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A RAND NOTE

**The Development of the F100-PW-220 and
F110-GE-100 Engines: A Case Study of
Risk Assessment and Risk Management**

Frank Camm

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**The Development of the F105-PW-220 and
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Risk Assessment and Risk Management**

Frank Camm

**Prepared for the
United States Air Force**

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PREFACE

This Note presents one of seven case studies developed as part of the Project AIR FORCE study "Managing Risks in Weapon Systems Development Projects," which has developed case studies on the level, distribution, and risk in the range of major U.S. Air Force development programs conducted primarily during the 1980s. Notes based on those case studies offer concise descriptions and analyses of the policies used by the Air Force to manage and distribute risk. They are aimed primarily at high-level government officials concerned with the management of research and development, including senior Air Force staff, senior Department of Defense (DoD) officials, and congressional staff. The Notes should also be useful to policy analysts concerned with the management of large-scale research and development, especially in DoD.

This Note examines risks associated with the program used to develop the new F100-PW-220 and F110-GE-100 derivative fighter engines. The derivative development described here has important implications for future policies that could place greater emphasis on such development to facilitate quick and flexible responses to unexpected changes in a diffuse threat. Information is current as of summer 1991.

Other Notes written in this project include the following:

- S. J. Bodilly, *Case Study of Risk Management in the USAF B-1B Bomber Program*, RAND, N-3616-AF, 1993.
- S. J. Bodilly, *Case Study of Risk Management in the USAF LANTIRN Program*, RAND, N-3617-AF, 1993.
- F. Camm, *The F-16 Multinational Staged Improvement Program: A Case Study of Risk Assessment and Risk Management*, RAND, N-3619-AF, 1993.
- K. R. Mayer, *The Development of the Advanced Medium Range Air-to-Air Missile: A Case Study of Risk and Reward in Weapon System Acquisition*, RAND, N-3620-AF, forthcoming.

Two unpublished papers also have been written by T. J. Webb on risk management during the development of the Global Positioning System Block I satellite and risk management in preparing for development of the Joint Surveillance Target Attack Radar System (Joint STARS). A summary of these Notes and papers and the policy conclusions based on them is

found in T. K. Glennan et al., *Barriers to Managing Risk in Large-Scale Weapon System Development Programs*, RAND, MR-248-AF, forthcoming.

The Air Force sponsor for the study is the Deputy Assistant Secretary of the Air Force (Contracting) (SAF/AQC). The work has been conducted in the Resource Management Program of Project AIR FORCE. The principal investigator at RAND is Dr. Thomas K. Glennan.

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SUMMARY

The "Great Engine War" pitted Pratt and Whitney (P&W) and General Electric (GE) against one another to supply engines, the F100-PW-220 and the F110-GE-100, respectively, for the Air Force's new F-15 and F-16 fighters. Known more formally as the Alternate Fighter Engine competition, this acquisition used "derivative" engines—engines that incorporated small changes in selected parts of existing engines to greatly improve operability, durability, and the operating and support costs of fighter engines. This Note examines the exceptionally successful development programs that created these engines and seeks the basis for that success, giving special attention to risk assessment and risk management in the two development programs. This summary briefly reviews the history of the two developments, raises four basic policy issues revealed by our analysis to be important, and then reviews briefly several lessons offered by these developments for the future.

A BRIEF HISTORY

These engines were effectively a response to the Air Force's operational experience with the P&W F100-PW-100 and -200 engines, used by the Air Force to power its F-15 and F-16 fighters, respectively. The F100 met its initial and primary design goal of doubling the thrust-to-weight ratio for operational fighter engines. But, following deployment in 1974, it experienced serious difficulties, two of which were significant: "stall-stagnation" and extremely short life with high maintenance costs. Stall-stagnation occurred under certain operating conditions, requiring the pilot to shut down and restart the engine in flight. It presented a danger in the two-engine F-15 and a serious threat to safety in the single-engine F-16. The engine's extremely short *lifetime*—the period between depot overhauls—and high maintenance requirements drove up its operating costs. As these problems came to light, the Air Force tried to induce P&W to resolve them. The Air Force and P&W could not agree on who should pay to fix the problems, and the relationship between them deteriorated as the problems persisted in the fleet, forcing the Air Force to restrict operations and pay high maintenance costs.

During the same period, GE faced a different problem. It had lost to P&W in the competitions to provide engines for the F-14, F-15, and F-16, which effectively locked it out of the U.S. market for fighter engines. Seeking a way back in, in 1975 GE used its own funds to develop a demonstrator engine, the F101X, that it hoped to use as the basis of an engine to

persuade the Navy to reengine its F-14s. The Navy was not interested, but the Air Force was. It was seeking a low-risk engine to use in its experimental Engine Model Derivative Program (EMDP). The Air Force also saw the F101X as the basis for a possible alternative to the F100, and a potential threat that it could use to obtain better performance from P&W. In 1979, the Air Force used its EMDP to fund a limited development program based on the F101X, the F101 Derivative Fighter Engine (DFE) program. At the same time, it also began a much smaller F100 EMDP effort to enhance the performance of the P&W F100.

Pratt and Whitney intensely resisted this threat to its monopoly position with the Air Force, but the Air Force maintained its support for the GE engine. The F101 DFE EMDP demonstrated that the GE engine could eliminate stall-stagnations and dramatically improve durability and operating costs; the new engine directly (and quite deliberately) met the Air Force's principal concerns about the F100. These results provided the basis for an Air Force decision to develop an engine that could formally compete with the F100 for future production. In 1982, the Air Force initiated a full-scale development based on the F101 DFE to verify what it now called the F110-GE-100 engine, for use in future, newly produced F-15 and F-16 fighters. At the same time, it initiated full-scale development of three modifications to the F100 engine. Drawing on those modifications and a fourth development effort also under way at the same time, P&W drew up specifications for an improved F100, the F100-PW-220, that it could offer to compete against the F110-GE-100 for future production.

These two engines provided the basis for the Alternate Fighter Engine competition. The Air Force held the production competition in 1983 and, in 1984, decided to buy engines from both contractors. Full-scale development continued, achieving product verification for both engines in 1985 and delivering the first engines to the field in 1986. Although typical problems arose, both developments yielded engines for deployment that operated as expected, on schedule, and without cost overruns.

ISSUES FOR ANALYSIS

Why were these developments so successful? What risks did they present and how were those risks assessed and managed? In this Note, we view *risk* as a source of uncertainty that creates the possibility of a negative outcome; the worse the outcome or the larger its probability is, the larger is the risk involved. All participants in these developments agree that the assessment and management of such risk are central to the management of an engine development. By definition, a system development systematically reduces a set of *technological* risks—the possibility that the development will be unable to achieve the technological goals set for it—over time. Over the course of such a development,

its managers face another set of risks, from inside and outside a program, that must be addressed continually by the development manager in the normal course of conducting the program. Such risks concern especially the level of political support and funding for the development, the requirements set for the development, the cost and schedule for the development itself, and economic factors affecting the cost of the system that is finally developed.

In the subject developments, four factors were especially important to the assessment and management of risk:

- Low level of technological risk posed by the derivative developments undertaken.
- Use of competition to motivate the contractors involved.
- Experience of the Propulsion SPO overseeing the developments.
- Nature of the contracts used to structure the developments.

Each of these factors contributed to the success of the two developments.

Low Inherent Risks

With one exception, the developments did not present serious risks for the Air Force or its contractors. The exception resulted from the presence of competition, which we discuss next.

Technologically, both developments relied heavily on existing technology. Using different approaches, GE and P&W discovered that they could resolve the principal problems with the F100 engine by making adjustments in existing engines. GE started with the engine it had developed for the B-1, the F101, and scaled portions of it for a fighter. P&W changed parts of its F100 engine that were selected specifically to resolve the problems at hand. Hence, neither approach posed major technological risks.

Furthermore, the developers did not face serious risks from outside the programs. Higher level Air Force officials raised initial questions about funding, and the Air Force conducted the initial limited developments as spare, "success-oriented" developments. But in the end, the development managers were able, with minor exceptions, to conduct the developments on their own terms. They did not need to respond seriously to risks created by unexpected changes in policy outside the developments, changes that might have affected the support for or requirements of the developments.

Competition

The presence of competition clearly increased risk for P&W by threatening its status as the dominant fighter-engine supplier to the Air Force. It also increased GE's uncertainty, but in a positive way, creating an opportunity for GE to parlay its small investment in the F101X into a large stake in the fighter-engine market. Such competition reduced the risk faced by the Air Force by giving it options: If P&W did not become more responsive to its needs, the Air Force could favor GE in production buys, and that threat was likely to make P&W more responsive. For example, if the Air Force contracted only with GE or P&W, the contractor could easily exploit any surprises—unanticipated events—to reopen its agreement with the Air Force and adjust the agreement to make its terms more favorable to the contractor. Competition between two contractors enhanced the Air Force's power in the situation, limiting the negative consequences if either contractor reopened the agreement unexpectedly. Each contractor knew that the Air Force could credibly threaten to counter such an action by favoring the other contractor in future production buys.

Many participants suggest that the key to the competition's success was the warranty that accompanied the production contracts. That warranty forced both contractors to fairly clearly reveal their expectations about the actual performance (broadly defined) of their engines following deployment. And future performance lay at the heart of the developments.¹ Such information in itself reduced the Air Force's risk, and the warranty's terms defined a formal approach to sharing risks in the future.

One would expect the incentives created by warranties to improve the engines created by these developments, but participants in the developments disagree. They believe that the engine developers created the same designs they would have created in the absence of the warranties. To the extent that warranties affected the developments at all, they did so only by improving the information available during the competition and thereby enhancing the efficacy of the competition.

Experienced Developers

The Propulsion SPO was formed in 1977 as a focal point for solving previous problems in engine development. Its managers came to that task with considerable experience in developing engines and a common vision of their task—to bring better empirical data to bear on engine development, to take advantage of new formal methods for assessing risks

¹In the engine community, *performance* refers primarily to the thrust or thrust-to-weight ratio of an engine. In the broader acquisition community, *performance* includes all aspects of a system's technical characteristics. For engines, *performance* includes thrust, operability, durability, supportability, and reliability. Unless otherwise stated, we use the broader definition in this Note.

associated with the durability and supportability of engines, and ultimately to field engines only after developers had demonstrated and verified that they would be sufficiently durable, operable, and supportable. This vision matched the subject developments well, and the developers brought considerable experience to bear as they mounted the developments.

Many aspects of that experience were important. The key managers in the two engine developments came to the SPO with considerable experience and familiarity with engine-related technologies. Because the SPO managed a number of developments, it could continue to accumulate experience and compare experience across developments more easily than SPOs responsible for only one development. Such experience in particular increased the SPO's understanding of its principal contractors, who were also the contractors responsible for the developments; enhanced the SPO's working relationship with its principal test facilities; and allowed rapid application and refinement of new risk assessment techniques. When such developments were initiated, the standard procedures to which the SPO would attribute its general success with new engines were already in place. Together, these factors gave the SPO an ability to plan and coordinate fairly complex developments and to react confidently to surprises. This ability and confidence probably reduced the risk associated with unexpected events, allowing the SPO to react flexibly and creatively to surprises that might have stymied a less experienced staff.

Contracts

The two developments proceeded under many separate but coordinated contracts. One aspect of the F100-PW-220 development occurred under a cost-plus-award-fee contract; all other development occurred under firm-fixed-price contracts. Although many current observers believe that firm-fixed-price contracts impose excessive risks on contractors in development programs, GE and P&W readily accepted such arrangements and conducted the developments satisfactorily despite risks that such contracts might have imposed.

Such contracts could be written in part because the developments did not pose large risks for the contractors. The full risks the contractors associated with the production competition would be felt in the future. But other aspects of the contracts also limited the risks faced by the contractors. The contracts' statements of work tended to focus on the conduct of development, not its products. Such attention is consistent with a general observation among developers that the way a contract is monitored can easily be more important than how it is written. It also reflects the Propulsion SPO's reputation as a hands-on organization that worked more closely with its contractors than most SPOs. In addition,

special clauses provided well-articulated means of sharing important risks associated with specific problems of funding and test failure.

LESSONS FOR OTHER DEVELOPMENTS

What can be learned from these developments that might be applied elsewhere? We must be cautious about drawing firm conclusions based on such a limited set of developments. But information on these two developments is consistent with a number of hypotheses.

Derivative development can reduce risk in limited circumstances. The Air Force uses derivative engine developments when those developments allow the Air Force to achieve its development goals. But derivative developments do not allow large advances in broadly conceived system performance. Large advances require more traditional, "centerline" engine developments, which inherently entail more technological risk than that observed here.

Continuity in SPO management significantly enhances risk management. As a standing SPO whose existence extends beyond that of individual development programs, the Propulsion SPO has accumulated experience, doctrine, procedures, and knowledge about its contractors, all of which contribute significantly to its ability to anticipate and manage problems. These sources of order and stability, perhaps ironically, gave the SPO the skill and confidence required to react flexibly and creatively to unexpected events in these developments. Analogous statements apply to the contractors themselves.

Formal risk assessment plays a limited but important role in general risk management. New concepts and methods developed in the 1970s, including the accelerated mission test, the four-step development process, and the engine structural integrity program, gave the two engine developers tools to manage numerous important risks. Although such tools enabled the developers to achieve the durability and supportability goals sought for the two engines, they do not help managers deal with broader, less-defined risks. Here, there remains no substitute for the judgment of experienced managers familiar with the routine management of risk in system developments.

Higher level cognizance increases some program risks and reduces others. The general absence of higher level interest in these developments allowed their immediate managers to set realistic performance, schedule, and cost goals and ultimately to meet those goals. In this sense, the lack of interest reduced the external risk experienced in the two developments. But that same lack of interest also left the developments without high-level advocates to protect the programs' funding, increasing external risk. Such risks must be

balanced. One way to reduce this conflict is high-level oversight that recognizes the importance of setting and achieving realistic goals and of actively challenging goals that do not appear realistic.

Competition redistributes risk in a development program. Competition increases the risk perceived by the contractors and reduces the risk perceived by the Air Force. At any time, the Air Force can change the market shares of its contractors, increasing their risks and, by so doing, can reduce its dependence on the poorer performer, thereby reducing its own risk. Given the price the Air Force pays its contractors for contracts, competition also increases the risk that the Air Force can induce its contractors to bear. Such changes result from a basic shift in relative power that increases the contractors' responsiveness and reduces the Air Force's cost of monitoring their contract compliance.

Other aspects of contracting are at least as important as contract type in risk management. The choice of contract type affects the business environment for development; contractors clearly prefer a cost-based to a fixed-price contract, if each is offered with similar terms. But a contract's statement of work and special clauses can be written to soften the risks implied by a fixed-price contract, potentially dominating the choice of contract type by their effects on contractor risk. And the techniques that the SPO uses to monitor contract compliance can have larger effects on risk management than the formal terms of the contract.

ACKNOWLEDGMENTS

I thank especially Albert Misenko, chief of the Aeronautical Systems Division History Office, and his staff. Without their cooperation in providing access to official documents and other historical material on the Alternate Fighter Engine Program, this study would not have been possible. I also thank the many officials in the Aeronautical Systems Command who gave generously of their time for interviews that facilitated this study. The Propulsion SPO in particular also provided access to knowledgeable officials and relevant historical contracts. Continuing discussions with my RAND colleagues, Susan Bodilly, Thomas Glennan, and Timothy Webb, and with Kenneth Mayer of the University of Wisconsin, were also helpful. Arnold Levine of RAND provided a useful review of an earlier draft. I retain responsibility, of course, for any errors in fact or interpretation.

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GLOSSARY

AEDC	Arnold Engineering Development Center, Tullahoma, Tennessee, the Propulsion SPO's principal government test center for ground tests.
AFE	Alternate Fighter Engine, an official name for the engines included in the production competition between the F100-PW-220 and F110-GE-100.
AFFTC	Air Force Flight Test Center, Edwards Air Force Base, California, one of the Propulsion SPO's two principal government test facilities.
afterburner	augmentor, a component of the engine facilities.
AMT	advanced mission test, a durability test that simulates the conditions in which an engine will operate over its life.
ASD	Aeronautical Systems Division, home of the Propulsion SPO.
ATF	advanced tactical fighter, the fighter designated to replace the F-15 in the Air Force inventory.
augmentor	an engine component that burns fuel to add "peaking" power for short periods to that provided by the combustor.
BPV	bypass valve, a modification to the F100 associated with the gear-type fuel pump.
CDR	critical design review, the final review required of a component or system before full-scale development is begun.
CED	continuing engineering development, a final phase of full-scale development used to implement the last step of the four-step development process.
CFM-56	a nonmilitary GE engine that uses a core similar to that in the F101, F110, and F119.
CIP	Component Improvement Program, a formal development program used by the Air Force to increase the operability, supportability, availability, reliability, and durability of fielded engines.
combustor	an engine component in the engine core and hot section that burns fuel to provide the primary motive power in the engine.
core	the central section of the engine, including the combustor, compressor, and sometimes the high-pressure turbine.
CPAF	cost-plus-award-fee, a contract type that uses a qualitatively determined award to compensate the contractor by a small quantity in excess of its measured cost.
DADTA	durability and damage tolerance assessment, a formal risk assessment method used to evaluate the risks associated with critical parts of the engine.
DAR	Defense Acquisition Regulations
DEEC	digital electronic engine control, a key component of the F100-PW-220; enabled the improved engine to avoid stall-stagnations.
DoD	Department of Defense
DSARC	Defense System Acquisition Review Committee, predecessor of the Defense Acquisition Board (DAB).
EFH	engine flight hour

EMDP	Engine Model Derivative Program, a variation of the CIP that the Air Force could use to improve aspects of engine performance not allowed by Congress in the CIP.
EMS	Engine Monitoring System
ENSIP	Engine structural integrity program, an engineering approach to predicting engine failures and reducing their effects.
F100-PW-100	first version of the F100 used to power the F-15.
F100-PW-200	first version of the F100 used to power the F-16.
F100-PW-220	an improved version of the F100 and a primary focus of this study.
F100-PW-229	the derivative IPE based on the F100-PW-220.
F101	an engine with a core similar to that in the F110 that GE developed for the B-1.
F101-GE-102	the variation of the F101 that GE developed for the B-1B.
F101 DFE	the variation of the F101 that GE developed with Air Force funds that provided the basis for the F110.
F101X	a GE-funded demonstrator, based on the F101, that provided the basis for the F101 DFE.
F110-GE-100	the first derivative engine that GE developed for the F-15 and F-16 and a primary focus of this study.
F110-GE-400	the variation of the F110 that GE developed for the F-14.
FCA	functional configuration audit, a critical portion of the product-verification process.
FFP	firm-fixed-price, a contract type that sets price independently of all cost considerations.
FFR	full flight release, the second step in the four-step development process.
FH	flight hours
FSD	full-scale development
GAO	General Accounting Office
GE	General Electric Co., specifically its Aircraft Engine Business Group in this Note.
GP	gear-type fuel pump, a key component in improved variations of the F100, including the F100-PW-220.
hot section	components exposed to the hot gases from the combustor, including the turbine vanes and blades and combustor; it does not include the turbine shafts or disks.
IFR	initial flight release, the first step of the four-step development process.
ILC	increased-life core, a key component in improved variations of the F100, including the F100-PW-220.
IPE	improved performance engines, the F100-PW-229 and F110-GE-129, derivative engines based on the AFEs.
IR&D	independent research and development, a form of contractor-directed R&D funded by the government as an element in overhead on defense contracts.
ISR	initial service release, the third step of the four-step development process.
KIAS	knots-indicated airspeed
LOD	light-out detector, a subcomponent of the augmentor included in improved versions of the F100, including the F100-PW-220.

