade's military aircraft budgets, programs, and policies' effect on industry's capability to design and build military aircraft during 2005-2025. Capability includes not only the ability to carry out a project but also the cost-effectiveness of the effort. With the information gathered in this questionnaire, we will recommend to the Air Force what policies they should pursue now in order to maintain, with high confidence, a military aircraft industry appropriate for future military aircraft development and production requirements.

This is a joint ASC/Industry/RAND project where the research approach has been collectively developed by ASC, industry, and RAND personnel. RAND is the data integrator because, as a private non-profit firm, it can handle company proprietary information as well as "No Contract" budget data. It can integrate and analyze these for research purposes; and publish policy implications that do not disclose sensitive specifics. (A non-disclosure agreement will be executed between RAND and your company as part of this joint project.) Interim and final results will be shared with Process Action Team (PAT) members.

RESEARCH APPROACH

Our research plan is to visit the companies represented in the ASC Industry/Government PAT to discuss viability issues with expert personnel. The attached questionnaire is meant to be a guide to the structured interviews. Persons attending the discussions should provide the best answers available to the questions below before our meetings.

The approach we would like you to take toward this interview instrument is to provide readily available data and information. We require *representative* data, not necessarily precise data if doing so requires lengthy or personnel-intensive data searches. We simply request your best estimate of the answer. What we ask for here is *informed expert judgment*.

The reasons for this philosophy are two-fold. First, trying to get very accurate data would take a long time, and the urgency of this issue requires that we come up with results rather quickly (initial briefing in November 1994). Second, we are confident that useful analysis can be done on the basis of informed judgment. It is our experience that the critical policy issues can be illuminated by this process. If necessary, after initial results are established the ASC, industry, and RAND project team members can consider further data refinement.

We realize that for many of the areas in this questionnaire the person answering may want to qualify their answers based on specific assumptions. Please feel free to add any commentary you think is appropriate to your answers, and any additional information you think may help us in carrying out the research project. If it is not possible to get the answers quickly and easily for some of the questions, please just say so and leave that part blank.

As indicated above, we plan to visit each of your organizations to discuss these issues with knowledgeable personnel. We have found in our initial contacts that many valuable insights about the general problem of maintaining industry viability come from these discussions. This questionnaire should simply be viewed as an instrument for the interview process. We look forward to our meeting with you.

OUTLINE OF QUESTIONNAIRE

There are six areas in this questionnaire. They are:

A. General Information about your Company or Division

B. Resource Requirements for a Recent Project

C. Effects on a Recent Project's resource requirements given a lower experience base

D. Resource Requirements for a Future Project

E. Minimal and critical work required to keep your company viable (i.e., able to carry out projects in a cost-effective fashion)

F. Penalty of not obtaining the minimal work required

Note, do not be misled by the structured data tables in Section A. While Section A provides important contextual information, core questions requiring expert judgment are contained in Sections B-F.

A. GENERAL INFORMATION ABOUT YOUR COMPANY OR DIVISION

Name and address of company/division:

Name and phone number of person coordinating questionnaire:

Some of the useful division level contextual information is requested in Table A.1. It requests overall revenue (government and commercial), funds supporting R&D, and total engineering and technical management employment. By "revenues that supported R&D activity," which may not be part of your accounting system, we simply mean the dollar volume of R&D work you did, whether on contract or with internal funds. We realize this number is impossible to get precisely, but we ask for your best estimate. We say "engineers and technical managers" to mean those who do or supervise engineering work, whether it support R&D, or other activity like production or maintenance of systems. Once again, we realize that there is some ambiguity to this term, but we ask for your best judgment, and encourage you to comment on the relative accuracy of your answer. Please complete Table A.1 for as many years as possible.

Table A.1

Company/Division Revenue, R&D Funding and Employment History

Year	Total Revenue (Millions of Dollars)	Percent Funding R&D	Engineers and Technical Managers Employed (Thousands)
1993			
1992			
1991			
1990			
1989			
1988			
1987			
1986			
1985			
1984			
1983			
1982			
1981			
1980			
1979			
1978			
1977			
1976			
1975			
1974			
1973			
1972			
1971			
1970			
19??			

NOTE: Please include as many years for which data are readily available. Indicate if the dollars are adjusted for constant purchasing power in any way. (Otherwise, we will assume they are not and make the appropriate adjustments.)