LOGO	limitation-of-government-obligation clause, a key clause in development contracts that are not fully funded to limit government obligation to the level of funding available.
LRU	line replaceable unit
MFP	main fuel pump
MMH	maintenance man hours, a measure of maintenance resources required to support an engine.
MQT	mission or military qualification test, a test used to clear engines for production before the subject developments began.
NRIFSD	nonrecurring investment full-scale development
OCR	operational capability release, the last step in the four-step development process.
OSD	Office of the Secretary of Defense
P&W	Pratt and Whitney, a subsidiary of United Technologies Corporation.
PB/TR	program business/technical review, a bimonthly review in the Propulsion SPO used to move information on problems and alternative solutions up to the commander and across the SPO matrix.
PDR	preliminary design review, a review of plans required before development begins.
PFRT	preliminary flight rating test, a test used to clear an engine for flight test before the subject developments began.
PID	Prime Item Development Specification, a criterion for completing a development task.
RDT&E	research, development, test, and evaluation, a formal category of federal funding.
RFP	request for proposal
ROP	Resolution of Operational Problems clause, the key mechanism for facilitating flexibility in CIP contracts.
SAF	Secretary of the Air Force
SER	significant-event report
SFC	specific fuel consumption, a measure of the fuel required to achieve a certain level of thrust.
slimline	the flight-weight version of the F110 developed to fit in the F-15.
SPO	System Project Office
TAC	Tactical Air Command
TAF	test-analyze-fix, the basic approach used to develop engines.
TF30	Pratt and Whitney engine used to power the A-7, F-14, and F-111.
TF34	General Electric engine used to power the A-10 and S-3.
TF41	Rolls Royce/Allison engine used to power the A-7.
UER	unplanned-event report
YZ	two-digit symbol for the Propulsion SPO.

1. INTRODUCTION

Much has been written about the "Great Engine War" between General Electric and Pratt and Whitney to supply engines for the Air Force's F-15s and F-16s.¹ Observers from the Department of Defense (DoD) and industry often cite this production competition as evidence of the potentially strong, positive effect of competition on defense contracting. This case also provides useful information on development procedures for new weapon systems. Much less has been said about the development of the two Alternate Fighter Engines—Pratt and Whitney's F100-PW-220 and General Electric's F110-GE-100—that made this production competition possible. A testament to the success of these developments is the Air Force's decision to develop a follow-on set of improved performance engines using a similar competition.

This Note examines the Alternate Fighter Engine developments, giving special attention to the Air Force's methods of assessing and managing risk in these developments. By *risk*, we mean uncertainty that can allow negative outcomes during a development. In our analysis, risk increases as the potential negative outcomes increase in size or become more likely.² Risk is inherent in any weapon development program. All participants in the two engine developments agree that the assessment and management of such risk are central to the management of an engine development.

Some risks are internal to a development:

- The managers' expectations about the technology being pursued may not be realized, with good or bad outcomes relative to their expectations.
- The resources and time required to make progress during a development may differ from those expected by the managers.

And because development takes time, the circumstances surrounding the development can change before the development is complete:

- Changes in the threat or other political changes can alter the nature of the system expected to emerge from the development.

¹See Drewes, 1987; Kennedy, 1985; Mayes, 1988; Ogg, 1987.

²Section 2 clarifies this definition.

- Changes in the high-level support for the effort can modify the funding and other resources available to the development.
- Technological advance elsewhere may have unexpected implications for any one development effort.
- Economic changes outside the development may unexpectedly alter the cost or availability of the resources required to conduct the development.

These changes may lead to management decisions to change the final performance of the system or the time and resources required to complete development.³

TWO ENGINE DEVELOPMENT PROGRAMS

Table 1.1 summarizes the basic physical specifications for the two engines examined in this Note. Both engines have similar engineering characteristics; the F110 has somewhat higher thrust and weighs more. In their final developed forms, they could both be used in the Air Force F-15 and F-16 fighters. A slight variation on the F110, the F110-GE-400, could power the Navy F-14.

In addition to the presence of competition mentioned above, five features of the two engine developments may have special relevance to acquisition policy in the future, as defense budgets decline. First, interest is growing in "derivative" developments—developments that build directly on an existing design and do not attempt to take a major

Table 1.1
A Comparison of the F100-PW-220 and F110-GE-100
Engine Specifications

Specification	F100-PW-220	F110-GE-100
Length, in.	210	181.9
Maximum diameter, in.	47	46.5
Airflow, lb/sec	228	254
Pressure ratio	24	30.4
Bypass ratio	0.63	0.87
Weight, lb	3218	3895
Thrust, lb	23,830	27,000
Specific fuel consumption	0.73	0.67

SOURCES: Ogg, 1987, pp. 37, 39; U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1986.

³In the engine community, *performance* refers primarily to the thrust or thrust-to-weight ratio of an engine. In the broader acquisition community, *performance* includes all aspects of a system's technical characteristics. For engines, *performance* includes thrust, operability, durability, supportability, and reliability. Unless otherwise stated, we use the broader definition in this Note.

technological step into the unknown. With these engines, a successful program of derivative development, the Engine Model Derivative Program (EMDP), was initiated in the Air Force engine community. Second, interest is growing in ways to maintain flexibility in development programs without losing oversight or control of the programs. These engine programs displayed an unusual degree of flexibility; more generally, all Air Force engine programs use a special kind of development, the Component Improvement Program (CIP), that has been successful in maintaining considerable flexibility without losing control. Third, there is strong policy emphasis today in DoD to move away from the use of fixed-price contracts in full-scale development and toward cost-based contracts. These engine developments used an extreme form of fixed-price contract, a firm-fixed-price contract without economic price adjustment, that operated satisfactorily for the Air Force and its contractors. Fourth, interest continues in the development of improved formal risk assessment and risk management tools. The Air Force engine community developed a series of such tools shortly before the subject engines were developed; looking at these tools' effects on these engine developments provides valuable insights into their potential use elsewhere. Fifth, the Propulsion SPO that oversaw these developments had a stable structure and an experienced and expert staff in place before these developments began, and it was beginning to apply a consistent doctrine to the development of a series of engines. Although that SPO remains in place today and has overseen a series of successful developments, recent events have diminished its role in the development of future engines.

APPROACH

To gather information on the two engine developments, we used official Air Force documents, secondary sources, and interviews with key Air Force and contractor personnel in the two developments. We focused on the 1979–1986 period, because the Air Force began to fund development work on the engines in 1979 and received the first engines from those developments in the field in operational aircraft in 1986.

We reviewed relevant contract documents, weekly activity reports, and biannual command assessment reviews from the Propulsion SPO; Propulsion SPO briefings on the Alternate Fighter Engine competition and its management and development philosophy; and official Air Force histories and reports to the Aeronautical Systems Division History Office from the Propulsion and related aircraft SPOs.

We used this material to prepare for interviews on the technological, political, and managerial environment in which development took place, and on major events during development and the Air Force and contractors' methods of dealing with those events. These

interviews ultimately yielded information on a wide variety of management issues related to the two engine developments. Using that information together with material from the documents we had collected, we distilled the major points discussed in the following sections.

Resource constraints prevented us from covering all aspects of these developments. We focused on events and circumstances within the developments themselves, especially within the SPO. As a result, we focused less on the general environments in the Air Force, General Electric, and Pratt and Whitney during these developments. We gave very little attention to the markets for and development of commercial engines related to the engines addressed. Future analysis should address these topics.

ROAD MAP

Section 2 briefly reviews our view of risk assessment and management in this Note. Section 3 reviews the Air Force's general approach to engine development and innovations in risk assessment and management that played an important role in the subject developments. Section 4 offers a brief history of the two developments and the environment in which they proceeded. Section 5 examines in more detail the risks inherent in the developments and three key factors that affected the management of risk in these developments—competition, general management and planning practices, and contracts. Section 6 concludes the study with simple lessons learned and implications for future policy and policy analysis.

2. RISK ASSESSMENT AND RISK MANAGEMENT¹

Weapon system development is an inherently risky activity—a statement with which many defense personnel and contractors would agree but the precise meaning of which would be difficult to agree on. Most would concur that *risky* connotes that weapon system development is not a predictable process, and that the activity involves many *surprises* or events with negative outcomes. That is, the word *risk* suggests not only unpredictability but danger. This definition becomes especially meaningful when we discuss not just risk but risk management. Those who manage risk have a distinct desire to ameliorate the negative effects associated with the unpredictability of a weapon system development.

If we accept this view, many ways remain to define precisely what risk is. The very unpredictable nature of risk itself, however, tends to defy further formalization. Any attempt to be precise about what risk is tends to sacrifice some aspect of unpredictability. It is hard—and perhaps even misleading—to characterize too precisely a situation about which we are profoundly uncertain. That said, analysis benefits from precision. This section briefly examines how development managers view risk, risk assessment, and risk management and defines these concepts to order our inquiry in the sections that follow.²

A REALISTIC WAY TO THINK ABOUT RISK IN ANALYSIS

The predominant analytic definition of *risk* is probably that of economists and decision theorists, which emphasizes unpredictability. For economists, risk or uncertainty exists whenever unpredictability exists.³ Risk associated with a process increases as the range of possible outcomes of that process increases. More formally, risk increases as the variance of outcomes associated with the process increases. To illustrate, consider the two distributions in Figure 2.1. The outcome of a process is represented on the horizontal axis in terms of a single metric of performance. *Subjective* probability density lies on the vertical axis. Based on this definition, distribution D1 is riskier than distribution D2 because D1 is more diffuse

¹A slightly revised version of this section appears as Section 2 in Camm, 1993.

²After this work was complete, Steven Garber of RAND brought the following references to my attention. They confirm that the views of risk assessment and risk management that we observed in the Air Force are consistent with those observed more broadly in private industry. Cf. Garber, forthcoming; MacCrimmon and Wehrung, 1986; March and Shapira, 1987; and Shapira, 1986.

³Many economists would go further to distinguish *risk* from *uncertainty*. Risk occurs when the unpredictability is associated with the outcomes of a well-understood stochastic process; uncertainty occurs when unpredictability results from outcomes of a poorly understood process. A related distinction will be useful to us below.

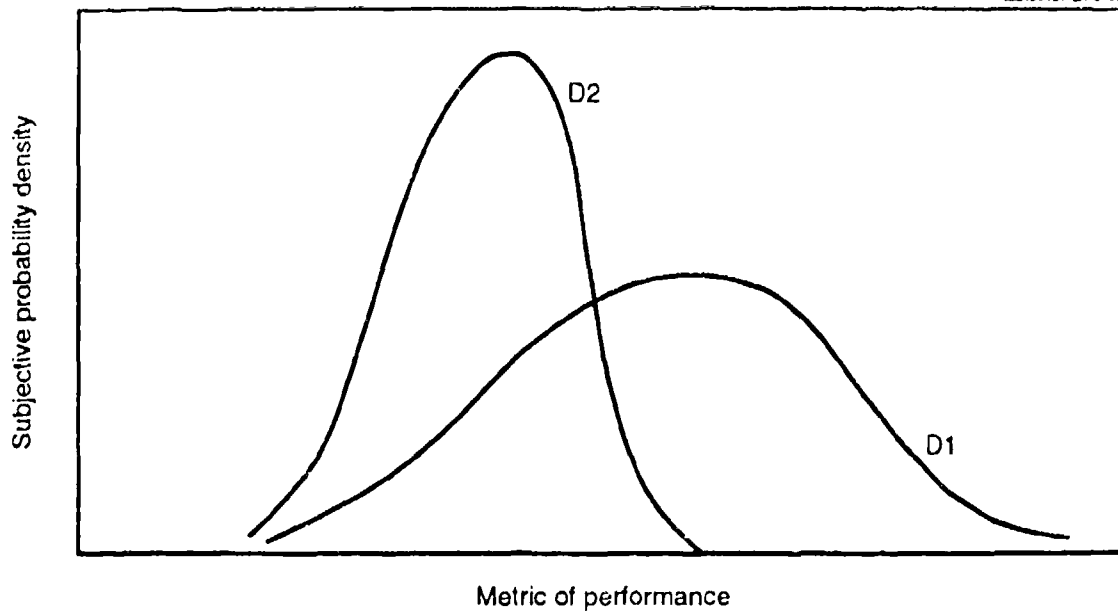


Figure 2.1—Subjective Probability Density Distributions D1 and D2 for Two Programs

than D2. D1 is riskier even though the central tendency for D1 is well above that for D2 and would be riskier even if D1 stochastically strictly dominated D2.⁴

Now suppose that D1 and D2 represent the anticipated outcomes of two different approaches to developing a weapon system. The metric of performance might be the shop visitation rate, a measure of supportability, for an engine. Viewing these alternatives, weapon system developers would agree that D2 represents the riskier approach. They would justify this position by pointing out that poor outcomes are more likely with D2 than with D1. Going further, some might be willing to set a minimum standard measure of performance S for the engine and characterize risk as the subjective probability associated with outcomes lower than this standard. For example, if the standard were S in Figure 2.2, which recreates the distributions in Figure 2.1, the risk associated with each alternative would be proportional to the shaded areas $R1$ and $R2$, representing the subjective probabilities that the engine designed by each process failed to meet the set standard.

Development managers would find this view of their decision environment grossly oversimplified. For example, such managers do not generally attempt to estimate, even

⁴That is, suppose that we imagine random draws from both distributions simultaneously. If we believe that outcomes for the two distributions are correlated so that the outcome for D1 always dominates that for D2, then D1 stochastically strictly dominates D2.

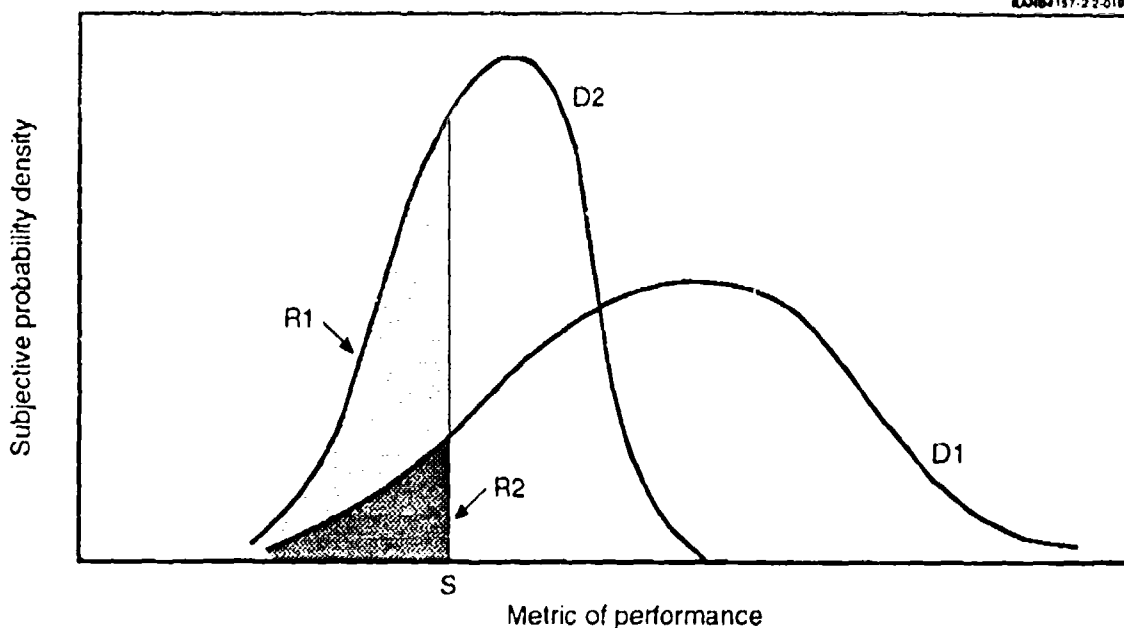


Figure 2.2—Risks R1 and R2 Associated with Two Weapon System Development Programs and Occurring Below the Set Standard for Performance S

approximately, the probability of failure as defined above or to compare such estimates across policy alternatives. Understanding this, we can still use the approach offered in Figures 2.1 and 2.2 to provide a useful *metaphor* for thinking about decision making in weapon system development. Let us continue with this metaphor for a moment before returning to the question of how precise managers' views of risk might be.

The density functions in Figures 2.1 and 2.2 are essentially *risk assessments*. Risk managers cannot effectively make such assessments independently of the policies they intend to use to manage risk. That is, they effectively view *risk management* as a way to alter the shape of the distributions shown. At any point during a development, we can think of the manager's subjective beliefs about the program's outcome. Such beliefs change through the course of a development. If the manager expects success at a certain point in time, he or she has adopted policies that restrict the degree of risk associated with such areas as R1 and R2 to an acceptably low level. Some of those policies, such as an acquisition plan, system specifications, contract, or test plan, can be established by the manager today. Some of them cannot be made explicit in advance. The manager must expect surprises, the details of which cannot be known and planned for in advance. Each such surprise will presumably

alter the manager's risk assessment and force a change in policy in some way to get risk under control again.

Viewed in this way, risk management begins to look very much like the general management of a development program. And, in fact, development managers draw little distinction between the two. In a sense, the central task of a development program is to eliminate basic uncertainties about a new design so that it can be transformed into a useful product. Doing so takes time, introducing risks associated with the environment in which development occurs and in which the product will be used. Development managers are quite comfortable thinking about development in these terms, bringing risk management per se close to their core concerns in the course of a development.

That said, risk management—or more generally, program management—for a development is much more complex than the simple metaphor above would suggest. Managers do not generally think in terms of subjective probability densities such as those presented above. They think more in terms of contingencies: What would happen if *this* happened? Roughly, how likely is it? What kind of trouble would it cause? What can I do now to mitigate that trouble? What kind of resources or staff would I want then to deal with it? This process of assessing risk, planning for it, and reacting to it is what we want to understand better in this Note. The metaphor above helps us understand that managers generally make such assessments by focusing on surprises that can hurt them and seeking ways to mitigate the effects of those surprises.

A SIMPLE STRUCTURE FOR INQUIRY

Surprises come from many sources. They affect a development program in a variety of ways. And managers have a number of tools for planning for and responding to surprises.

Sources of Risk

Managers look for surprises in two places: outside the development and within it. First, development takes time. While it occurs, the world outside the development can change, precipitating surprises for a development program. Most basically, changes in the threat can affect either willingness to continue funding the program or the requirements set for the final product. Changes in technology can affect the availability of subsystem capabilities relied on by the development or the need for the system under development. Changes in the economy can modify the cost of the development itself, that of the final product, or the availability of funds to maintain the development as expected. Changes in the Air Force testing-and-evaluation community can affect the availability of test assets. All these factors are essentially beyond the manager's control. However, their effects can

generally be reduced by restricting the length of a development, so that fewer opportunities for surprises arise over the course of the development. More likely, the manager must anticipate specific types of surprises and tailor individual responses to each type.

Second, even if the world outside the development remains stable, surprises can be expected from within the development. Examples are development efforts that require more time or resources than expected to reach a particular performance improvement, and certain technical goals set in the program that turn out to be infeasible. The manager has greater control over such factors, but can still not expect to eliminate such surprises.

Program Attributes Affected by Risk

When surprises occur, they can affect a number of program attributes. First and foremost, they can affect the probability that the program will survive to yield a useful product. Assuming successful program completion, they can affect the resources and time required to complete the program; these are the "cost" and "schedule" criteria normally associated with development. Surprises can also affect various measures of final system "performance." Traditional measures of system performance emphasize combat capability and can normally be measured in a variety of ways specific to each system. Logistics-oriented factors such as reliability, availability, maintainability, and operating and support costs are increasingly considered important parts of system performance. Producibility and production cost for the system round out the performance factors relevant to the manager.

As a development program is normally defined, a manager will have a hard time meeting his or her goals on all of the above factors. To increase the probability of program survival early in the program's life, the manager must make the program look attractive relative to alternative programs. Hence, the manager generally attempts to understate goals for development cost and schedule and overstate the performance goals of the system. To the extent that such goals are adopted as standards like those in Figures 2.1 and 2.2—that is, a program fails if it fails to meet all its goals—misstatement of goals actually increases the risk associated with a program. In most cases, however, the manager must accept such risk to reduce the risk of losing overall support for the program to a competing development program. Managers well understand this tension between the goals of program survival and other goals of the program; they accept it essentially as a price of entry for conducting development activities. In the end, however, such acceptance means that the manager cannot expect to meet his or her goals and must expect to make trade-offs in allocating shortfalls among goals.

When surprises occur, the manager must again make trade-offs among goals. Some surprises will loosen constraints on the manager; an unexpectedly high performance outcome in one area may allow the manager to reduce risk associated with performance in another area or to hold the line on the costs or schedule of development. Negative surprises, on the other hand, will lead a manager to spread the negative effects across goals. A test failure, for example, may lead to a schedule slip and additional development work to achieve the initial performance goal at the expense of schedule and cost goals.

How a manager makes such trade-offs should depend on the relative priorities that he or she places on different goals, based either on guidance from higher echelons of government overseeing the project or his or her own personal goals. We should expect these priorities to differ from one development program to another and perhaps even to change over the course of a development. Patterns in such trade-offs are of great interest to us.

Methods for Anticipating and Responding to Risk

A manager can use two basic approaches to plan for or react to surprises. The first emphasizes formal documents and processes. The second approach emphasizes good people.

The first approach uses the performance specifications for a new system to set the general level of risk for the program; more ambitious specifications are riskier. The approach spells out a formal acquisition plan for the development, specifying lines of authority, the nature of competition, or prototyping used during the development. It uses contracts and memoranda of understanding and agreement to balance the concerns of the Air Force and other parties to the development. It uses a master test plan to anticipate required testing assets, set sequences of events, and respond to test failures over the course of the development.⁵

Broadly viewed, a development *is* a test program that repeatedly tests newly developed systems, analyzes problems identified during test, and fixes them in preparation for another test. This "test-analyze-fix" or TAF, approach applies at the macro level as a metaphor for the program as a whole and can be applied in a more targeted, explicit way to deal with specifically identified problems.

Formal risk assessment can be associated with any one of these activities. Formal risk assessment works best when the processes in question are well understood and good data

⁵Such documents create a paper trail that developers can use to cover themselves if things go wrong; that is, they can prove that they did everything that was required of them. We are more interested in the way developers use such documents to anticipate risk and plan for it; that is, we are interested in how a creative planning process can tailor documents to a development program's needs, not simply fulfill regulatory requirements.

exist on those processes. Hence, it is most likely to support design of selected parts of the test program or of warranties included in a contract. Risks associated with the development as a whole, as noted above, are more difficult to state in clear, quantitative terms. Formal risk assessment is of limited use in such a setting.⁶

The presence of contracts among these tools raises an important point about risk. Risk can be perceived from different perspectives. For example, although a contractor is probably better able than the Air Force to affect surprises that arise in the day-to-day development of a system, the Air Force is, presumably, better able than the contractor to affect overall funding for a development program. Contracts can be written to shift the effects of surprises toward those parties best able to mitigate their effects. Hence, the contractor often bears much of the risk associated with unexpected cost growth during a development, whereas the government bears the risk associated with premature termination of a program. More generally, the Air Force as a whole is probably better able to bear the effects of surprises than is an individual contractor. Contracts can be written to shift the effects of surprises that cannot be mitigated to the party better able to bear such effects. In practice, of course, even when the Air Force as a whole can bear large negative outcomes, officers in a SPO concerned about their futures in the Air Force probably cannot. Hence, SPO managers may resist bearing risks best borne by the Air Force.

Once a contract is negotiated, it splits the effects of many surprises so that one party benefits from the surprise while the other is injured. Our approach to risk implies that one party need not associate any risk with a surprise that imposes a substantial risk on the other party. For example, under a fixed-price contract, the contractor bears the full risk of unexpected cost increases while the Air Force feels no effect. On the other hand, the contractor enjoys the full benefits of unexpectedly low costs. When costs are unexpectedly low, the Air Force can see such a benefit as a foregone benefit for the Air Force—that is, as a negative outcome. That is, although the fixed-price contract determines their costs, Air Force officials may view the foregone benefit as a risk worth planning against. Such a perception complicates our simple view above that risk is associated only with negative outcomes.

Although formal contracts are written only between the Air Force and contractors or between contractors, these considerations apply to many other situations in which more than one party plays a role. A SPO typically has many relationships with other SPOs, test facilities, other parts of the Air Force, and sometimes other services. Some of these relationships are codified in memoranda of understanding and agreement; others rely on

⁶For a further discussion of these points, see Bodilly, Camm, and Pei, 1991.

established custom. In all cases, more than one perspective on the risks associated with a particular surprise is possible and can affect how managers plan for and react to that surprise.

The second basic approach to planning for and reacting to risks is quite different from that taken above. It relies on good people rather than on documents and procedures. At some level, good people are required to negotiate and prepare documents and procedures. The point here is that a good staff adds value beyond the planning function. In fact, a good staff's primary value may well lie not in planning for the future but in reacting confidently and creatively when things go wrong.

The importance of good people is repeatedly emphasized by development managers. Contractors favor coveted development programs not just with resources, but with their best people. The Air Force responds by allocating its best people to its highest priority development projects. Such practices occur in production programs as well. They take on a special meaning in development programs because of the nature of the risks present in those programs.

Although good planning can provide a framework for dealing with routine risks—risks encountered in the past or risks that are fairly obvious in a new program—it cannot manage well the totally unexpected. When the totally unexpected occurs, well-informed and timely discretion is required to respond to the surprise. The better the staff available to do this is, the better is the response and the less managers must rely on the blunter rules that an acquisition plan or contract might incorporate to manage surprise. A well-organized, competent staff offers an additional benefit in the face of uncertainty. Because surprises can bring benefits as well as risks, the presence of a solid staff allows managers to maintain greater flexibility in a program to exploit opportunities as they arise.

The presence of parties with different points of view, of course, complicates the use of skilled people to respond flexibly to surprises. Each surprise offers opportunities to reopen an agreement made earlier to change the balance achieved earlier. Among the skills in a well-organized staff will typically be abilities to exploit such opportunities. However, exploiting surprise to renegotiate earlier agreements can damage the basic relationship between two parties over the long term if it happens repeatedly, ultimately leading to more rigid arrangements designed to discourage such exploitation, even if they stifle the flexibility that allows a program to benefit from pleasant surprises. Such exploitation is most likely to occur when the skills of two parties are not well balanced. For example, if an inexperienced SPO faces a contractor using a team with considerable experience working together, we can

expect trouble downstream as surprises provide opportunities for the contractor to exploit its greater experience.

SUMMARY

Although our primary interest lies in risk assessment and risk management in development programs, the nature of development activities suggests that we should be prepared to examine a fairly broad range of management activities. This is true despite our narrow definition of risk as the presence of unpredictable events with negative consequences. Many development managers use this definition and see their task as general managers as one of identifying and controlling such risk over the course of a development.

Surprises can arise outside a development program—beyond the control of those involved in the development—or much closer to home and closer to their control. They can affect the basic survival of a program or, assuming that it survives, the cost, schedule, and performance associated with the program. Development managers use two different approaches to plan for and react to surprises. They develop documents and procedures that define both risk and the methods for reducing or redistributing it. These include system specifications, acquisition plans, contracts, memoranda of understanding and agreement, and test plans. And development managers develop and nurture experienced, skilled staffs. Without such staffs, managers cannot respond adequately to the wide range of surprises that arise. With them, they can rely less on formal documents and processes and thereby maintain the flexibility that allows them to take advantage of new opportunities as they arise.

In the end, then, it is difficult to distinguish risk management from general management. In the following sections, we explore a broad range of management issues.

3. THE AIR FORCE'S GENERAL APPROACH TO ENGINE DEVELOPMENT

In the late 1970s, the Air Force was actively changing its entire approach to the development of engines. A series of unsatisfactory development programs led the Air Force to believe that it needed more continuity in engine development to make sure that new developments could learn more satisfactorily lessons from the past. The Air Force also sought a more sophisticated approach to risk assessment that would improve its ability to predict sources of failures in engines and use this information to improve engine operability, supportability, and durability. In particular, it sought better methods to predict the behavior of an engine over its lifetime and use this information to extend its lifetime. To achieve continuity in engine development, the Air Force organized a new SPO in 1977 to oversee all engine system development. The Propulsion SPO became the focal point for consolidating and applying a rapidly growing body of new development concepts that the Air Force hoped would help it improve the supportability and durability of new engines.

This is the environment in which the development programs for the F100-PW-220 and F110-GE-100 engines began. Among the first Air Force engines to benefit from this new approach, they began development too soon to benefit from the full application of the new concepts, but they offer a good example of initial applications that helped shape the Air Force's continuing effort to improve its engine development methods. This section opens with a brief discussion of the way the Propulsion SPO thinks about risk, risk assessment, and risk management, and how its approach to risk management affects the broader management of engine development. It then gives a brief overview of the development concepts the Air Force and its contractors were instituting in the late 1970s to help assess and manage risk, paying special attention to the accelerated mission test, the four-step development process, and the Engine Structural Integrity Program (ENSIP). Sections 4 and 5 say more about the effects of these new methods on the F100-PW-220 and F110-GE-100 developments.

MANAGING RISK IN THE ENGINE DEVELOPMENT PROCESS

The management of engine development *is* risk management. This is the overwhelming consensus of managers in the Propulsion SPO and engine contractors. System development by its very nature involves the systematic identification, reduction, and management of risks. And as complex, technologically sophisticated systems whose performance is critical to personnel safety, the survivability of other Air Force systems in an

airframe, and mission success, engines present an array of development risks that has forced engine developers to learn to assess and manage such risk. As important as this technological risk is, it must be understood in a broader context. To create and maintain support for an engine development process, the Air Force and its contractors must also manage a broad range of political and funding risks. The Propulsion SPO was created in part to enable the Air Force to better understand and manage these risks in engine development. It is proud of the success it has had in doing so and, in particular, of the success it had in managing the F100-PW-220 and F110-GE-100 developments early in its existence.

Two kinds of risk management are important in engine system development—planning for future surprises and managing surprises that actually occur. Planning for the future considers surprises that can occur throughout an engine's life cycle:

- design
- manufacture
- operation
- maintenance.

The Propulsion SPO focuses on the first two stages but influences the others through the pilot's handbook, logistics planning, and other products that it manages as part of the development process.¹

Planning during the design stage seeks a low-risk design and then seeks a management plan that minimizes the risk of the activities required to transform the design into a final configuration ready for production. Actual development uses a pragmatic test-analyze-fix process that iteratively tests a particular engine configuration, analyzes failures in that configuration, and posits solutions to be tested in a revised configuration. This process continues until the configuration stabilizes, as it ultimately must for the development process to succeed.

Planning during the manufacturing stage "perfects" the final product design by identifying variabilities in the actual materials used in manufacturing, the skills of manufacturing labor, and the engineering drawings used to specify the manufacturing design of parts. Such variabilities can all lead to quality assurance problems. Once it identifies

¹Developers of other kinds of systems would obviously face similar types of general risk-management concerns. How they dealt with them, however, would depend on the specific problems faced in a particular development.

these variabilities, the Propulsion SPO and its contractors must manage them. Management of such manufacturing-related risks has changed substantially over the last ten years:

- Manufacturing has become more integrated with design, in part because problems with affordability and safety discovered in the 1970s could only be addressed by solving manufacturing problems.
- Technology allows better analysis and quality assurance—for example, the Propulsion SPO can now x-ray new turbine blades before accepting them.
- Despite contractor resistance, the Propulsion SPO uses structured manufacturing reviews to monitor what manufacturers have done.

In such planning, developers must weigh these technical risks against other risks. The most important risks are associated with initiating and maintaining general support for a development program. The continuing competition for funds can easily lead developers to overpromise in terms of final system performance or the cost or schedule of development. Over-optimistic promises increase the risks of conducting a development by forcing the developer to run fewer tests, take less time, or work against less realistic performance goals than would a development concerned only with technical risk. Many managers agree that the principles for controlling risk in a development are well understood and not controversial—current DoD documents state them clearly. But they are difficult to apply in the broader environment that sets the requirements for and funds system developments.

When a surprise occurs, the Propulsion SPO must first manage the particular event itself, then figure out its implications for the fleet, and finally act. Determining implications for the fleet is not a serious concern during development, because there is little at risk. The key goal here, however, is not to allow a failure or an error corrected in one development program to reoccur in another. That principle calls for some coordination across development programs, even if it does not have as high a priority as monitoring effects important to the fleet as a whole.

The Propulsion SPO and its contractors believe that two general factors have given them an exceptional capability in risk assessment and management:

- Failure in an engine can have catastrophic consequences, for the pilot and for other subsystems on the aircraft. Knowing this has made engine developers well attuned to the need for careful risk assessment and has led them to adopt new techniques as they have become available.

- The Air Force is now working with the fifth generation of military engines. That experience has allowed the Propulsion SPO and its contractors to accumulate a great deal of practical knowledge about potential failures and methods of dealing with them. They have a substantial technical base to build on and experienced personnel to exploit it. When the Air Force and its contractors face new uncertainties, they have established methods for dealing with those uncertainties and experienced personnel familiar with these methods.

The Air Force and its contractors had less experience when they developed the F110-GE-100 and F100-PW-220. But they were attuned to the problem of risk assessment and working hard during those developments to apply what they knew. The remainder of this section addresses a set of formal concepts and methods that they were refining during the developments. These formal methods played an important part in assessing and managing the technical risks faced by the Air Force and its contractors during the two developments.

But engine developers all stress that risk management involves substantially more than formal methods. By its very nature, risk deals with unpredictable circumstances, circumstances that do not comfortably fit in any preconceived and well-defined, formal framework. In the end, the most important risk management occurs in the judgments of experienced development managers. One of the most important legacies of the developments we examine here has been their contribution to the education of a set of managers, many of whom have worked together in the Propulsion SPO for over a decade. They have been able to carry their accumulated experience in managing risk from one engine development to the next. We should not lose sight of the fact that the management of system development is risk management as we review important but narrower improvements in techniques of technical risk assessment and management. We review in turn the accelerated mission test, the four-step engine development process, and the engine structural integrity program (ENSIP).

THE ACCELERATED MISSION TEST

The accelerated mission test (AMT) runs a ground-test engine for hundreds or thousands of hours to simulate the stresses it would experience in flight over the course of an actual lifetime in a military aircraft. Now used routinely in engine development, the AMT marked a dramatic departure from earlier development practices in the 1970s.²

²We did not have time to contrast these changes with those occurring in commercial engine development during the same period. Although the major engine developers build both commercial and

In engine development in the 1960s and early 1970s, little attention was given to the specific way an engine would be used in an aircraft. Emphasized instead were performance characteristics, such as thrust, rather than the durability of engines or factors that would affect their long-term operating and support costs. In fact, the Air Force had great difficulty predicting the durability, operability, or supportability of new engines under development.

During that period, the Air Force used a 50-hr preliminary flight rating test (FFRT) to qualify engines for flight test and a 150-hr military or mission qualification test (MQT) to qualify them for production. Such evaluations had two basic problems.

First, such short tests, even if configured to reflect the type of activity expected when the engine flew in an operational aircraft, could not simulate the stress that the engine would experience over its full *lifetime*—its period in service between depot overhauls. They would not even help the designer determine what that lifetime would be, for the engine or critical constituent parts of it. The tests considered only high-power, high-temperature conditions and sought to identify (and hence allow designers to eliminate) high-cycle fatigue failure modes. They could not identify low-cycle fatigue failure modes driven by extended use in the field.

Second, the tests did not accurately reflect the types of missions anticipated for an engine during its operation. As a result, even if the tests had been extended to allow exploration of low-cycle-fatigue failure modes, they would not stress the engine parts as they would be stressed over their lifetimes during operation. That is, the tests could not identify the specific failure modes likely to occur during operation and hence the designs and maintenance practices required to ameliorate and manage those failure modes.

The AMT overcame both problems by simulating the full, expected life of the engine. Simulation begins with a "duty cycle" that describes as accurately as possible the engine's expected pattern of operational usage over a composite mission. The duty-cycle analysis begins by identifying missions and identifying the types and durations of all engine-damaging events associated with each mission. For example, air-to-air, air-to-ground, and navigation missions each generate predictable patterns of speed, altitude, and engine throttle setting. As the importance of these patterns became clear in the 1970s, the Air Force began a systematic collection of data on patterns experienced in actual flight operations. These data can be translated into specific series of throttle-dwell times at idle, cruise, intermediate,

military engines and General Electric in particular has attempted to use similar engines in both markets, the innovations described below respond to distinctly military problems associated with the high stress placed on a high-performance fighter engine.

and max afterburner speeds, as well as afterburner lights. A duty cycle is simply a composite of these series. Figure 3.1 provides an example.

Repeating this cycle to reflect the total number of these composite missions in the engine's lifetime then generates the engine's complete usage profile. The developer compresses this profile by removing non-damaging steady-state cruise time and retaining damaging cycles and hot time. He adds service activities, including scheduled and on-condition maintenance, that would occur in the field. The final product is a simulation of the engine's lifetime.

The AMT runs an engine through this simulation, stopping to replace damaged parts and periodically to inspect the condition of the core or the engine as a whole. When the AMT is completed, the engine and its components have effectively experienced a full lifetime of flight stress. Such a test allows developers to assess the accuracy of their predictions for specific components, judge the actual durability of those components, and design and test alternative component designs and maintenance plans to sustain flight safety and engine durability. Designers in fact expect different engine parts to have different lifetimes. An AMT can be performed for each part of the engine to reflect the lifetime expected. For

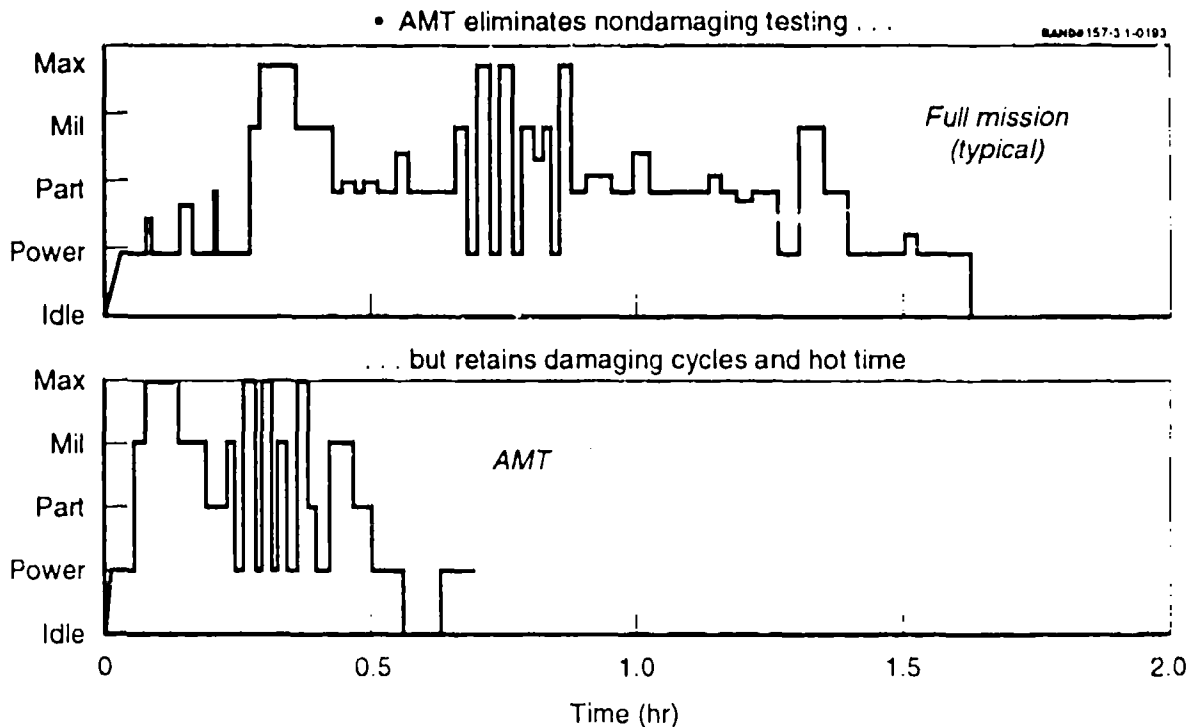


Figure 3.1—Illustrative Engine Duty Cycle

example, the engines we examine achieved a 4,000-cycle life in their hot sections—components exposed to the hot gases from the combustor—and an 8,000-cycle life in their *cold sections*—the remaining components.³

Engine testing is costly and time-consuming. But, without empirical tests, analytic methods of predicting the effects of stress on engine structure are not good enough to rely on. The compression used in the AMT is designed to reduce the cost and time associated with such testing so that the AMT can be used iteratively in a design effort that repeatedly tests components or maintenance concepts and then introduces potential improvements for further testing. The Air Force and its contractors developed and refined this technique in the 1970s on the F100, TF34, TF41, and F101. Using AMT to allow design improvements early in the life of the TF34, for example, significantly cut Component Improvement Program (CIP) expenditures for major design upgrades relative to those on the TF41.⁴ The AMT had become a standard part of the development process by initiation of the programs we are studying.