The following tables request data on your revenues and engineering and technical management employment. Table A.2.1 requests non-governmental revenue information while Table A.2.2 requests US government (USG) revenues by agency. If you had some revenues from a subcontract that you *know* was based on USG funding, please include it in USG Table A.2.2, and allocate it to the agency as best you can estimate. Please fill out Tables A.2.1 and A.2.2 with the revenue distribution by customer for as many years as you can.

Table A.2.1

Distribution of Non US Government Revenues
What Percent of your Total Revenues Came From:

Year	Total Non-USG Revenues	Domestic Commercial	Foreign Commercial	Foreign government/ military(a)
1993				
1992				
1991				
1990				
1989				
1988				
1987				
1986				
1985				
1984				
1983				
1982				
1981				
1980				
1979				
1978				
1977				
1976				
1975				
1974				
1973				
1972				
1971				
1970				
19??				

(a) Foreign government/military includes FMS as well as direct contract sales.
NOTE: Columns 3-5 should sum to the column 2.

Table A.2.2

Distribution of US Government Revenues
What Percent of your Total Revenues Came From:

Year	Total US Govt	USAF	USN	USA	OSD/ ARPA	NASA	Other US Govt
1993							
1992							
1991							
1990							
1989							
1988							
1987							
1986							
1985							
1984							
1983							
1982							
1981							
1980							
1979							
1978							
1977							
1976							
1975							
1974							
1973							
1972							
1971							
1970							
19??							

NOTE: Last six columns should total to second (total US government).
The second column of this table plus the second column of Table A.2.1 should add to 100.

We would now like to ask about the composition of your revenues from the US government. If it is possible, please divide them into the categories given in Table A.3. These categories are defined as:

S&T -- Science and Technology work, of the kind funded under "6.1, 6.2, and 6.3a" money by DoD

IRAD/ B&P -- Independent R&D and Bid & Proposal Some call this discretionary funding

Dem-Val -- Demonstration/Validation

EMD -- Engineering and Manufacturing Development

MOD R&D -- Any major modification R&D work that occurs after production begins in a program

Production -- any production work including MANTECH

Sustainment -- includes sustaining engineering, overhaul, mod installation, and component repair

Other -- We think the above categories exhaust what the USG pays for but if we have missed something please include it and identify it here

IRAD is a special case because, as you know, it is usually paid for as overhead on all sales. The ideal way for us to use these data would be to separate out IRAD and have the other funding categories *net of* IRAD.

Let us reiterate our data philosophy. We certainly are not asking you to do expensive and timely data searches and queries to answer this. If these data are not readily available, please give us your best estimate and if you feel no estimate is possible, please so indicate. Even one or two years would be vastly more helpful than none. We are looking for an approximately correct picture of the pattern and location of spending, not accounting quality data.

Table A.3

Percent Composition of USG Funding
What Percent of your USG Funding Was:

Year	S&T "6.1/2 /3a"	IRAD/ B&P	Dem-Val	EMD	MOD R&D	Production	Sus-tain-ment	Other
1993								
1992								
1991								
1990								
1989								
1988								
1987								
1986								
1985								
1984								
1983								
1982								
1981								
1980								
1979								
1978								
1977								
1976								
1975								
1974								
1973								
1972								
1971								
1970								
19??								

NOTE: Columns should add to 100.

If possible, please repeat Table A.3 for just your US Air Force (USAF) business.

Table A.4

Percent Composition of USAF Funding What Percent of your USAF Funding Was:

Year	S&T "6.1/2 /3a"	IRAD/ B&P	Dem-Val	EMD	MOD R&D	Production	Sus-tain-ment	Other
1993								
1992								
1991								
1990								
1989								
1988								
1987								
1986								
1985								
1984								
1983								
1982								
1981								
1980								
1979								
1978								
1977								
1976								
1975								
1974								
1973								
1972								
1971								
1970								
19??								

NOTE: Columns should add to 100.

Finally, in order to learn about the composition of your engineering and technical management staff please tell us what percent were involved in the four activities given in Table A.5?