FOUR-STEP DEVELOPMENT PROCESS

During the 1960s and early 1970s, the Air Force used a two-step development process in full-scale development based on the PFRT and MQT. An engine was first qualified for flight testing and then qualified for production. By the late 1970s, the Air Force had moved to a four-step process that was more a conceptual framework for structuring a full-scale development than a formal regulatory structure that had to be obeyed in each development.⁵ Table 3.1 matches the steps of this process to steps in the development process for an airframe and to steps in the earlier engine development process.

Roughly speaking, the first step, initial flight release (IFR), emphasized flight safety so that developers could fly the aircraft enough to learn about the engine. Flight was expected to occur only in a restricted portion of the ultimate flight envelope. This step, which

³Hot sections contain the turbine vanes, blades, and combustor. Cold sections contain all other parts, including the shafts and disks in the turbines.

⁴The Air Force maintains a CIP for each engine in the fleet to continue development activities after the engines are fielded. The CIP allows the Air Force to respond to problems identified during operation and to improve aspects of engines' maintainability, durability, and supportability. The subsections below discuss CIP in more detail.

⁵Air Force Regulation 800-30 currently implements this four-step process. It was not in place during the developments that we examine here.

Table 3.1

Basic Full-Scale-Development (FSD) Milestones in Airframe and Engine Development

Airframe	1960s/1970s Engine Doctrine	Four-Step Engine Doctrine
Preflight demonstration	Preliminary flight rating test (PFRT)	Initial flight release (IFR)
Initial flight demonstration		Full flight release (FFR)
Full flight* demonstration	Military qualification test (MQT)	Initial service release (ISR)
Final operational demonstration		Operational capability release (OCR)

SOURCES: U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, chart 42; Radloff, 1985, charts 26-28.

used an AMT about twice as long as the flight test program, just to be safe, corresponded to the old PFRT but was much more demanding.

Full flight release (FFR) emphasized performance and operability and opened the way for a full exploration of the flight envelope. It also used an AMT about one-eighth to one-quarter the full expected engine life. Using such an AMT at this point reflected less the safety requirements to explore the flight envelope than an expectation that engine durability would improve in tandem with other aspects of the engine during its development. Durability was expected to reach one-eighth to one-quarter expected engine life by the time FFR was approved.

Initial service release (ISR) prepared the engine for low-rate production and used an AMT of about half the expected engine life. It corresponds in many ways to the old MQT and essentially covered all the ground that the old test covered. The AMT applied, of course, was much more demanding. Another important difference is the relation of this step to the production decision. Because the old MQT cleared the way for full-rate production, long-lead production decisions had to be made well in advance of this milestone. Under the four-step process, long-lead production decisions occurred only after ISR, significantly reducing the concurrency between development and production present in the older system.

Operational capability release (OCR) prepared the engine for full-rate production and used an AMT for full expected engine life. The new approach essentially added this step to the process to reflect the Air Force's new interest in durability. To get from ISR to OCR, an engine essentially had to achieve supportability and durability goals that had not been important in the past. That is, the Air Force had traditionally used a Component

Improvement Program (CIP) to identify and solve such problems after engines were fielded. The CIP had played, and continues to play, an important role in improving the operation and support aspects of all Air Force engines. By introducing the OCR step, the Air Force attempted to solve early some of the problems normally handled in the CIP and thereby reduce the cost of retrofitting solutions to those problems into engines in the field.

The Air Force has assigned a carefully structured set of evaluation tasks to each step. Among other reasons, they are assigned so that problems identified late in the process tend not to require solutions that would require the Air Force to repeat tests conducted earlier. This structure allows the Air Force to eliminate the risks inherent in any engine under full-scale development, in an orderly and cost-effective manner.

When the subject developments began, this structure was not fully in place. The second step (FFR) played only a limited role in the derivative developments that we consider, in any case, because the design of these engines was well enough understood so that little delay was required between the first and second steps of the structure. The developments we examine expanded the flight envelope cautiously and methodically, but the risks associated with that expansion were not considered high enough at the time to warrant a full second step in the development process. The fourth step (OCR), on the other hand, was critical to these developments. Because that step gave prominent attention to the need for greater durability, we should expect development efforts aimed at achieving and demonstrating durability to be important.

ENGINE STRUCTURAL INTEGRITY PROGRAM

Durability is an issue because components fail; a body of methods that allows a designer to reduce the probability and cost of failure holds the key to extending an engine's life and reducing its operating costs. The engine structural integrity program (ENSIP), the third technique for improving technical risk assessment, focuses on durability. ENSIP is the distillation of a set of design ideas that Air Force developers had been thinking about during the 1970s.⁶ The Air Force was in the process of formalizing this program as the two developments began. As a result, ENSIP had very different effects on different parts of the development that we study here.

Simply stated, ENSIP represents a basic change in the way designers think about the components in an engine system. Before ENSIP, designers implicitly assumed that components could be designed so that they would not fail. ENSIP recognized that all

⁶This discussion draws heavily on "Trends in Engine Qualification" (U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982).

components can fail and set up methods to explore failure modes, consequences of failure, design changes that could reduce the probability and cost of failure, and maintenance procedures that could prevent catastrophic failures. Viewed in this way, the ideas embodied in ENSIP were central to the developments we study.

As engine development proceeded in the early 1970s, the Air Force gave *relatively* less attention to aero-thermo design and thrust and more attention to engine structure, materials, and management. These engine developments offered a fairly consistent set of lessons learned. Representative lessons include the following:⁷

- Identify critical parts—parts whose failure jeopardizes flight safety—and their potential failure modes early
- Adequately characterize the fracture properties of materials and processes
- Do not assume defect-free structure when assessing the safety of flight components
- Verify analytically predicted stresses for complex components with formal empirical tests
- Identify internal thermal and vibratory environments early in development
- Define potential engine/airframe structural interactions
- Reflect the anticipated service usage of the engine in stress, component, and full-scale engine tests
- Use closed-loop force management procedures to define and enforce
 - realistic inspection and maintenance requirements
 - individual engine tracking procedures
 - deficiency reporting
 - updates in procedures based on actual usage.

At the same time, a series of studies began to recommend a more comprehensive Air Force approach to improving its development of engines. For example, in 1976, the Air Force Scientific Advisory Board called for greater emphasis on “engine mechanical and structural integrity and durability” and “durability and damage tolerance assessments ... analogous to those being performed on several weapon system airframes.” Similarly, in 1980, the Comptroller General recommended to Congress that engine development be complete before

⁷U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, charts 8-9.

production and that gas turbine developers address "reliability, maintainability, and durability as well as performance."⁸

ENSIP was a formal response to these studies and to lessons learned from increasingly sophisticated efforts to develop engines in the 1970s. It effectively implemented the recommendations of the 1976 Scientific Advisory Board. It provided "an organized and disciplined approach to the structural design, analysis, development, production, and life management of gas turbine engines with the goal of ensuring:

- a) engine structural safety
- b) increase[d] service readiness, and
- c) reduce[d] life cycle costs"⁹

To do so, ENSIP employed a profile of use over the engine's lifetime, like that used in the AMT, as the basis for ascertaining an individual engine component's performance over its lifetime. How long components last defines their durability; how well they perform under the high stresses internal to the engine defines their damage tolerance. The Air Force used a technique called a durability and damage tolerance assessment (DADTA) to identify typical structural failure modes associated with each engine component; the effects of failure modes—in particular, whether they affected flight safety, how each failure mode occurred over time and how it could be predicted, and how specific failures could be prevented or managed to preserve flight safety and engine durability. DADTA presupposed engineering analysis to predict where and when failures would occur in an engine and an effective empirical test regime in which to test these predictions. The AMT provided that test regime.

For example, ENSIP initially attempted to design the cold parts of an engine with a life equal to that of the airframe and hot parts with a life equal to half of that. It then used DADTA methods to determine whether these goals are viable. ENSIP developed a set of component lives that could be sustained.

This process gave special attention to critical parts that might fracture during operation. Fractures generally develop from initial flaws whose progress can potentially be monitored. The analytic process determines how far such flaws can progress without inducing a fracture and how long such progress takes, in cycles or hours; this time becomes the design life for a critical part. The process then schedules an inspection to occur half way

⁸U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, charts 4–5.

⁹U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, chart 36.

to this design life for each critical part in the engine. This process yields damage-tolerant design.

The ENSIP approach and its constituent techniques could first be applied in the design of a new engine and then used repeatedly through the engine's lifetime. Table 3.2 presents the Propulsion SPO's 1982 view of the range of tasks that might be included in this loop.

At the beginning, the approach provided a way to set specifications on engine durability, reliability, availability, and maintainability. It provided an analytic approach to designing against such specifications and testing as the designs proposed.

Table 3.2
The Five ENSIP Tasks

I.	Design Information ENSIP master plan design service life and usage requirements design criteria
II.	Design Analysis of Components and Material Characteristics design duty cycle materials and processes design data characterized structural thermal analysis manufacturing and quality control
III.	Component and Core Engine Testing strength testing damage tolerance tests durability tests thermal survey vibratory strain and flutter boundary survey
IV.	Ground and Flight Engine Tests environment verification testing AMT test specification derived durability tests (AMT) damage tolerance tests flight test strain survey updated durability and damage tolerance control plan perform deterioration structural impact assessment critical part update
V.	Production Quality Control and Engine Life Management production engineering analysis structural safety and durability summary engine structure maintenance plan individual engine tracking Lead the Force program (usage) durability and damage tolerance control plan implemented technical order update

SOURCE: U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, chart 40.

But the process need not and should not stop when the engine was fielded. Linked to a good information system on the experience of individual engines, this approach provided a framework for managing problems identified during field operations and bringing them into the CIP for resolution or amelioration. If mission profiles changed, it allowed a way to predict the effects on an engine and the maintenance and redesign efforts that should be undertaken in anticipation of such a change. If new materials or component designs became available, it provided a way to predict and test the likely effects of exploiting such innovations and adjusting maintenance policy in anticipation of their introduction.

That is, such activities closed the engine-management loop by continually bringing operational information back to the ongoing development process and using the best operational information available to inform ongoing development under the CIP for the engine in question or other efforts to develop follow-on engines.

ENSIP was working its way from a proposal to a formal set of Air Force regulations when our developments began. As formal regulations implementing ENSIP neared completion, the Propulsion SPO looked for ways to implement the basic ideas underlying ENSIP in as many of its engine development activities as possible. It expected to implement all aspects of ENSIP in such new designs as the F109 and advanced tactical fighter (ATF). For established engines like the F100 and TF34, the Propulsion SPO expected damage tolerance assessments and AMTs to yield better estimates of component lives, improved maintenance and repair plans, and better improvements of new parts developed in the CIP. The Propulsion SPO planned to implement ENSIP on a more limited basis in the F101, F110, and F100 improvement developments. For these, it planned to use DADTA and AMT methods to improve their maintenance, repair, and support plans.

SUMMARY

The management of system development is risk management. System development is inherently risky; experienced managers seek a low-risk system design and then try to minimize the risks associated with development based on this design. While doing so, they must continually balance risks associated with the technology development itself against external risks associated with political and funding support for the program. Innovations in the formal methods available to the Air Force in the late 1970s improved its ability to manage the F100-PW-220 and F110-GE-100 developments and subsequent programs as well.

These innovations include the AMT, a rigorous, empirically based durability test; the four-step process, which reduced concurrency between engine development and production and increased the importance of operability, supportability, and durability in engine

development; and ENSIP, a set of formal methods for understanding component failures and changing design and maintenance policies to reduce the probability and cost of such failures.

All these innovations played a role in ensuring the success of the developments we examine here. In the end, however, risk management cannot be separated from the experienced manager and his or her judgment. The creation of the Propulsion SPO promoted continuity from one engine development to the next, bringing important lessons learned from the past to bear on the F100-PW-220 and F110-GE-100 developments, and contributing significantly to the Propulsion SPO's reputation as an organization that assesses and manages risk well.

4. A BRIEF HISTORY OF THE F110-GE-100 AND F100-PW-220 DEVELOPMENTS

The F100-PW-220 and F110-GE-100 are best known as the engines that brought competition to the Air Force in the Great Engine War of the early 1980s.¹ More formally, this competition was called the Alternate Fighter Engine competition between Pratt and Whitney (P&W) and General Electric (GE).

In the mid-1970s, P&W dominated the military engine business. It had triumphed over its primary competitor, GE, in the source selection to provide engines for the F-15 fighter in 1970, and the Air Force selected a minor variation on the same engine for its F-16 fighter, introduced in 1978. These were the F100-PW-100 and F100-PW-200 engines, respectively, and became the basis for P&W's F100 "family" of engines. GE won the source selection to provide engines for the B-1 bomber, but that procurement was subsequently canceled in 1977 before production began, leaving GE with little military engine business.

The first "skirmishes" of the Great Engine War effectively began when GE endeavored to use the engine it had developed for the B-1, the F101-GE-100, as the basis for a fighter engine. GE initially targeted the market for reengining the Navy F-14 but, on the basis of Air Force interest, shifted its emphasis to include the F-16 and then the F-15. That effort led to the development of the F110-GE-100. In the meantime, P&W tried to stop that development effort before it could yield a feasible alternative to its F100 engines, but ultimately countered with an engine based on its own F100, the F100-PW-220.

This section outlines the origination process for the F110-GE-100 and F100-PW-220 engines. It presents the key facts in the Air Force's efforts to develop two derivative fighter engines that could then contend against one another in its Alternate Fighter Engine production competition in 1984 and in subsequent years. It describes the basic engines involved, the development tasks required to reach the final competing engines, and the contracts used to implement those developments. It also describes the basic Air Force environment in which the developments occurred and the resources required to complete them.

THE INITIAL SETTING

When P&W designed the F100 for the Air Force, the Air Force emphasized a dramatic increase in thrust, a change from the 4:1 thrust-to-weight ratio in the best fighter engines

¹For useful general discussions of this competition, see Drewes, 1987; Kennedy, 1985; Mayes, 1988; and Ogg, 1987. This section draws on all these sources, especially Drewes.

preceding the F100 to 8:1. Early in the development, P&W engineers noted that the engine they were developing would be expensive to maintain. Air Force officials told them not to worry about that then; that was something they could address once the anticipated increase in thrust was achieved.² It was. The advance was so great that Air Force fighters for the first time had a thrust-to-weight ratio of greater than one, allowing pilots to change dramatically the tactics they had used in the past. One result was that pilots used many more engine cycles—essentially, throttle movements from low power to high power and back—per flight hour than they had in the past. This change placed even more stress on the engines than the designers had anticipated, increasing maintenance costs and reducing the engines' effective lives. In sum, the Air Force had a powerful new engine that was extremely expensive to use.

The F100 had an additional problem. In certain flight conditions, it experienced stall-stagnations: "An engine stall is a momentary hesitation in engine operation caused by a disturbance in the air flow and resulting in an aerodynamic stall of the compressor blades. If the stall is not self-recovering through immediate adjustment of the air flow, it is called a stagnation. The pilot must shut down the engine and restart it."³ F-15 pilots could readily recover with two engines and at high altitudes. But this problem made flight at lower altitudes or under pressure in combat unacceptably unsafe. And the Air Force expected the problem to increase for F-16 pilots, who would have only one engine to rely on.

The Air Force turned to P&W to fix both these problems. P&W pointed out that it had met the Air Force's specifications for the engine and had in fact warned the Air Force about the likely problem of high operating cost. P&W stood ready to help the Air Force resolve these problems, but only if the Air Force was prepared to compensate it fully for its work.

Pratt and Whitney's firm stand and aggressive negotiating style during a period when it was manufacturing an engine that many in the Air Force felt was inadequate increasingly alienated officials in the Air Force. Many of those officials came to regret P&W's dominant position in the fighter engine business, believing that P&W would not be so arrogant and unresponsive if it faced a viable competitor. Dissatisfaction with P&W deepened and spread through the Air Force as time passed with no resolution of the problems. Additional support for finding a competitor grew when a number of key P&W subcontractors went on strike in 1979, endangering the Air Force's ability to field new F-15s and F-16s as their manufacturers completed their airframes.

²For details, see Ogg, 1987.

³Drewes, pp. 51-52.

Meanwhile, GE was looking for an implementation of the technology it had developed for the F101-GE-100 engine. GE had a long-standing business philosophy of building families of engines based on similar cores. If GE could use the core components it developed in more than one engine, it could effectively recover its development costs more easily and use learning in production to drive down the costs of producing those components more rapidly. These factors would make it more competitive, especially in the civilian aviation industry where it had a significant foothold. GE was marketing the CFM-56 engine, an engine closely related to the F101, to the private sector. If it could find a military market for that engine or use of its core components in a related engine, it could increase its competitiveness.

GE's first target for a military engine was a fighter engine to replace the TF30 engines in the existing, under-powered Navy F-14. In 1975, GE assembled a demonstrator from components used in or based on its F101 and F404 engines. GE sized this demonstrator, which became known as the F101X, to power the F-14. But the Navy did not place a high enough priority on reengining the F-14 to pay for its likely billion-dollar cost. GE turned to the Air Force. The Air Force was impressed enough to continue monitoring GE's work. The Air Force also initiated several small studies in its own laboratories to explore several technical issues associated with developing the F101X further.

The Air Force was particularly impressed by the fact that the F101X seemed to address the two big problems it had with the F100: operating costs and stall-stagnations. First the F101X incorporated a long-life core section from the F101 engine that should have dramatically reduced operating costs. When the B-1 mission changed to require low-altitude flight, the number of cycles expected on the F101 engines increased dramatically and, hence, durability became a high priority for the engines. When the B-1 was canceled, GE engineers used what they hoped was a hiatus to continue increasing the durability of the engine core. Such a core could help address one of the key problems that the Air Force was then experiencing with the F100 engine. Second, GE used a closed-loop control system that effectively eliminated stall-stagnations. As Air Force aggravation with P&W grew, the F101X looked increasingly attractive as a viable threat that the Air Force could use to make P&W more responsive.

By 1979, the Air Force was ready to fund GE to present just such a threat. An Air Force-Navy memorandum of understanding provided initial funding for engine development in a way that heavily favored GE. The Air Force justified this imbalance at the time in testimony to Congress, which stated that

Pratt will be working from a development funding base on the F100 and TF30 engines in excess of \$2 billion and an experience base in afterburning turbofan fighter engines of 14 years. GE will be working from a development funding base on the F101 of \$0.7 billion with no previous experience.⁴

That statement quite succinctly summarizes the circumstances at the beginning of the two developments we examine here.