USG R&D -- persons who were doing R&D work on a contract basis for the US government (including IRAD)

USG non-R&D -- all other engineering and technical management personnel working on a contract basis for the US government

Non-USG -- all engineering and technical management staff doing either contract R&D for a non-USG customer, or those doing R&D on a commercial basis (i.e., paid for by company internal funds)

Non-USG non-R&D -- all other E&TM staff

Again, rough order of magnitude estimates are fine.

Table A.5

Utilization of Engineers
What Percent of your Engineering Personnel Were Engaged in:

Year	USG R&D	USG non-R&D	non-USG R&D	non-USG non-R&D
1993				
1992				
1991				
1990				
1989				
1988				
1987				
1986				
1985				
1984				
1983				
1982				
1981				
1980				
1979				
1978				
1977				
1976				
1975				
1974				
1973				
1972				
1971				
1970				
19??				

NOTE: Columns should add to 100.

B. RESOURCE REQUIREMENTS FOR A RECENT PROJECT

This section requests information on the resources required to complete an actual historical project performed by your company. We are focusing on engineering and technical management personnel, and facilities, as resources of interest. Basically we want to ask you to describe how many engineering and technical management personnel were used to carry out the project, and what facilities were used. (Next we will ask how the experience factor affected the resources used in the project, and its outcome.)

Please choose any recent project of your company that you think is relevant given the goals of our joint research project. Ideally, the project will have gone through all the phases of concept exploration and development, demonstration-validation, engineering and manufacturing development, and production. However, please choose a project based on your overall assessment of its relevance to this research. A project which did not go through all the above phases, or for which all of these phases are not applicable, is certainly OK if in your judgment it illustrates particularly important issues, etc.

Name of Project:

Table B.1 requests information on the phases of the project. The phases of the project are defined as:

Pre-CE&D -- Specific "pre Milestone 0" set of activities clearly related to this project (often none can be so identified)
CE&D -- Concept Exploration and Development
Dem-Val -- Demonstration/Validation
EMD -- Engineering and Manufacturing Development
Prod -- Production
MOD -- Any major modification R&D work that occurred after production began (please briefly describe in attachment)
Sustain -- Sustainment: sustaining engineering, overhaul, mod installation, and component repair

Table B.1 requests the time periods for each phase and two estimates of project cost. First is total project cost including profits or overruns, whichever may be the case, and excluding GFP/GFE. Second is the amount of subcontracts you awarded. Subcontracts that should be included in this dollar total are those that require engineering work and not those that are "build to print" -- agreements by which other companies do substantive independent pieces of the project, which you then use or install. The idea is that the first less the second is the amount of resources required to perform R&D, production or sustainment work. Please use your best judgment in answering this and attach some comments if there are real ambiguities in answering the question.

Table B.1

Summary of Time Line and Project Cost

Phase	Start date/end date	Total Project Cost (a) (Million $)	Major Sub-Contracts You Let (Million $)
Any Pre-CE&D	/		
CE&D	/		
Dem-Val	/		
EMD	/		
Production	/		
Sustainment	/		
Major MOD 1	/		
Major MOD 2	/		
Major MOD 3	/		

(a) Total Project Cost includes profits or overruns, whichever may be the case.

NOTE: Indicate if dollars are adjusted for purchasing power (preferred year is 1994). If you do not so note, we will assume they are then-year dollars and make the appropriate adjustments.

Next, we want to ask about your utilization of engineers, technical managers, and critical facilities, in the various phases of this project. We first ask you to fill out Tables B.2.X for each phase of the project, where X goes from CE&D (pre-CE&D if relevant) through Modification phases according to the following:

Table	Phase
B.2.0	Pre-CE&D
B.2.1	CE&D
B.2.2	Dem-Val
B.2.3	EMD
B.2.4	Production
B.2.5	Sustainment
B.2.6	Major MOD 1
B.2.7	Major MOD 2

etc.

In Tables B.2.X, we ask you for each project phase, to indicate the average number of engineers and technical managers employed by specialty and experience level. Please include *all* such personnel who were actually doing work for the project, whether they were directly or indirectly charged. We realize this requires some judgment since some persons effectively work on more than one project, but please make your best estimate.

Please include as many specialty areas as you think are relevant for this project. In our initial interviews, we found that *for aircraft development* projects, this list represents a fairly common categorization of engineering skills:

Structures/stress/materials and properties
Subsystems
Avionics
Software integration
Flight sciences
Flight test
Systems analysis/integration
Project management/systems engineering
Manufacturing
Quality
Environmental
Indirect Management N.E.S.

We realize that for other kinds of projects, such as engines or electronics, different specialties may make sense. Use whatever categorization scheme is appropriate for you. Descriptive information regarding key personnel would also be useful.

Finally, information on the critical facilities used in each phase of the project is requested. Use your judgment as to what facilities were key to carrying out the project.

The following table is offered as a template for indicating personnel and facility resources for each phase of the project. Please use a separate copy of the table for each phase of the project, i.e., complete "Table B.2.1" for "Phase of Project: Concept Exploration and Development;" a "Table B.2.2" for "Phase of Project: Demonstration-Validation:" and so on. Please include a critical facilities page (template also given below) for the phases for which such facilities were key to carrying out the project. The phases for which these data are provided should correspond to the phases in Table B.1.

Project Name: ______________________________

Phase of Project: ______________________________

Table B.2.__

Engineering and Technical Management Personnel: Average Employment Levels Over the Project Phase by Specialty and Experience Level

Specialty	Total	0-10 Years Experience	10-20 Years Experience	20+ Years Experience
Total				

If there were significant variations in manpower levels over the time span of this project phase, please attach some information about them. A graph showing total engineering and technical management personnel as a function of time would be useful, even if approximate.

Please list any critical facilities for successfully carrying out this phase of the project. Please indicate whether you owned them, whether you rented them or used them free of charge if another organization owned them. Indicate numerical annual usage (e.g., hours) of the facility if that is relevant.

We now want to ask several specific questions about how this project as a whole was carried out:

Please describe any science and technology (S&T) work performed previous to this project that was critical to successfully carrying it out. Interesting details include, but are not limited to, research area, time period, the number of people involved, etc.

At the peak level of engineers working on this project, about how many of them were hired *specifically because this project existed,* i.e., how many in your judgment would not have had employment in your company had this project not existed (and not been replaced by any other)?

Peak number of engineers: ______________________

Number hired specifically for project: __________

Of the engineers specifically hired for this project, what was their percentage breakdown by previous experience:

(1) Previously employed by you: ________________

(2) Previously employed by another organization doing similar kinds of projects (i.e., military aerospace related): ______________________________________

(3) Previously employed doing different kinds of projects: _____________________________

(4) Straight out of school: ____________________

Here we realize that you can only provide approximate answers, and that judgment is required to distinguish (2) from (3). As a guide, engineers who had worked in commercial aviation we would put in (2); those who had worked in automotive areas in (3). Feel free to add your own qualifiers.

C. EFFECT OF EXPERIENCE BASE

As stated above, the primary goal of this research is to determine the military aircraft development activity required to sustain a viable military aircraft industry, and to assess the consequences of falling below that level. To this end, we would like to ask about how the experience your company had *before* the project described above effected your ability to carry it out.

(1) What specific projects done before this project gave your company/division experience that improved the quality of this project? For each of these projects, can you specifically describe how the experience of the earlier project improved the outcome of the later one? We are especially interested in the distinction, if it is meaningful for you, between how earlier projects give *specific individuals* important experience which improves their performance, versus how earlier projects make *the organization per se* more effective.

Table C.2

Earlier Projects Relevant for Performance on This Project

Earlier Project Name (Time Period)	Comments on Its Relevance

(2) Now please choose one of the most important projects from question (1). Assume the company/division had *not* done this project. How would the specific historical project from Section B been adversely effected by this? The answer might be in terms of increased cost, stretched out schedule, lowered product technical performance, higher risk of adverse outcome in any of the above three dimensions, or some combinations of these. Please be quantitative to the extent possible. This is a case where we clearly understand that precision is not possible but where an informed judgment is much better than nothing. Feel free to make qualitative comments about (a) the impact of the earlier project's absence on the given project, and (b) the uncertainty you have regarding any quantitative statements made.

In answering this question, please be specific as to the reasons why the project outcome would have suffered. For example, if more personnel would have been required (i.e., higher cost for engineering staff) what would the additional personnel have had to do? If the project would have been stretched out, what would have been the change in the level and sequencing of activities? Would there have been more frequent re-designs; would more resources have been required for training; would some steps have taken longer because of trial-and-error methods; etc. Would additional time have been required for finding and hiring personnel; building facilities; building or buying tooling or equipment; etc.