THE GE F101 DFE AND F110-GE-100

Air Force support for competition coalesced in stages. Table 4.1 summarizes the major events in the competitive developments. Development began in an Engine Model Derivative Program (EMDP) in 1979 that completed the initial design for the engine based on the GE F101X and began initial testing. After the EMDP began, the Air Force expanded it to perform more extensive development and design work. When the work verified that GE could in fact provide an alternative to the F100, the Air Force added funding to keep the design team in place while it considered whether to initiate a formal competition. By 1982, the Air Force was committed to a competition and issued a full-scale development contract for the new GE engine, which would be known as the F110-GE-100. In 1985, the Air Force extended this effort to include a number of post-qualification tasks. As production engines became available, the Air Force set up an accelerated operational testing, or "Lead the Force," program to check performance in the field. It also set up the Component Improvement Program, which DoD customarily employs to handle problems in engines that come to light after they are introduced. This section reviews each stage of the development program for the F110 engine.

The Engine Model Derivative Program

The first clear step in development occurred in 1979, when the Air Force was looking for an opportunity to initiate an Engine Model Derivative Program.⁵ The F101X looked like a good candidate. An EMDP could be executed for a small cost to the Air Force and at fairly

⁴Quoted in Drewes, 1987, pp. 101-102.

⁵EMDP was based on the Component Improvement Program, a class of development effort that the Air Force had used to respond to operational problems in fielded engines. Over time, the Air Force used its annual CIP program more and more, not just to realize the expected performance of existing engines after they were fielded, but to improve the performance expected from them. Congress saw such efforts as an attempt to end-run its oversight authority on new engines. In 1968, Congress created the EMDP vehicle as a formal device that allowed such derivative development, but gave it more direct visibility. The Air Force did not actually use the vehicle until 1979.

Table 4.1
Timeline for F110-GE-100 and F100-PW-220 Developments

Date	Production Competition	F110-GE-100 Development	F100-PW-220 Development
1979			
Feb		F101 DFE EMDP begins	
Jul			F100 EMDP begins
1980			
Apr			Testing begins
1981			
Jan	Air Staff has acquisition strategy for competition		
Jun			EMDP expands
Aug	RFI issued		
1982			
May		TED begins	
Sep			FSD begins
Nov		FSD begins	
Dec	Draft RFP issued		
1983			
May	Final RFP issued		
Jun			-220 specification called for
Dec	Best-and-final offers		
1984			
Feb	Source selection		
1985			
Jan		Product validated	
Feb		First production engine	
May			DEEC/GP qualified
Jul		CED begins	GP/BPV qualified
			ILC upgrade qualified
Nov			-220 product validated; first production engine
1986			
Aug			First delivery to operational unit
[n.d.]		First delivery to operational unit	

low risk, demonstrating the value of the EMDP concept. And it offered the potential benefit of threatening P&W with competition and thereby simplifying the Air Force's problem of managing its most important engine at the time, the F100. Despite intense opposition from P&W, the Air Force acquired the funds needed to initiate this demonstration. By February 1979, a 30-month firm-fixed-price contract for \$79.7 million was in place for the F101 DFE

(Derivative Fighter Engine) EMDP. The Air Force was the lead service in this joint program with the Navy and dominated the development throughout.⁶

The contract called for GE to "complete the initial design [for], develop, and test a Derivative Fighter Engine" based on the F101 engine and "using the F101 core engine design to the full extent possible.... A primary goal [was] to define and develop the Derivative Fighter Engine to the point where a flight test demonstration [could] be safely and economically conducted in F-16 and F-14 aircraft. An equally important goal [was] to provide a base of design knowledge and test experience with the engine design to form a basis for decision making on future engine development and production options for the USAF and USN." This "limited development program" called for at least 1,000 engine ground-test hours and the refurbishment, acceptance testing, and delivery of three nameplate engines to the Air Force for flight testing. "At the conclusion of the Limited Development flight test program, ... [GE was to] submit engine characteristics [that GE would guarantee during full scale development, including] engine life, maintenance parameters, performance, reliability, and cost."⁷

GE came to this program with a well-articulated design. The proven F101 core required little further work. In early 1979, an Air Force review of risk factors associated with controls and accessories, augmentor, high-cycle fatigue, and inlet compatibility concluded that the use of many well-characterized engine components, a well-characterized inlet, and a logical pre-flight testing sequence ensured a low-risk F-16 flight test evaluation. And Air Force planners expected the F101's ruggedness to help them control some of the higher risks normally present in an engine test program. The primary tasks remaining in the engine design were characterization of the design in the full, anticipated flight envelopes of the F-14 and F-16 and refinement of software, parameter settings, and other aspects of the design that remained variable in a fixed hardware design.

At first glance, it might appear that developing a new engine for the one-engine F-16 would be riskier than developing one for the two-engine F-15, which could always fly with one proven engine while testing the new engine. Unfortunately, GE's F101 DFE would not

⁶The principal differences in the goals of the Air Force and those of the Navy at the beginning of this development were in the airflows they sought and resulting differences in the control schedules they needed. The Navy wanted to exploit the full potential of the engine; the Air Force chose initially not to. To deal with these differences, each service depended on its contractors. Most interservice coordination took place through GE, General Dynamics (the F-16 prime contractor), and Grumman (the F-14 contractor).

⁷U.S. Air Force, Aeronautical Systems Division, Letter Contract F33657-79-C-0176, Wright-Patterson Air Force Base, Ohio, 26 January 1979, Attachment 1, pp. 1-8. This language is consistent with that in the definitized contract, issued as Modification PZ0003 of Contract 79-C-0176 on 16 July 1979.

fit in the F-15. Developers expected risks to be higher if they attempted to alter the engine to fit the F-15 than if they used a simpler test engine, closer to earlier proven designs, in the one-engine F-16. For a similar reason, early efforts with the F101 DFE did not contemplate any changes in the F-16 inlet. Changes from earlier designs were kept to a minimum to control risk in the early stages of development. Only later, as the design matured and proved itself, did developers adapt the F101 to the F-15 and optimize aircraft inlets for the new engine.

During the course of the EMDP, the Air Force expanded its work scope to include construction of an additional engine that GE could use to "improve the operability, life, and performance balance of the F101 Derivative Fighter Engine limited development design . . . based on the experience gained during the limited development program. Engine design faults identified in both the ground- and flight-test programs [were to] be addressed and eliminated where possible. No high-risk design changes [were to] be made to the limited development design." As part of this expanded work scope, the Air Force required explicit but limited structural durability and damage tolerance assessments and additional durability testing.⁸ The Air Force also contracted for design work to make the F101 DFE compatible with the F-15.⁹ This effort initiated a significant redesign effort in the context of this development, which yielded a "slimline engine" with a profile compatible with the F-15 engine bay, which required a smaller engine than the F-14 and F-16. The slimline engine simply changed the locations of some auxiliary engine equipment. These changes increased the size of the contract to \$101.8 million.

The largest problem that GE and the Air Force faced in this development was funding. In part because P&W attempted repeatedly in the Congress and elsewhere to derail the development effort, the F101 DFE EMDP operated in a continuously precarious funding environment. In the end, however, P&W's tactics produced precisely the opposite effect from that intended: P&W's aggressive efforts to cut funding to GE, together with its unwillingness to correct problems with the F100, consolidated support for the F101 DFE within the Air Force and probably ensured that sufficient funding and management support would be available to complete the EMDP.¹⁰

Meanwhile, other events increased the likelihood that GE's efforts would yield a viable engine. President Reagan's totally unrelated decision to reinstate the B-1 program, made in

⁸U.S. Air Force, Aeronautical Systems Division, Modification P00017 to Contract 79-C-0176, Wright-Patterson Air Force Base, Ohio, 1 October 1980, Attachment 1, pp. 1-5.

⁹U.S. Air Force, Aeronautical Systems Division, Modification P00020 to Contract 79-C-0176, Wright-Patterson Air Force Base, Ohio, 14 August 1981, Attachment 1, p. 1.

¹⁰Details of P&W's efforts to stop the GE effort are well documented in Drewes, 1987.

February 1981, and the Air Force's decision around the same time to use the CFM-56 in the KC-135, meant that production runs for major subsystems in the F101 DFE would be much longer than expected, substantially reducing the cost of producing the F101 DFE. In addition, commonality in tooling for these engines would cut the cost of tooling for the F110 by more than 50 percent. Together, these considerations reduced the production costs for the F110 by 25 percent, helping it to become a viable competitor with the upgraded F100.¹¹

When GE successfully completed this program of development, it was clear that the F101 DFE could in fact provide an alternative to the troublesome F100 if the Air Force wanted one. As early as January 1981, the Air Staff established a fighter-engine acquisition strategy to compete the F101 DFE against an improved F100.¹² An active debate escalated within the Air Force.¹³ How much would it cost? What engine capabilities would the two contractors deliver in a competition? A request for information from GE and P&W issued in August 1981 produced some useful answers to these questions, but Air Force decision makers needed more time before they would commit to a competition.

Transition to Engineering Development

To keep the F101 DFE design team intact while deliberations continued, the Air Force extended the F101 DFE EMDP through March 1983, adding \$31.2 million to the contract to allow additional testing and to prepare for a potential full-scale development. This preparation included the design of a common configuration for engines to be used in the F-14, F-15, and F-16 that could be qualified for production in full scale development. To achieve that design, GE initiated associate contractor agreements with McDonnell Douglas and General Dynamics, the manufacturers of the F-15 and F-16, and initiated the development of interface control documents to specify the details required to integrate this engine with the two aircraft. This effort also included design tasks to make the engine producible, including "cost reductions, weight reductions, and corrective actions resulting from evaluation of engine flight test data." And it included developing a "rationale for the level of the engine monitoring system to be developed for the F101 DFE engine." The Air Force called this extension the Transition to Engineering Development.¹⁴

¹¹Drewes, 1987, p. 145; Kennedy, 1985, p. 11.

¹²Our description relies in part on official Air Force histories of various Aeronautical Systems Division programs written by C. J. Geiger in 1981-1982. Because those unclassified histories are chapters in classified Air Force documents, we cannot provide explicit citations in this document.

¹³For details, see Drewes, 1987; Kennedy, 1985.

¹⁴U.S. Air Force, Aeronautical Systems Division, Modification P00022 to Contract 79-C-0176, Wright-Patterson Air Force Base, Ohio, 1 May 1982, Attachment 1, pp. 3-4.

Full-Scale Development

In October 1981, the Air Force Council on Fighter Engine Acquisition Strategy recommended qualification programs for the F101 DFE and F100 DEEC, an improved version of the F100.¹⁵ By the end of 1981, the Air Force had concluded that a competition made sense. The Air Force worked through 1982 to build support for the idea and ultimately issued a draft request for proposals to GE and P&W in December 1982. That action effectively began the formal Alternate Fighter Engine production competition. In anticipation of that action, in November 1982, the Air Force initiated a full-scale development contract for the production version of the F101 DFE, the F110-GE-100.¹⁶ Under this firm-fixed-price contract, GE would modify one engine from the EMDP and fabricate two additional engines to the full-scale-development specification to use for durability and other testing. GE would then "perform those development activities necessary to verify that the F110 engine meets the requirements of the F110 Prime Item Development (PID) Specification. . . . [GE would also] accomplish the necessary studies with the F-15 and F-16 contractors to assure engine/airframe compatibility." The contract required GE to assess its new engine relative to the standards set by ENSIP standards and to develop a maintenance plan based on those standards. It also required GE to develop an engine monitoring system, using existing systems to the full extent possible. GE and the Air Force negotiated a price of \$109.3 million for this work.¹⁷

Development ran fairly smoothly on this contract. GE and the Air Force completed the critical design review on the production-verification design in January 1983. Construction of the first slimline engine was completed shortly thereafter. Full-scale development consisted in large part of efforts to test this slimline version, and to construct and qualify final production-verification engines. The Air Force and GE negotiated a series of small adjustments in the work scope during 1983 and 1984, but for the most part development proceeded as planned. The primary difficulty was a persistent tendency for GE to be late on the test plan and other parts of the development plan and on reports and other deliverables; Section 5 discusses this problem in more detail.

¹⁵Nelson, 1983a. We discuss improved F100 engines below.

¹⁶The EMDP effort did not stop at this point. It continued in an effort to demonstrate and validate concepts that would lead to the next derivative engine based on the F110, the F110-GE-129 improved performance engine (IPE). That engine would allow engine competition to continue when the Air Force procurement of the F110-GE-100 was complete. It reflected the Air Force's continuing commitment to competition for engines.

¹⁷U.S. Air Force, Aeronautical Systems Division, Contract F33657-82-C-0257, Wright-Patterson Air Force Base, Ohio, 15 November 1982, pp. 2, 4-6; Attachment 1, pp. 1, 8-9, 14.

In the meantime, the Air Force issued the final request for proposals to GE and P&W for a production competition in May 1983 for 2,004 engines for F-15s and F-16s during fiscal years (FYs) 85-90.¹⁸ Among its many stipulations, the request required a warranty with clearly defined and stringent terms that essentially shifted the risk of failing to meet stated performance goals to the contractor. GE submitted a best-and-final offer in December 1983. And in December, acting on a request from the Office of the Secretary of Defense earlier in the year, the Defense System Acquisition Review Committee (DSARC) reviewed the proposed production competition. In its approval, it noted the importance of the planned warranties to the management of remaining risk in the development efforts. In February 1984, the Air Force awarded production contracts for FY 85, giving GE an award for 120 engines in F-16s, or 75 percent of the total awarded in the competition. That award provided the first tangible evidence that a market would exist for the engine that GE was verifying in full-scale development. Three days later, the Navy chose a close variation, the F110-GE-400, to reengine the F-14. A number of foreign governments quickly followed suit.

Continuing Engineering Development

The plans in the full-scale-development contract brought GE very close to completing all tasks required for initial production release. Using a modification in the full-scale-development contract, the Air Force initiated a continuing engineering development focused on four "post qualification" development efforts that would yield operational capability release under the four-step development process:

- (a) "development and test requirements of F110-GE-100 engine parts not included in the FCA [functional configuration audit] configuration[,] . . . parts never qualified and parts which have been qualified, but may be manufactured by a second, supplemental vendor;"
- (b) improvement and verification of "the predicted life of life-limiting parts of the F110-GE-100 engine, thus permitting the achievement of the 4,000 TAC cycle (AMT VII) inspection interval goal;"
- (c) "simulated altitude testing to characterize engine performance and deterioration, to update the computer model and to define control schedule tolerances;" and

¹⁸The production run could be much larger. One estimate at the time expected the Air Force to buy 1,200 engines during FYs 85-87 and 1,500 in FYs 88-90 for the F-15 and F-16, and the Navy to buy 600 engines for the F-14 during FYs 87-90. Significant foreign military sales were also expected.

- (d) "definition and qualification of selected improvements and modifications to problems identified during . . . testing."

That effort effectively extended the full-scale-development contract until December 1985 and added \$22.3 million to the contract.¹⁹

Multinational coproduction of F-16 subsystems made point (a) important. The F-16 was seen as a multinational fighter, and the identification of the F-15 as the first application for the F110 opened the way for more detailed selections of manufacturing vendors for engine subsystems. The Air Force's new doctrine on extending engine lives added point (b) by effectively requiring that all cold-section components have a life of 8,000 cycles, twice that of the hot section demonstrated in the full-scale development. Persistent "screech" and "thump," and other problems discovered late in development motivated point (d). Screech was a dangerous condition that resulted from dynamic pressure oscillation in the augmentor under certain predictable flight circumstances; thump resulted from a shock wave in the engine inlet that was not dangerous, but that disturbed enough pilots for the Air Force to seek a solution. Section 5 returns to these problems.

Like FSD, this effort ran fairly smoothly. The inspection interval for cold sections of the engine was successfully extended. The sources of the screech and thump problems were determined, and an interim fix was developed for screech. The Air Force began to flight-test a large-mouth inlet on the F-16 that allowed the aircraft to take greater advantage of the engine's thrust potential and, coincidentally, eliminated the thump problem. Problems with qualifying the engine monitoring system, on the other hand, persisted. The Air Force and GE negotiated a number of small changes in work scope. The largest was a (not to exceed) \$5 million adjustment in the contract price to pay for additional work on F110/F-15E integration in May 1986. Development activities continued, but the focus of the F110 program shifted rapidly to production as the Air Force accepted the first production engine in February 1985, accepted the first operational engine in October 1985, and fielded the first squadron of F-16s equipped with F110 engines on schedule in late 1986.

Further Testing and Development

As F-16s designed to use the F110 became available, the Air Force implemented a Lead the Force program called Pacer Ten to monitor the engines' performance in the field

¹⁹U.S. Air Force, Aeronautical Systems Division, Modification P00039 to Contract 82-C-0257, Wright-Patterson Air Force Base, Ohio, 26 July 1985, definitized by Modification P00045 to Contract 82-C-0257, p. 1; Attachment 1, pp. 1-4.

and prepare to respond to operational problems detected. That program provided for an accelerated usage rate on early engines delivered to the field and special monitoring to look for problems that might appear in the fleet as engine flying hours accumulated. And funding for the Component Improvement Program, conducted jointly for the F101 and F110 engines to reflect the close relationship, provided a way for the Air Force to develop solutions for problems that arose among fielded engines. Congressional decisions in late 1986 to reduce funding for the CIP and encourage contractors to assume more responsibility for the cost of engine modifications promised to complicate the continuing development and refinement of the F110 engine.²⁰

The Expenditure Profile

Figure 4.1 summarizes the total Air Force expenditure profile for that development. GE put additional resources into the continuing development, the most important being at least \$20 million during its development of the F101X demonstrator. The total cost of \$330 million (in then-year dollars) was substantially less than the \$1.5 billion that the Air Force would have expected to pay to develop a new "centerline" engine—an engine based on a

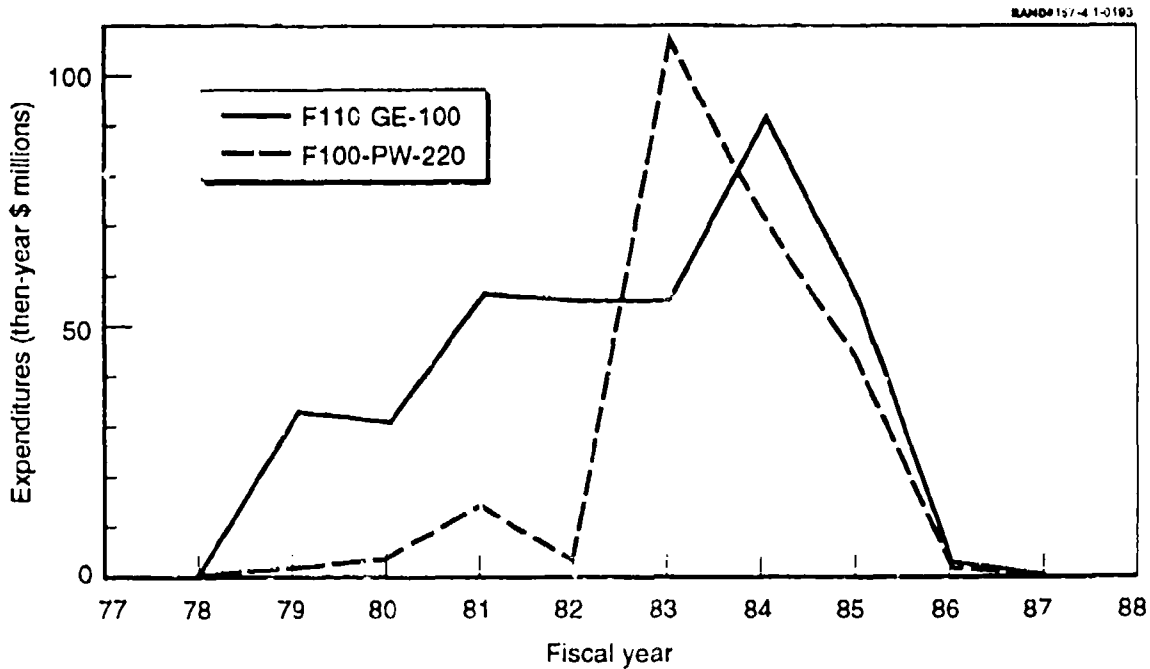


Figure 4.1—Air Force Expenditure in F110-GE-100 and F100-PW-220 Developments

²⁰Aldridge, 1986, p. 219.

new design instead of a derivative design.²¹ In the end, relative to the F100(3) engine used by the F110 development as a baseline for comparison, the new engine essentially eliminated stall-stagnations, instability in the augmentor, and trim during maintenance;²² improved pump reliability an order of magnitude; halved resources required for intermediate maintenance; more than doubled the time between depot overhauls; and substantially reduced performance loss over the life of the engine (see Table 4.2). The basic improvements realized actually exceeded those expected when the development began. It became a successful competitor not just for Air Force purchases but also for foreign military sales, where its thrust advantage over the F100-PW-220 gave it additional appeal.