(3) Now repeat question (2) for a second earlier project. Either assess the effect of this project's absence assuming that the question (2) project was or was not carried out. That is, make the impact of the second earlier project cumulative or independent as you choose, but please indicate which assumption you made.

(4) We realize you have limited time and do not want to be unreasonable in going on and on. Please answer question (2) for as many earlier projects as you wish. Realistically, we will be happy if you can give us an answer for just one earlier project, ecstatic for two, and words fail us after that.

D. RESOURCE REQUIREMENTS FOR A FUTURE PROJECT

We would now like to repeat the questions in Section B, but with reference to a hypothetical future project that is representative of the kind of military aerospace work you reasonably expect to compete for in the future. Subsequent sections (E and F) contain questions about the minimum experience level required between now and the beginning of that project to effectively carry it out, and the implications of attempting the project without that minimum experience level.

Because of the time frame of the study, it would be best to pick a project that will begin after 2005. However, this should not be a hard constraint. If there is a planned (or partly planned) future project that you feel is more appropriate for the analysis, please choose it. Here, expert judgment is the only way to get the answers and they will necessarily be imprecise. Remember the nature and spirit of the study.

So we begin asking you to characterize the project in general. The description may include such information as time period, performance characteristics, planned production, etc.

Name of Project:

Time Period:

General descriptors:

Please fill out Table D.1 for this hypothetical project, which is parallel to Table B.1 for the actual historical project in Section B.

Table D.1
Summary of Time Line and Cost of Future Project

Phase	Start date/end date	Total Project Cost (a) (Million $)	Major Sub-Contracts You Let (Million $)
Any Pre-CE&D	/		
CE&D	/		
Dem-Val	/		
EMD	/		
Production	/		
Sustainment	/		
Major MOD 1	/		
Major MOD 2	/		
Major MOD 3	/		

(a) Total Project Cost includes profits.
NOTE: Indicate if dollars are adjusted for purchasing power (preferred year is 1994). If you do not so note, we will assume they are then-year dollars and make the appropriate adjustments.

Next, we want to ask you to answer questions about resource use for this project parallel to those asked about the historical project. Once again, to save paper, we include only one set of questions, which should be duplicated for each phase of the project addressed.

Phase of Project: ______________________________________

Table D.2.__

Engineering and Technical Management Personnel: Average Employment Levels Over the Phase by Specialty and Experience Level

Specialty	Total	0-10 Years Experience	10-20 Years Experience	20+ Years Experience
Total				

If you expect significant variations in manpower levels over the time span of this project phase, please attach some information about them. A graph showing total engineering and technical management personnel as a function of time would be useful, even if approximate. Qualitative information on key personnel would also be helpful.

Please list critical facilities that will be important for successfully carrying out this phase of the project. Indicate if ownership is crucial or whether access to them in the market is sufficient. As above, please indicate annual usage of the facility required if relevant.

Finally, please list any science and technology (S&T) work that you believe will be critical to the success of this project. Interesting details include, but are not limited to, research area, time period, the number of people involved, etc.

If you had to hire new engineers to do this project, is there any minimum percent that would have to:

(A) Have some experience, i.e., not be straight out of school? (If this is not adequately captured by assuming that all the "0-10 Years" category can be brand new graduates.)

(B) Have some experience in doing similar types of projects (i.e., military aerospace related) as opposed to any kind of engineering work (i.e., automotive or general programming)?

Please elaborate on the above answers in an attachment if you feel we should consider a more complete characterization of the experience required in new hires (e.g., if it varies by stage of the project).

E. MINIMUM EXPERIENCE REQUIRED

This section requests information on the minimum level of experience in military aerospace development or production required to successfully carry out the project described in Section D and other future projects. (We focus on the Section D project for specificity.)

We begin with the engineering and technical personnel aspects. What we have in mind is a continuing minimum level of military aerospace related work represented by employment of engineers and technical managers. This minimum allows the organization to maintain its ability to stay in the military aerospace business, and to cost-effectively develop and produce new products.

This minimum level of military aerospace work can be characterized in the same way as resource requirements are characterized in Tables B.2.X and D.2.X. It will show the required employment of engineering and technical management personnel to preserve your organization's capability to carry out the future project in a cost effective manner. (In the next section, we will ask you the consequences of not maintaining this "minimum" level.) As a technical definition, we will use the following: The minimum level of employment is that required to maintain your organization's capability to carry out development projects at the same level of efficiency you had in 1987. (We realize, of course, that assessing an organization's level of efficiency is in itself a matter of judgment.) We choose the year 1987, the peak of US defense spending in real terms, to account for the fact that declines in defense spending may have already adversely effected your capability in your judgment.

So, please fill out Table E.1, indicating the level and composition of the engineering and technical management personnel, by specialty and experience level, required to be employed to maintain your organization's military aerospace development and production capability. Assume these personnel require continuous employment. Also, please answer the following questions:

What would the *complete total* annual cost be to support this group (in dollars of 1994 purchasing power) be? Please include all fringes, overheads, fees, cost of money, and total costs of materials, supplies, and depreciation, maintenance and amortization of facilities required for this group to maintain its capabilities (i.e., this is the total cost (from whatever funding source) to maintain your organization's ability to cost-effectively carry out military aerospace projects).

Do all of these personnel have to be employed on military aerospace projects? If not, what percent must be? (We are asking here whether some percent of these people *may* be able to be maintained on commercial projects.)

Table E.1

Minimum Engineering and Technical Management Personnel Who Must be Continually Employed To Maintain Military Aerospace Development Capability by Specialty and Experience Level

Specialty	Total	0-10 Years Experience	10-20 Years Experience	20+ Years Experience
Total				

What facilities must be maintained to preserve these capabilities. Indicate if ownership is crucial or whether access to them in the market is sufficient. As above, please indicate annual usage of the facility required if relevant. (The cost of maintaining or renting them at the required level should have been included in your cost estimate for maintaining overall capability above.)

Finally, are these estimates contingent on specific assumptions about the future business environment, technologies, ways of doing business, etc.?

F. EFFECT OF EXPERIENCE BASE

Finally, please explain how *not* having the minimal experience base described above would effect your ability to carry out the postulated future project from Section D.

(1) Say that your organization's work level between the end of your current projects and the beginning of the future project defined in Section D is cut to one-half of the minimum level required to maintain a viable capability (defined in Section E). How would that effect your capability to carry out the project described in Section D? Please answer in terms of: increased cost, stretched out schedule, lowered product technical performance, higher risk of adverse outcome in any of the above three dimensions, or some combinations of these. Once again, please be quantitative to the extent possible. Moreover, feel free to make qualitative comments about this change's effect on the project including statements about the uncertainty you have about quantitative statements.

Please answer this question assuming an external environment (i.e., total military aircraft business) essentially the same as today's, with today's level of production and development and employment pools. That is, assume there is a pool of recently experienced persons who you *may* hire if you wish. Some have been recently released from other similar companies; some you may have to hire away from other companies.

In answering this question, please give specific reasons why the outcome of the project would suffer. For example, if there are more personnel required (i.e., higher cost for engineering staff) what must the additional personnel do? If the project is stretched out, what is the change in the level and sequencing of activities? Are there more frequent re-designs; are more resources required for training; do some steps take longer because of trial-and-error methods; etc. Is additional time required for finding and hiring personnel; building facilities; building or buying tooling or equipment; etc.

(2) Please repeat question (1), but now assume that the external environment is one of greatly reduced military aircraft development and production activity from today's. Specifically, assume that the levels of military aircraft production and development activity are about one fifth of today's, and that they have been for some time. Also assume that the engineers and technical managers who are at work today (i.e., 1994) will have been out of the industry for at least ten years. Thus, in hiring you either have to search out, find, and hire these people who have left the industry, or hire neophytes.

(3) Please repeat question (1) for a reduction of your organization to a truly minimal level, i.e., one that simply guarantees your survival as an organization, but which does essentially no substantive work. This is essentially starting from scratch, except that you still have your legal corporate structure. What would the impact be on your ability to carry out the project?

As in question (1), please answer this question assuming an external environment (i.e., total military aircraft business) essentially the same as today's, with today's level of production and development, and today's employment pools, as characterized above.

(4) Please repeat question (3), but now assume (as in question (2)) that the external environment is one of greatly reduced military aircraft development and production activity from today's. As in question (2), specifically, assume that the levels of military aircraft production and development activity are about one fifth of today's, and that they have been for some time, and that prospects for hiring are the same.