THE P&W F100-PW-220 AND RELATED F100 ENGINES

In comparison with the development of the F110-GE-100, that of the F100-PW-220 looks much less focused (see Table 4.1). But that development occurred in a different context. In the late 1970s, the F100 was the Air Force's most important engine, both because of its prominence in the fleet and its continuing high-level production rate and because it was creating such difficult problems for the Air Force. The Air Force and its manufacturer, P&W,

Table 4.2
Performance Improvements Allowed by the F110-GE-100 and F100-PW-220

Characteristic	F100(3)	F110-GE-100	F100-PW-220
Operability/Safety			
Stall-stagnations/1000 FH	0.2-1	0	0-0.05
Pump reliability/ 100,000 FH	0.9	0.05-0.1	0.1-0.2
Augmentor operation	R2, R3 instability	no instability	no instability
Supportability			
Trim time (minutes)	80	none	none
Cost/FH	\$585	\$215-315	\$285-345
MMH/FH	8.5	3.3-4.3	4.0-4.6
Removals/1000 FH	7.3	3.0-4.0	3.6-4.4
Life of Hot Section (cycles)	1,800	4,000	4,000
Performance Loss	1%/400 cycles	<2%/4,000 cycles	<2%/4,000 cycles

SOURCE: Bethel and Wood, 1986.

NOTES: R2 and R3 are the names of spray rings in the augmentor. Trim is a time-intensive maintenance activity analogous to tuning an engine. FH is flight hours. MMH is maintenance man-hours.

²¹Kennedy, 1985, p. 1.

²²Trim is a time-intensive activity analogous to tuning an engine; it could be eliminated when the F110-GE-100 offered a closed-loop control system.

were actively attacking those problems on a number of fronts. Efforts on five engine subsystems are of particular interest to us:

- increased life core (ILC)
- improved augmentor (including a light-off detector, LOD, and a dual-ignition system, DIS)
- digital electronic engine control (DEEC)
- gear-type fuel pump and bypass valve (GP, BPV)
- engine monitoring system (EMS).

P&W ultimately incorporated all five new systems, together with some less important ones, in the F100-PW-220 engine it offered for competition with the F110-GE-100 in the Alternate Fighter Engine competition. For all intents and purposes, however, the -220 development was just one of a series of closely related efforts that P&W pursued to enhance its F100 family of engines. P&W incorporated each of the above changes either in new production F100 engines or, through retrofit, in existing F100 engines in the fleet. Because all such development efforts occurred in tandem, it is hard to disentangle them. In fact, the development program for each modification created information that supported the ultimate creation of the -220 engine. In the end, however, a single office in the Propulsion SPO had responsibility for the -220 development itself and ensured that it occurred in an orderly, efficacious manner.

On the basis of a series of business strategy meetings and an evaluation of an unsolicited F100 growth proposal from P&W, the Air Force initiated an EMDP for the P&W F100 at the same time that it began the F101 DFE EMDP. The Propulsion SPO saw this program as part of a broader effort to improve the F100, motivated at least as much by the opportunity to use the EMDP funding vehicle as by specific interest in an engine competition at the time. While the EMDP would address operability problems, the CIP would address durability, and P&W's independent research and development (IR&D) program would address enhanced thrust. The discussion below focuses on the EMDP, then the CIP, and finally the full-scale-development program that yielded the F100-PW-220 and related innovations.

The Engine Model Derivative Program

The firm-fixed-price F100 EMDP contract called for P&W to "conduct a pre-FSD limited development/validation activity which introduces demonstrated advanced component

technology into the F100 production engine design to provide the basis for capitalizing on improvements in specification performance and lowering ownership costs." The work involved a "limited development and flight test program required to obtain data defining the operational benefits and capability of a F100 engine in incorporat[ing] a Digital Electronic Engine Control (DEEC) System, a Swirl Augmentor (SA), an augmentor Light-Off Detector (LOD), and augmentor Dual Ignition System (DIS)." To do so, P&W was to complete initial design of the LOD and DIS and refine other designs as necessary, procure or refurbish hardware for two F100 EMDP flight-test kits, conduct a specified set of ground tests, and support up to 19 F-15 and 53 F-16 test flights. This effort was priced at \$19.6 million and scheduled to continue through September 1983.²³ The Navy and NASA pursued related interests, adding their own funding and engines to the research effort.

The development got off to a rocky start. A lack of funding early in the contract delayed the start of testing at Arnold Engine Development Center (AEDC), the Air Force's principal engine ground-test facility, from July 1979 to March 1980. The delay threw off the test schedule at AEDC and complicated P&W's effort to get access when funding did become available. Once testing began, P&W quickly established that the swirl augmentor, which it had proposed to use as a proven technology in the EMDP configuration, would not enhance performance as expected; Section 5 addresses this problem in more detail. The development then settled down, and the program generated results as expected.

The work scope for this effort expanded dramatically in 1981. Early plans for the EMDP anticipated program growth to cover a broad range of engine improvements. Perhaps growing Air Force interest in competition at the time also encouraged growth in the F100 EMDP. In June 1981, the Air Force added \$11.2 million to the contract price to pay for additional ground tests, which included selective testing of an expanded engine configuration. The new configuration added an increased airflow fan, compressor durability and performance improvements, and an increased-durability hot section.²⁴ Strong Congressional support led to additional modifications in August 1982 and July 1983 that changed the tests required by the original plan and substantially increased the work scope to address a new long-life, low-pressure turbine; design changes in the anti-icing and fuel pump hardware; and substantially more sea-level, altitude, and AMT testing of the expanded F100

²³U.S. Air Force, Aeronautical Systems Command, Letter Contract 22657-79-C-0541, Wright-Patterson Air Force Base, Ohio, 1 July 1979; definitized in Modification PZ0001 to 79-C-0541, 1 May 1980. Attachment 1, pp. 1-8.

²⁴U.S. Air Force, Aeronautical Systems Command, Modification P00008 to Contract 79-C-0541, Wright-Patterson Air Force Base, Ohio, 8 June 1981; definitized in Modification P00010 to Contract 79-C-0541, 5 November 1981.

EMDP configuration. Those changes added a total of \$51.4 million to the contract price and extended the contract to August 1986.²⁵ Additional changes continued to expand this contract. Only the early portion of work done under this program fed into the F100-PW-220, however. Additional work would lead to the next generation of derivative P&W engines, the F100-PW-229 improved performance engine (IPE).

The Component Improvement Program

At the same time, the Air Force was using its F100 CIP to increase, among other things, the durability of the F100 engine core and thereby reduce operating costs. The CIP used a standard cost-plus-award-fee (CPAF) contract to cover this work and all the other tasks included in the CIP work scope at that time.²⁶

This effort represented the first formal application of the Air Force's new ENSIP framework for risk assessment. Progress on the life of the engine core continued over a long period as the time between depot overhauls rose from 1,250 cycles in 1979 to 4,000 cycles in the F100-PW-220. Progress made during 1981-1985 has been directly associated with the effort to develop the increased life core used in the F100-PW-220.²⁷ The CIP yielded a stand-alone upgrade package that could retrofit existing F100 engines with a 4,000-cycle core by late 1985. This same effort yielded the increased-life core required in the F100-PW-220. During this time, test engines passed frequently among the CIP, EMDP, and full-scale-development programs, illustrating the coordination among these efforts. And the CIP program played an active role in final product verification of the F100-PW-220, running endurance and other ground tests. In the closing months of the product-verification effort, -220 testing was the most important effort in the F100 CIP. CIP testing continued following product verification, in preparation for the normal role of CIP of identifying and resolving problems that arise in the course of normal engine operations.

During the 1981-1985 period, budgetary delays frequently led to the use of continuing resolution authorization to fund the CIP. Because the actual tasks undertaken in the CIP are extremely responsive to the level of funding available in any year, such delays created substantial uncertainty and confusion in the CIP. Apparently because CIP efforts related to

²⁵U.S. Air Force, Aeronautical Systems Command, Modification P00012 to Contract 79-C-0541, 13 August 1983, and Modification P00014 to Contract 79-C-0541, 1 July 1984, Wright-Patterson Air Force Base, Ohio; definitized in Modification P00015 to Contract 79-C-0541, 31 July 1984.

²⁶By 1980, the CIP concept was fairly mature and the contractual vehicle used to implement it each year was fairly standard. Some CIP flight-test activities were conducted under firm-fixed-price level-of-effort terms before 1980. But CPAF terms dominated the CIP during the years of greatest interest to us. The CIP normally uses such terms.

²⁷See U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, n. d.; Nelson, 1983b.

the increased-life core and the F100-PW-220 itself had high priority, this uncertainty did not seriously slow these efforts.

Full-Scale Development

The Air Force initiated the full-scale-development program relevant to the F100-PW-220 in September 1982. The full-scale-development program of interest to us initially sought to qualify three engine improvements for production incorporation, none of them the F100-PW-220 itself, but each closely related to it:

- (1) A digital Electronic Engine Control System/Gear-Type Main Fuel Pump (DEEC/Pump) System for F100-PW-200 engine production availability in March, 1984;
- (2) A Gear-Type Main Fuel Pump/Bypass Valve (Pump/Valve) System for F100-PW-200 engine production availability and field retrofit availability in July, 1984; and
- (3) An Engine Monitoring System (EMS) for use in conjunction with the DEEC System for engine production availability and field retrofit availability in July, 1985;

which are intended to improve durability, maintainability, operability, reliability, safety and life cycle cost of the F-16/F100 Weapon System."

This firm-fixed-price effort, priced at \$65.4 million, would design the four electronic units that made up the EMS, complete the design of the gear pump and the DEEC/Pump system, and modify the engine case design to mount new components. It would fabricate new hardware for the bypass valve and modify existing engine hardware to accept the DEEC. And it would conduct extensive ground tests and F-16 flight tests.²⁸ The effort set clear performance goals for selected parts of the development (see Table 4.3 for an example from the DEEC/gear pump portion of the F100 development); they would provide a basis for goals in the F100-PW-220 program.

The FSD program proceeded smoothly into 1983, exercising some important options. The program finally developed a specification for the F100-PW-220 engine in June 1983. Recall that the Air Force issued its final request for proposals for the Alternate Fighter Engine production competition in May 1983. This new specification brought together the DEEC, gear-type fuel pump, and engine-monitoring system envisioned in the initial work scope for this contract, and the increased-life core that P&W had been developing in the

²⁸U.S. Air Force, Aeronautical Systems Command, Contract F33657-82-C-2199, Wright-Patterson Air Force Base, Ohio, 30 September 1982, Attachment 1, pp. 1-2.

Table 4.3
Improvement Goals for the F100 DEEC/Gear Pump Development

Performance Goal	DEEC/Gear Pump System		Predicted Improvement
	F100(3) Lot X	F100(3) ^a DEEC/Pump	
Maintainability			
Engine trim ^b	Yes	No	Self-trim
MMH/EFH	5.6	4.2	25% reduction
Support costs, \$/EFH	480	395	18% reduction
Shop visit rate, SV/1000 EFH	4.0	3.6	10% reduction
LRUs, LRU/1000 EFH	5.9	4.1	30% reduction
Operability			
Stall rate per 1000 EFH	2.5	0.65	74% reduction
Stagnation rate (F-16)	0.15 per 1000 EFH	0.048 per 1000 EFH	68% reduction
Air start envelope (primary) ^b	250 KIAS	200 KIAS	50 knots
Augmentor transient ^b	36.5K/0.8Mn	45K/0.8Mn	9000-ft altitude improvement (2σ engine)
Backup mode ^b	Limited engine flight envelope	Unrestricted engine flight envelope	Unrestricted engine flight envelope
Safety			
Class A mishaps (F-16)	3.5	1.1	68% reduction
NRIFS) (MFP/100,000 EFH)	0.9	0.13	85% reduction
Cost			
Life-cycle cost	Base	\$185M reduction	Savings

SOURCE: U.S. Air Force, Aeronautical Systems Command, Contract F33657-82-C-2199, Wright-Patterson Air Force Base, Ohio, 30 September 1982, Attachment 1, pp. 3-4.

NOTES: MMH is maintenance man-hours; EFH is engine flying hours; LRU is line replaceable unit; NRIFS) is nonrecurring investment full-scale development; KIAS is knots-indicated speed; MFP is main fuel pump; SV is shop visit.

^aDoes not include diagnostics.

^bTo be demonstrated during this development program with primary fuel only.

F100 CIP, to create an engine that could satisfactorily compete with the F110-GE-100.²⁹ Initially, it was "simply" referred to as the F100 DEEC/GP/EMS/ILC, emphasizing that the developers viewed it at the time as just one more member of an expanding F100 family. It can be thought of as an enhancement that incorporates all of the changes discussed here in a single block change. The F100-PW-220 specification was completed later in 1983, and final testing of the configuration began shortly thereafter. The DSARC accepted the Air Force's plans for dealing with remaining risk and the Alternate Fighter Engine source selection in February 1984 awarded P&W 41 -220 engines for F-15s, a quarter of the total number of engines that the Air Force purchased in the first year of the competition.³⁰ This led quickly to additional buys by Egypt, Korea, Thailand, and Singapore; other foreign buyers joined them later.

Shortly before then, in September 1983, the full-scale-development program expanded to include an F-15 application of the DEEC/pump system by December 1985, adding \$5.7 million to the contract price.³¹ In November 1985, the Air Force officially qualified the F100-PW-220 engine for application in the F-15 and F-16. The Air Force accepted its first -220 engine in the same month. The first engine reached the field in an operational aircraft in August 1986, six months ahead of schedule. As noted above, CIP shifted its emphasis from supporting the qualification effort to supporting the -220 in the field. Anticipated shortfalls in CIP funding, however, were expected to hamper this effort.

In the meantime, development continued on the -220. Application to the F-15E continued. The Air Force added \$4.2 million to the contract price in August 1985 to redesign components of the F100-PW-220 EMS and develop software and maintenance procedures for the -220 EMS by February 1987.³² It added another \$1.9 million as recently as 1990 for additional work on the EMS.³³

As the scope of the full-scale-development contract makes clear, the developers were not wrong to think of the F100-PW-220, a.k.a. the F100 DEEC/GP/EMS/ILC, as only one

²⁹U.S. Air Force, Aeronautical Systems Command, Modification P00005 to Contract 82-C-2199, Wright-Patterson Air Force Base, Ohio, 29 June 1983.

³⁰In effect, P&W produced engines for the F-15 during the first year of the production contract while GE produced engines for the F-16. As time has passed, P&W's share of new production contracts has increased, enabling it to supply engines for F-16s as well.

³¹U.S. Air Force, Aeronautical Systems Command, Modification P00006 to Contract 82-C-2199, Wright-Patterson Air Force Base, Ohio, 30 September 1983; definitized by Modification P00009 to Contract 82-C-2199, 31 May 1984.

³²U.S. Air Force, Aeronautical Systems Command, Modification P00012 to Contract 82-C-2199, Wright-Patterson Air Force Base, Ohio, 30 September 1983; definitized by Modification P00014 to Contract 82-C-2199, 27 February 1987.

³³U.S. Air Force, Aeronautical Systems Command, Modifications P00017, P00018, and P00020 to Contract 82-C-2199, Wright-Patterson Air Force Base, Ohio, 11 May 1990, 6 September 1990, and 10 October 1990, respectively.

among several related efforts. Other F100 development efforts continued during this period. The gear pump/bypass valve effort qualified a new production kit by July 1984 and a retrofit kit a month later, beginning the most complex, comprehensive retrofit effort to date in the F100 program. Following its introduction, the Air Force ran a one-year field service evaluation of the retrofit. Eight modified engines were flown on an intensified operational schedule and carefully monitored for problems. Few appeared, and none was serious. By May 1985, P&W had qualified the DEEC/gear pump modification, allowing the Air Force to initiate a similar two-year field service evaluation of 41 production engines. It too found no serious difficulties. By late 1985, the Air Force was using the CIP to run yet another field service evaluation for an F100-PW-200 DEEC/pump/ILC retrofit, with equally good success. And P&W and the Air Force had reached agreement on an extensive program to retrofit existing F100-PW-100 and -200 engines with a 4,000-cycle core upgrade. All these efforts produced data very likely to assist developers as they approached the final qualification of the F100-PW-220.

The Expenditure Profile

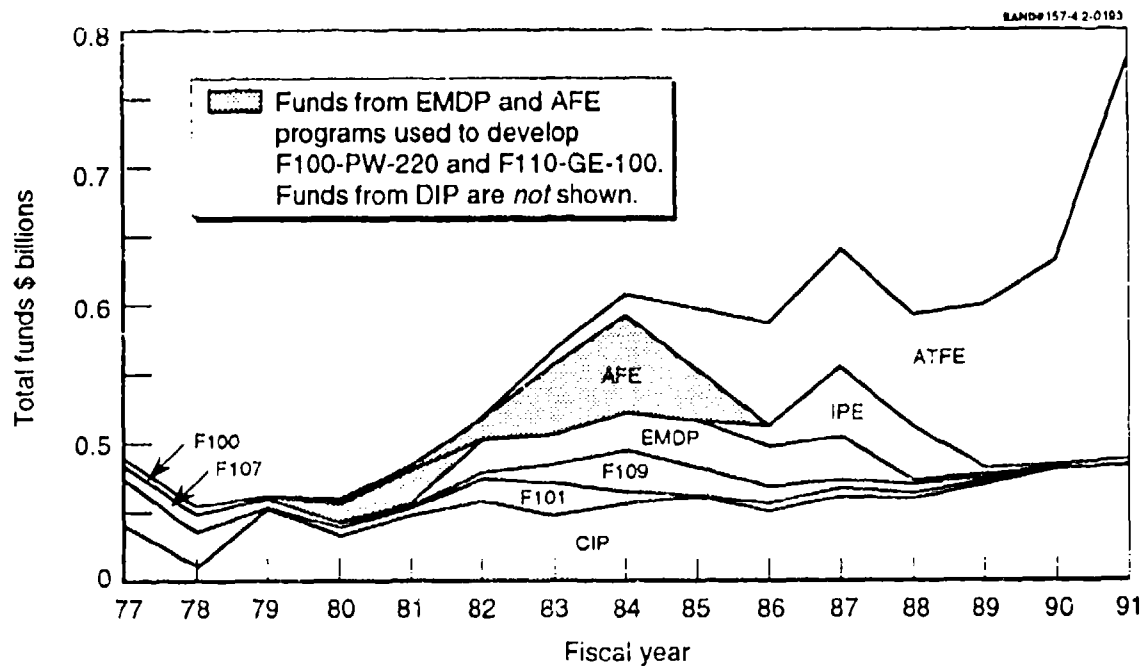
Such joint testing makes it difficult to attribute all costs to one program or another. The Air Force relates the costs shown in Figure 4.1 with the -220 development.³⁴ As with the F110 development, the -220 development cost the Air Force substantially less than development of a new centerline engine would have cost—\$227 million rather than \$1.5 billion. Relative to the F100(3) engine used by the Air Force as a baseline for comparison, the F100-PW-220 almost eliminates stall-stagnations, eliminates augmentor instability and trim, increases pump reliability five- to ninefold, reduces the resources required for intermediate maintenance 40 to 50 percent, doubles the time between depot overhauls, and significantly reduces performance loss over the life of the engine (see Table 4.3). The realized basic improvements actually exceeded those expected when the development began. The -220 engine continued to compete successfully with the GE F110 for Air Force production contracts until the IPE engines replaced both engines in the continuing GE-P&W competition in 1991.

³⁴ These costs include funds from program elements 27133F (gear pump), 64209F (F100 durability), 64223F (F100-PW-220 FSD), 64268F (ILC). See ASD Propulsion SPO, Office of Program Control (YZPR), Report to ASD History Office for January-June 1986, Wright-Patterson Air Force Base, Ohio, n.d.

BROADER CONTEXT

Within the Air Force, the Propulsion SPO oversaw the development and subsequent production of the two derivative engines. Unlike most SPOs, the Propulsion SPO oversees a number of systems and in fact remains intact as one system starts up and another closes down. During the development of the F110 and -220 engines, the Propulsion SPO oversaw RDT&E activities for a fairly large number of engine programs. Figure 4.2 illustrates the position of the two engines we are studying relative to the other programs overseen by the Propulsion SPO at the time. The figure shades relevant funds from the F101 and F100 EMDPs, which appear early in the overall EMDF, and the Alternate Fighter Engine (AFE) program, which effectively paid for full-scale development.³⁵ As the figure indicates, these engines accounted for a small fraction of the SPO's RDT&E activities over a period of about six years.

Two other points about this figure are worth emphasizing. First, the F110-GE-100 and F100-PW-220 engines are part of a continuum. They grew out of established engine



SOURCE: U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1986, p. 6-A-11.

Figure 4.2—Air Force RDT&E Expenditures on Engine Programs

³⁵As noted above, the CIP accounted for a portion of the -220 development and continued a low level of expenditure for both programs following FSD. But these quantities are not large enough to change the general picture offered by Figure 4.2.

programs (the F100 and F101) and provided the basis for follow-on, derivative engine programs (the improved performance engines, or IPEs). This explicit derivative development strategy is a reflection of a more general principle in engine development. Even new centerline engines inherit a great deal of technology from earlier engines. The management continuity offered by using a single SPO to oversee all engine developments facilitates transfer of technology from one engine to another, transfer of lessons learned in managing one engine development to the next engine development, and transfer of lessons learned from working with a particular contractor from one engine contract to another. (We return to these themes in Section 5.) Both the F110-GE-100 and F100-PW-220 developments were strongly shaped by earlier technological, management, and operational experience with the F100-PW-100 in particular.

Second, at any point in time, engine developments do not occur in isolation. Clearly, the competition between the F110-GE-100 and F100-PW-220 developments was apparent in both developments from beginning to end. It, more than any other factor, is what observers associate with these engines. In addition, the F100-PW-220 was only one of several closely related developments making incremental improvements in the F100; RDT&E expenditures for such improvements and for development to go beyond the F100-PW-220 are captured in the F100 and EMDP areas. The F110 and F101 developments were also working with very similar engines; however, unlike the improved F100 developments, they saw little coordination or synergy. The tight schedule imposed by Congress on the B-1B development led the Propulsion SPO to isolate its F101-GE-102 development to minimize outside factors that might complicate the development. In this case, the Propulsion SPO effectively had to forgo an opportunity for the kind of synergy it exploited in its F100 improvements.

Figure 4.3 offers another way to look at the F100-GE-100 and F100-PW-220 programs in relation to other Propulsion SPO activities. The percentage of entries in the Propulsion SPO Commander's "Weekly Activity Report" relevant to a particular program appears on the ordinate. If we take the percentage of citations as a measure of the Propulsion SPO commander's interest in a certain program,³⁶ we see interest growing with the expenditure on the F110-GE-100 and F100-PW-220 programs, but reaching a higher proportion of the commander's focus than of his budget. In fact, the competition between these engines

³⁶Alternatively, because the ASD commander is the consumer of this weekly report, we might take it as a measure of the ASD commander's interests in activities within the Propulsion SPO. Either way, the percentage offers a useful index of Air Force management interest.

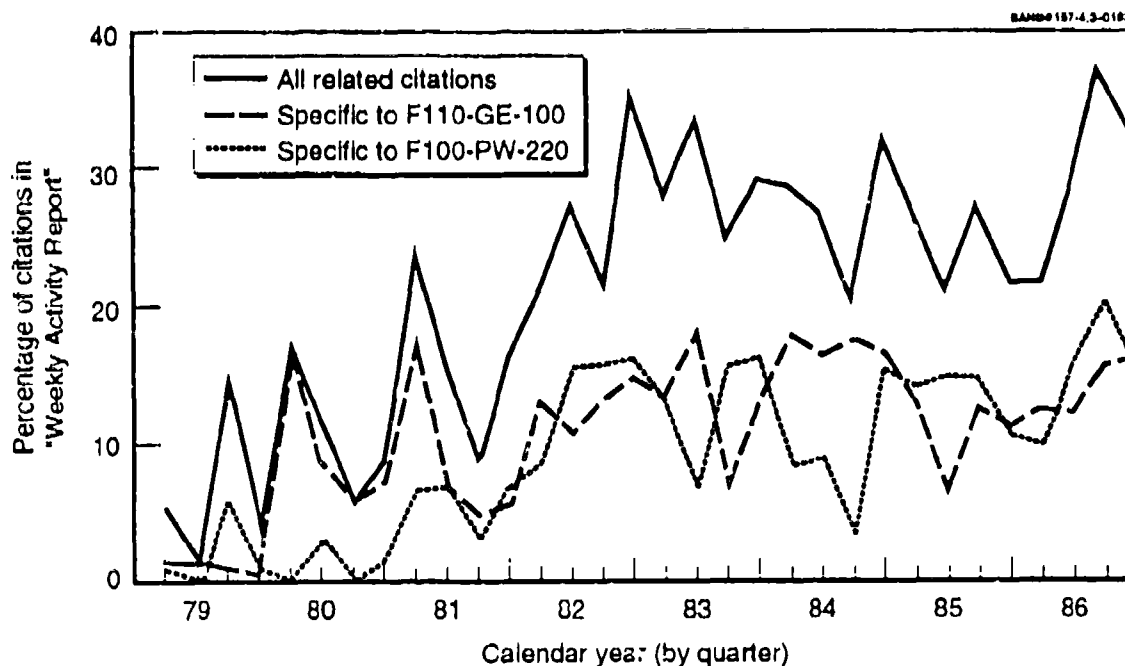


Figure 4.3—Propulsion SPO Management Focus During the F110-GE-100 and F100-PW-220 Developments

became the single most important item on the commander's agenda during 1982–1986³⁷ that is reflected in the percentages in Figure 4.3. The fact that the SPO commander gave a disproportionate amount of attention to these programs during their developments may help explain their success.³⁸

SUMMARY

The Great Engine War between the F110-GE-100 and F100-PW-220 is generally regarded as a major success in Air Force acquisition. A significant part of that success can be attributed to the quality of the two engines and the success of the development programs that made the Great Engine War possible. Although the development programs for the two engines are intricately intertwined, the two proceeded quite differently and involved significantly different technological and management problems.

³⁷Based on interviews with former SPO staff.

³⁸The commander's interest remained high as these programs left development, and RDT&E expenditures fell as production began. Budgets and SPO staffing to oversee these programs rose more than enough as production began to increase total annual program expenditures. The commander's interest did not rise in proportion to this change; the development phase attracted a disproportionate share of his interest.

The two share the feature of being derivative developments, but they were derivative in different ways. The F110-GE-100 evolved systematically from the F101X demonstrator that GE constructed to extend the capability it had created with the F101 engine developed for the B-1. The Air Force used the F101X as the basis for a low-risk demonstration and validation program that required only marginally new design work; mainly, it called for GE to characterize the engine it had previously designed and demonstrate it in a limited flight-test program. This program began the final refinement of that design, which the formal, full-scale-development program then completed and carried through product verification.

The F100-PW-220 did not follow as linear a path. P&W and the Air Force had a variety of programs under way to introduce demonstrated advanced components into the F100 to solve serious problems that the Air Force had with operability and ownership cost. Each of these developments involved marginal adjustments in the F100-PW-100 and -200 engines that dominated the Air Force fighter fleet around 1980. The Air Force brought these efforts into final engineering and product verification as individual changes in the F100 engine family, and the F100-PW-220 effectively coalesced from those changes as a composite change that could compete with the F110-GE-100 in the Great Engine War. Once P&W finalized the F100-PW-220 configuration, product verification followed immediately and smoothly. In the end, both engines provided a limited set of marginal adjustments in existing engines to resolve the most serious problems facing the Air Force fighter fleet in the late 1970s.

Although the formal production competition of the Great Engine War is inseparable from these developments, it is worth keeping in mind that the developments themselves did not occur in a formal competition. In fact, while the improved F100 developments were in progress, P&W managers spent a significant portion of the time attempting to prevent a formal competition. In a formal development competition, we would have expected much more nearly equal treatment of the competitors and more formal coordination of the competition with common milestones. What we see instead is a form of competition more familiar to the private sector, in which two product developers see the potential for head-to-head competition when they field their products and jockey for position as they develop the products they expect to compete. With an extensive F100 improvement program in place to support the existing Air Force fighter fleet, the Air Force promoted this kind of competition by initially focusing more resources on the weaker contender, GE. Only when GE had demonstrated that it had a viable product did the Air Force begin to fund the two developments at similar levels. But even then, each development continued to proceed in a very different way.

Both the Air Force and its contractors maintained great flexibility during the development of the two engines. Although these engines had greater high-level visibility than we might expect engines to get during development, high-level officials did not play a significant role in the developments other than to assure funding to allow them to continue. We would not expect a derivative development of a subsystem with no immediate combat function to divert their attention from riskier developments more nearly focused on a combat mission. To the extent that high-level officials noticed the developments, it was because of their novelty—the development of a new engine to support competition—and P&W's efforts to derail that competition before it could start. The DSARC intervened once; otherwise, the two developments proceeded mainly under the watchful eyes of concerned Air Force overseers.

The existence of the standing Propulsion SPO, with a useful accumulation of experience in developing engines even in the early days, when these developments began, maintained an appropriate balance of flexibility and control in the absence of high-level oversight. The SPO repeatedly found creative ways to assemble funding, maintain support for continuing two parallel developments, coordinate related and complex developments, and react to unexpected outcomes. This body of experienced managers maintained a form of sophisticated control that a SPO of the same size, assembled only for the purpose of these developments, probably could not have provided.³⁹

The dominant contract type in both developments was a firm-fixed-price contract. Although such contracts have been criticized as inappropriate for development programs, they appear to have worked well for these two developments. Neither the Air Force nor the contractors were surprised by actual development costs and final delivery dates, and performance levels were met as expected when the developments began. The fact that derivative developments limited the risk in these programs helps explain part of the outcome. Many close observers and participants also credit the presence of competition and the experience of personnel in the SPO.

This brief overview of the two developments can only hint at the details relevant to these summary remarks. The next section returns to details of risk management.

³⁹Looking across several cases, Glennan, forthcoming, notes that greater oversight does appear to be associated with higher occurrence of difficulties in a development. In part, that is because inherently more difficult developments receive more oversight. It also appears to be true because increased oversight attenuates the flexibility that developers have to deal with the difficulties they encounter.

5. RISK MANAGEMENT IN THE F100-PW-220 AND F110-GE-100 DEVELOPMENTS

With this basic history in hand, we can now look at a set of specific topics in more detail. This section first looks at the risks inherent in the two engine developments and the policies associated with those risks. Given the risks, it then considers three primary aspects of the environment in which the developments proceeded and asks how they affected the management of risk during the developments. The first aspect is competition, the characteristic observers associate with the developments first and the dominant factor that participants point to when they discuss the developments. The second aspect is the nature of management within the Propulsion SPO. As a standing SPO not exclusively committed to one program, the Propulsion SPO had experienced managers who could work as a team and implement a well-articulated philosophy of development. Perhaps paradoxically, the sense of order offered by this organization promoted a flexible management style that allowed creative reaction to surprises. The third aspect we examine is the contracts used to implement the developments. Although contract type tends to dominate most discussions of risk management, other aspects of contracting appear to have played a larger role in the developments.

RISKS INHERENT IN THE DEVELOPMENTS

Two factors tended to limit the risks inherent in the F100-PW-220 and F110-GE-100 developments. First, as derivative developments, they faced limited technological risk. Second, they faced little external pressure to achieve unrealistic schedule, cost, or performance goals. These factors limited the risks that their developers had to plan for and hence simplified both developments significantly.

Technological Risk

Engine developments tend to be incremental. More than with most major systems, we can trace genealogies of engines back through one or more previous engines to the demonstrators that first displayed the technologies embodied in the current engines. "Incrementalism" is a response to the highly complex nature of engines. Engine designers and developers must integrate many different engineering disciplines to be successful. The moving parts of engines rotate at high speeds. Their hot sections experience extremely high temperatures and temperature transients during operation. Air flow and pressure transients within the operating engines are extremely complex. The air pressure and temperature of the environment in which engines operate continually change in flight. And various parts of

the engines can have unanticipated effects on other parts as transients move through the engine in flight. High-performance engines jointly optimize these elements. Hence, unless each of these elements is working as expected, an engine cannot achieve the performance and safety expected of it. As a result, developers tend to make changes in engines carefully, drawing on existing engines whenever possible.

But incrementalism can occur in different ways. And in fact, engine developers distinguish two kinds of development—derivative engines and centerline engines.

The engines we examine here are derivative engines, making marginal adjustments in selected portions of the engines without reoptimizing the design of the engines as a whole or adding fundamentally new materials or operating concepts. Such changes allow engines to evolve. Engine developers see a need for such evolution to match the typical evolution of aircraft. Over the course of a typical aircraft design's life, it normally takes on new subsystems that add weight, drag, or both. To maintain the performance originally envisioned for the aircraft system as a whole, the engine must keep pace, adding thrust or shedding weight to offset changes elsewhere in the aircraft. Therefore, a tradition of derivative development of engines exists in the engine community.

The developments we examine have a slightly different goal—to overcome basic problems with operability and cost in the F100 engine used to power the F-15 and F-16. But the goal could be achieved by similar means. GE's derivative approach responded directly to the Air Force's concerns about the F100 without taking any large technological risks. P&W's derivative approach used modifications it was developing to counter the GE challenge without taking large technological risks. Both developments took advantage of the derivative tradition to make impressive improvements that essentially solved the problem at hand without taking large risks.

Such an evolutionary approach is not always sufficient. For example, it would not have allowed the doubling in thrust-to-weight ratio achieved by the F100 engine. Nor would such an approach have yielded an engine that would allow the advanced tactical fighter (ATF) to cruise at supersonic speeds without lighting the afterburner. Such revolutionary changes require the development of a new centerline engine. In the tradition of engine development, centerline engines draw heavily on existing technology. But they do not allow the low-risk approach that we saw in the F100-PW-22C and F110-GE-100 developments. It is significant that the Air Force continued its derivative engine program while it was developing the engine for the ATF. The derivative engines that build on those examined here, the increased performance engines (IPEs), addressed a set of goals for improving thrust

in the F-15 and F-16 fleets that could be achieved without the risk involved in the ATF program.

Externally Imposed Risks

Two kinds of external risks were important to these developments. One was the risk imposed by oversight, which can force developers to compromise their own concerns about risk minimization to achieve higher level goals imposed from above. The other was associated with competition. We discuss the first here and save competition for the next subsection, in which we can treat it in some detail.

These developments were remarkably free of intervention from above. They occurred outside the normal DSARC process used to oversee large developments in DoD, because engines rarely enter that process independently of airframes being developed at the same time. With no airframe being developed to use these engines, the DSARC entered their development only once, after full-scale development had begun, and required no changes in them. As derivative engines, these developments also had a relatively low joint cost of about \$610 million over seven years, not enough to draw high-level interest unless they experienced a major shortfall of some kind.¹ They did not.

In the end, these developments did not impose a major risk on the Air Force or any organization above it. Even a substantial cost overrun in such a small program would not threaten any of those organizations. And the Air Force was prepared to end the F101 DFE effort if cost got out of hand. Ending the program would complicate the Air Force's management of the F100, but it would not eliminate any critical capability or keep the Air Force from addressing any important part of its perceived threat. For similar reasons, the Air Force could accept schedule slips or performance shortfalls in either the GE or P&W program, understanding that the other was available as a backup. We will say more about this role of competition below. The key point here is that these developments did not have inherent features that we would expect to draw high-level interest.

That is not to say that there was no high-level interest in the development. In its efforts to eliminate funding for GE and to preempt the competition between GE and itself, P&W brought the development to the attention of a number of congressmen, senators, and administration officials. In fact, P&W's high-level efforts were unusual in engine development and encouraged the Air Force itself to resist outside interference. In response to P&W's efforts, congressional staffs held hearings, began GAO investigations, demanded written documents from the Air Force, and succeeded in threatening the funding necessary

¹This cost estimate is based on the data presented in Table 3.1.

for competition to go forward.² These efforts brought the development to the attention of high-level Air Force officials. The Air Force responded by closing ranks at the highest level.

In the end, higher level officials never intervened in the details of managing the developments. Once funding was provided, high-level officials withdrew and allowed the developments to proceed on the terms set by the Air Force. High-level interest never became strong enough to override the judgments of the managers directly responsible for the developments. This basic fact significantly simplified the developers' lives by allowing them to build slack into the full-scale developments that could absorb surprises that might have adversely affected cost, schedule, or performance. We will say more about this when we discuss flexibility below.

Summary

A derivative approach makes sense when it can achieve the developer's goals. Given those goals, it helps the developer minimize the risks associated with development. But a derivative approach will not work in all applications. Where larger advances in technology are desired, higher development risk is usually unavoidable. Because these developments were fairly small and essentially supported a reengining program, they did not impose a high risk on the Air Force or any organization above the Air Force. Despite P&W's effort to draw higher level interest to the programs, such interest had little effect. Air Force managers were fairly free to structure the developments as they saw fit.

COMPETITION

The presence of competition profoundly affected the environment in which the Air Force and its contractors managed development risks; most observers suggest that it is the single most important factor in the engine developments. It is certainly the most distinctive: Competition rarely continues through full-scale development into production, and the competition during the development of these engines was unique. The Air Force and its contractors saw competition as the primary element of the developments that they reacted to directly. They also saw it as a factor that shaped many specific aspects of risk management.

Not a Formal Competition

When we think of competition in development, we normally expect a competitive demonstration/validation stage that leads to a prototype, and perhaps a formal fly-off to

²For good accounts of these efforts, see Drewes, 1987, pp. 91-125; Ogg, 1987, pp. 58-74.

choose one contractor for full-scale development and presumably production.³ Such a competition provides common criteria to the competitors, similar funding to complete the demonstration and concept validation, and similar milestones to track progress and make decisions.

This competition included none of these features. The Air Force used similar contractual vehicles to fund pre-full-scale development for both engines, but the tasks, milestones, and especially the funds used were quite different. The Air Force gave GE substantial pre-full-scale-development funds just to get up to speed with P&W before full-scale development. As a result, the Air Force spent at least \$150 million or 65 percent, more on GE than on P&W. Treatment was more nearly similar during full-scale development, but even here we see major differences. While GE developed one engine during this period, P&W developed three engine modifications and rolled them together with yet another modification to develop a new derivative engine. Specifications and criteria for the two developments were quite different. The draft request for proposal, the first formal suggestion of what the specifications and criteria might be for the real competition—the production competition—was not written until after both full-scale developments had begun. And these developments did not change markedly as the production competition proceeded.

The competition involved during development, then, was not consistent with any form of formal competition normally prescribed. It was, rather, a less tangible, but no less persuasive, form. As far back as 1975, observers recognized that GE might successfully challenge P&W in the fighter-engine market. As time passed, the possibility became more serious. The Air Force and its contractors recognized the high stakes involved and reacted accordingly. Growing anticipation of a head-to-head formal production competition created an intense competitive environment throughout the developments, even though the Air Force managed no formal development competition.

Competition Viewed Broadly

The Air Force, GE, and P&W each saw the role of competition differently. Whereas the Air Force consistently saw it as a way to reduce development risks both contractors saw it as increasing uncertainty in their business environments—GE in a positive way and P&W in a negative way. To understand these reactions, let us consider the relationship between

³See, for example, DoD Directive 5000.1, *Policies Governing Defense Acquisition*, 15 August 1990, or DoD Instruction 5000.2, *Defense Acquisition Management Policies and Procedures*, 15 August 1990.

the Air Force and P&W before GE proposed the F101X and then look at the changes GE's entry effected.

For most of the 1970s, P&W essentially had a bilateral relationship with the Air Force. Who was going to pay to fix the F100 was an issue they would have to resolve between themselves, and P&W felt confident that it could do well in this relationship. The F100 CIP allowed P&W to pursue a set of solutions with Air Force funding and the two parties were continuing to set up other arrangements to fund improvements. For P&W, GE appeared as an external risk to this relationship in the late 1970s, essentially an unexpected alternative source of technological capability. P&W managed this risk by trying to eliminate it. GE's presence seriously threatened the effectiveness of P&W's aggressive stance with the Air Force. P&W reacted by applying this stance to stamp out the threat and preserve their exclusive relationship with the Air Force. This reaction had precisely the opposite effect. GE's presence sensitized the Air Force to P&W's aggressive attitude and gave the Air Force a potential way to escape it. Acting as though it were trapped in a paradigm of its own making, P&W repeatedly antagonized the Air Force, driving it toward GE and ever increasing the risk that it was trying to eliminate.

GE saw this risk from the other side. The F101X demonstrator was a small-scale effort with a very large potential payoff. It offered the opportunity to make a large inroad into the military engine market. GE nurtured this opportunity, using its own corporate funds to create the opening, listening carefully to what the Air Force said it wanted, and funding innovations to meet Air Force needs as precisely as possible.⁴ The approach was a stark contrast to P&W's. In fairness, P&W had been responsive to the Air Force's interest in increased thrust in the F100 and, after the Air Force made additional demands, did not trust the Air Force's statements about what it wanted. Nonetheless, GE listened carefully, with the result, under these circumstances, that it succeeded.

The Air Force found itself as being between the competitors. What each competitor saw as great uncertainty actually reduced the Air Force's perception of risk in the development. Air Force managers had not been successful in getting what they wanted from P&W. They saw the relationship with P&W as essentially a zero-sum game, in which P&W seemed to hold the cards and the Air Force faced the prospect of very high costs to fix the F100. All of that changed when GE appeared. The Air Force saw a highly motivated company, willing to put its own money behind its ideas, and committed to making the F101

⁴GE was seeking a way to enter the military market at the time. It wanted a way to increase the scale of production of engines that it could then produce at lower unit cost to sell in both commercial and military markets. For more information, see Drewes, 1987, or Kennedy, 1985.

DFE succeed to open the door to the fighter market. This motivation gave the Air Force a safe contractor to work with in its new, essentially experimental, EMDP. And it gave the Air Force a stick to wave at P&W. It changed the balance of power between the Air Force and P&W: the Air Force now had the F101 DFE to force P&W to make concessions that the Air Force could not get before. And if P&W did not come through, GE looked like a motivated alternative that could deliver. For the Air Force, then, GE's appearance changed a fairly high-risk confrontation with P&W into a lower risk opportunity to solve serious problems, one way or another. That was and remains the primary appeal of the competition to the Air Force.

Relational Contracts

Seen in this light, the competition was different from that typically encountered in economics textbooks. The primary concern of the buyer was not to use competition to push product price down to marginal cost, although this was certainly a consideration. It was to change the balance of power in the long-term relationship between P&W and the Air Force. P&W had a technological and production capability that the Air Force expected to exploit over the long term. (The same could be said of GE.) Regardless of the specific terms of the contracts the Air Force would sign with P&W over the years, the Air Force expected to maintain the relationship and use it to mutual advantage. This was true despite the extreme anger that many Air Force officials felt toward P&W about its handling of problems with the F100.

Such a long-term relationship is governed by a "relational contract," an implicit set of rules that allow the relationship to survive and function well over the long term.⁵ Such rules are rarely formalized. They evolve naturally over time to establish a sense of equity in the relationship that leads both parties to remain in the relationship voluntarily. That does not mean that both parties benefit equally; they can still benefit in proportion to the power they exercise in the relationship. The developments we examine here offer ample evidence that competition can significantly alter the balance of power in such a relationship. GE's entry shifted power toward the Air Force. It made P&W more responsive to Air Force needs. It also reduced the Air Force's need to monitor P&W's actions to make sure they were consistent with Air Force needs. (P&W's presence in the market over the long term, of course, also assisted the Air Force in its continuing relationship with GE.)

⁵See, for example, Macaulay, 1963; Macneil, 1980; and Williamson, 1979.

Competition and Responsiveness

Air Force and contractor personnel both agree that the most important effect of the Alternate Fighter Engine competition was to increase contractor responsiveness to Air Force needs. Greater responsiveness led the Air Force to perceive lower risk in the program as a whole. When unexpected events occurred, the Air Force could expect greater success in getting an attractive settlement, thereby reducing the probability and size of large, negative effects. Such responsiveness in effect shifted risk to the contractors without compensating them for it. That is, one consequence of competition was to induce contractors to bear risk on a continuing basis at a lower cost to the government.

The increase in contractor responsiveness was especially evident over the course of the production contracts, following the initial source selection that demonstrated the Air Force's seriousness of purpose in maintaining competition. The production contracts were set up to allow a series of annual competitions in which the contractors could improve the terms of their offers on a wide variety of factors. These competitions brought small concessions on engine unit price, the factor to which traditional economic arguments give greatest attention. More important were many small reactions to modernization programs and modification programs that characterize the continual negotiation that occurs under a relational contract. Observers agree that GE and P&W were both much more responsive in these negotiations than they were in similar programs in which they felt no direct competition.

During the engine developments themselves, competition was not as tangible or formal as during production. But even here, it generated similar effects. A good example is the continuing set of contract-change proposals that occur in any development as information accumulates and the parties to the contract adjust their mutual goals. The Defense Acquisition Regulations set out formal rules for making equitable adjustments in contracts to reflect contractual changes. But those rules leave considerable room for negotiation. Competition shifted the balance of power toward the government in such negotiations, allowing the Air Force to get many contractual changes at no cost to itself or to trade one change for another on more favorable terms. This was true in the Air Force's relationships with both GE and P&W. But it was probably more visible in the relationship with P&W because the Air Force had a pre-competition history with P&W to contrast with P&W's behavior under competition. In fact, following its stunning success in the early production competitions, GE became less responsive in the eyes of Air Force officials charged with overseeing the contract, emphasizing the fact that competition would be important in the Air Force's continuing relationships with both contractors.

A second specific place that SPO officials believe competition improved responsiveness was in the F100 CIP, in which important parts of the F100-PW-220 development took place. For the most part, the F100 CIP occurred under a cost-plus-award-fee contract. Award-fee contracts allowed the Air Force to determine twice a year, under very broad guidelines, what fee the contractor should earn above and beyond measured costs. The parties to the CIP preferred such an arrangement precisely because the CIP required an open, flexible relationship that was difficult to codify in detail. In the past, the Air Force and its contractors could not identify a satisfactory set of explicit criteria that they could use as the basis for a more precise incentive arrangement. The Air Force considered responsiveness in determining the award fee and believed that GE and P&W actively competed in their responsiveness (and other behaviors) to best one another in the size of this award each period. That is, the Air Force saw more responsiveness under this contractual arrangement when competition was present than when it was not.

Such increased responsiveness supported the flexible decision making that contributed to the success of these developments; we address this issue in more detail below. But we should not overstate the effects of competition. One of the primary goals of these developments was to reduce the cost of ownership for engines by increasing their durability and improving maintenance policies. Air Force officials believe that the contractors had strong incentives to resist any effort to improve reliability or durability, incentives that competition alone could not overcome. Contractors, as the primary source of spare parts for engines, had an incentive to design engines that would not seriously threaten a continuing demand for spare parts. A source of Air Force ill will toward P&W was what the Air Force perceived to be a P&W policy to overprice spare parts for the F100. Given that policy, the Air Force was committed to changing its procurement of spare parts for the derivative engines discussed here. Competition did encourage GE to provide data packages that would allow second sourcing to reduce monopoly-based gains from the spare parts market; P&W strongly resisted such arrangements. Both contractors resisted intensive application of ENSIP methods to promote Air Force cost-cutting goals. If the Air Force had not been conversant in ENSIP methods, competition alone probably would not have ensured their full application.

Competition and Opportunistic Behavior

One important characteristic of relational contracts is that, over time, the participants make investments—in physical capital, skills, techniques, and other knowledge—that are specific to the relationship. These investments are less valuable outside the relationship than in it. To the extent that these assets are unique to the relationship, both parties have

an incentive to do things that allow them to capture the full value of this uniqueness: The parties put themselves at one another's mercy. They are willing to do so because the relationship creates enough value to offset the resources consumed by the parties in their efforts to exploit one another. But such efforts, known as "opportunistic behaviors," can potentially consume a significant portion of any value added by the relationship.⁶

A development program is a particular example of such a situation in which the two parties agree in the beginning to invest resources in an increasingly unique asset—the design of a new system. As time passes, more and more resources are sunk, presumably creating an asset with ever-increasing value over time. It becomes harder and harder for either party to withdraw if something goes wrong and more and more tempting to seek changes that modify the terms of the initial agreement on the share each party has in the value of the accumulating asset. In the absence of clearly defined controls and rules that both parties understand in the same way, risk can actually grow over the course of such a development, because it becomes harder and harder for either party to withdraw.

The Alternate Fighter Engine competition can be viewed in these terms. The Air Force became increasingly convinced that, despite its investment in P&W, it might be worth withdrawing from the relational contract on the F100 in response to P&W's opportunistic behavior within that contract. P&W, at least for some period of time, did not consider the threat a real one and continued its opportunistic behavior. As the threat became more realistic, P&W saw the gains it had achieved through opportunistic behavior being threatened and attacked the threat rather than stopping the behavior that had precipitated it. That is, the threat of competition did not stop P&W's opportunistic behavior. The realization of that threat in the source selection, however, changed everything.

P&W changed not only its behavior, but its management. The result was a basic shift in corporate culture. Part of this was reflected in greater responsiveness, as suggested above. Part of that shift was reflected in fewer efforts to exploit its relationship with the Air Force. In fact, the presence of competition fundamentally changed the ability of P&W or GE to engage in opportunistic behavior. The Air Force had made very large investments in a large fighter engine, but it could procure it from either of two sources, making it much easier for it to withdraw, at least incrementally, from its relationship with either contractor. If either contractor attempted to exploit the relationship, the Air Force could turn to the other contractor without reducing by much the value of its own investments in the large fighter engine. Neither of its contractors had similar alternatives. The net result was that the

⁶For an extensive discussion of such behavior, see Williamson, 1985.

potential for opportunistic behavior by either contractor dropped as competition became more tangible.

The Air Force responded by reducing the amount of monitoring and oversight that it had found to be necessary in the past. Any relational contract requires knowledgeable participants on each side to monitor the other party and discourage the kind of exploitative behavior suggested above. Competition does not eliminate the need for such knowledgeable monitoring. But by reducing the opportunities for exploitation, it reduces the need for monitoring and closely controlled relationships. In particular, it allows additional flexibility in the relationship to respond to unexpected events. When competition disciplines the plausible responses that parties can have to a surprise, both parties can proceed with less deliberate caution and control. The net result is that they can move ahead together more effectively than if caution is paramount.⁷ Seen in this way, competition can play a profound role in risk management. Observers of the developments discussed here agree that it played such a role. In this role, it significantly supported program managers' abilities to exploit flexibility to promote their developments.

Ironically, competition's ability to discourage opportunistic behavior also limited the Air Force's ability to use competition to do so. Although not well understood at the beginning of the production competition, it became clear that the Air Force valued competition enough, for the reasons suggested above, that it was not willing to withdraw entirely from its relationship with either GE or P&W. That is, both competitors came to appreciate that they could engage in certain opportunistic behaviors without inducing the Air Force to withdraw entirely. Perhaps the clearest indication of this fact was the Air Force's response to P&W's offer in the first production competition. P&W priced its offer in a way that strongly encouraged the Air Force to buy all of its engines from P&W; any decision to buy engines from GE significantly increased the price of P&W's engines and especially of its warranty on those engines. P&W essentially stated in that offer that it was willing to bear more risk with regard to its warranty if the Air Force dealt exclusively with P&W, effectively reducing the risks to P&W associated with competition.⁸ The Air Force accepted a large increase in the price it paid P&W for the engines it did buy to ensure continuing competition and thereby to keep both contractors at risk. Knowing that the Air Force would not wholly withdraw from

⁷The argument is analogous to Schumpeter's discussion of an economy with effective controls. Controls that limit responses to unexpected shocks in the economy allow the economy to move faster in the same way that good brakes in a car allow the car to proceed at higher speed. In both cases, the "driver" need not be so careful. By limiting responses to surprises, competition enables the driver in a development to proceed more rapidly. Schumpeter, 1950, p. 84.

⁸Cf. Drewes, 1987, p. 127.

either contractor maintained competition, but limited its positive effects (for the Air Force) over the developments' duration.⁹

Summary

The Air Force did not develop the F100-PW-220 and F110-GE-100 engines in a formally competitive setting, but no one discouraged the presence of competition, which became more tangible and influential as the developments proceeded. These engines are best known in the acquisition community for the role that competition played in their development and production. No one can offer quantitative or detailed evidence on the effects of this competition, suggesting that a careful analysis of the competition itself might be fruitful. We can, however, offer a set of general statements about the competition and its effect on risk management.

Although GE and P&W's growing awareness of the presence and importance of competition appears to have tempered their pricing behavior over time, its major effects were quite different from those typically emphasized in discussions of competition policy. While reducing the Air Force's general risk of managing serious operability and cost problems in the F100 fleet, it significantly increased P&W's risk and opened a major opportunity for GE. The expectation and final realization of competition in production fundamentally altered the nature of the relational contracts between the Air Force and its engine contractors, GE and P&W, effectively shifting power toward the Air Force. P&W fought this change as GE promoted it. Realization of competition and its attendant uncertainties for both of them ultimately led both contractors to become more responsive and reduced their gains from pursuing opportunistic behavior. In this lower risk setting, the Air Force found its monitoring job significantly simplified and its opportunity for flexible and creative management significantly enhanced.

GENERAL MANAGEMENT

The Propulsion SPO has a reputation as a well-run organization. As noted in Section 3, development of engines has heightened the SPO's awareness of the importance of risk assessment and risk management. Managers in the SPO see their general management mission as inherently a form of risk management. Even when the engines we study were under development, those managers built on their joint experience to develop a set of

⁹This discussion raises questions about the benefits of full and open competition as currently promoted by the spirit of the Competition in Contracting Act of 1984. The findings reported here are compatible with those in Kelman, 1990, which raise serious doubts about pursuing unfettered competition among vendors to the U.S. government, and those in Smitka, 1991, which raise similar doubts in a private-sector context. I am continuing to examine this question in ongoing analysis.

standard operating arrangements that produced substantial structure without overwhelming developers with bureaucratic requirements. In fact, the order provided by the managers' experience and procedures appears to have promoted flexibility and creativity. This subsection reviews key factors in the Propulsion SPO's general management approach during the development of the F100-PW-220 and F110-GE-100 and presents examples of flexibility and creativity promoted by this approach.

Experience

When the Air Force formed the propulsion SPO in 1977, it consolidated all of the engine programs in the Aeronautical Systems Division, bringing together a group of managers and engineers with many years of experience overseeing the development of engines. Personnel from the F-15 SPO transferred to oversee F100 programs, including the EMDP that began in 1979. The chief engineer for the F100 program, Mr. James Day, had been a manager in the F100 program from its inception. Personnel who had worked on the F101 development were available for the F101 DFE program. For example, Mr. Joseph Wood, the program manager for the F101 DFE, had been chief engineer for the F101. His chief engineer for the F101 DFE, Mr. Joseph Batka, was an engineer from the Propulsion Laboratories who had already spent several years overseeing the analysis of risk-related issues on the F101X, including inlet compatibility of the F-16 and F101 DFE, software that the new closed-end-loop control system in the F101 DFE would use to eliminate stall-stagnations, and statistical models relevant to ENSIP and the estimation of operating and support costs.

Such personnel formed the backbone of the development efforts' formative stages. They formed the core of the development staff over the developments' duration. Four SPO commanders played a role in these developments through 1986, none with more than three years in place. But the primarily civilian staff they commanded remained in place as they came and went. The civilian managers brought with them a clear understanding of the reasons the SPO had been organized, reasons closely related to the goals set for the new engines. They sought fundamental changes in the Air Force's approach to engine durability, operability, and supportability. The engines we study were the first directly affected by this new interest, but it carried well beyond these developments alone. The entire SPO, not just the sections of it committed to the two engines, maintained an interest in a new approach.

Similar continuity existed at the contractors. As general manager of the F100 family of engines at P&W, Mr. Ed Ford oversaw the F100-PW-220 and its immediate precursors from 1970 on. Continuity in the F100 program leading up to these developments allowed

P&W to maintain its key staff. At GE, Mr. Brian Brimelow worked on the F101 DFE and then managed the F100-GE-100 full-scale development. GE maintained key personnel from the F101 development following cancellation of the B-1 procurement and worked with the Air Force to create a Transition to Engineering Development that maintained the staff during the move from the F101 DFE EMDP to the F110-GE-100 full-scale development.

From the very beginning, the Propulsion SPO employed a matrix structure that enhanced the accumulation and application of experience during the developments. Table 5.1 shows the major offices in the matrix at two points before and after 1981, when the SPO experienced the one significant reorganization that occurred during the developments. Functional offices allowed expertise to accumulate for application to all programs. Although such accumulation was limited before the developments began in 1979, it occurred much more rapidly over their lives than would have occurred if these were the only developments that the SPO handled during this period. The SPO handled a number of other developments during this period, and those rapidly expanded experience in the engineering, test, contract, program control, and other functional offices key to development. On the program side of the matrix, EMDPs begun in the new programs office (YZN) transitioned smoothly, with relevant personnel, to the main program offices as the developments progressed. These offices maintained unity in the programs while drawing on the accumulating functional expertise whenever necessary.

Table 5.1
Matrix Structure of the Propulsion SPO

1979	1984
Programs	
F100 joint engine project office	Tactical engines program office
F107 joint engine project office	Strategic engines program office
In-service joint engine project office	Airlift and trainer engines program office
New engine project office	New engines program office
Functions	
Commander's office	Commander's office
Management operations	Management operations
Program control	Program control
Configuration management	Acquisition support
Contracting and manufacturing	Contracting
	Manufacturing/quality assurance
Propulsion logistics	Propulsion logistics
Engineering and test	Engineering

SOURCES: U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion organization charts, October 1979, October 1984.

This matrix and the personnel working in it maintained a special kind of experience that was important to our two developments—cumulative experience with the developments' contractors, P&W and GE. The Air Force actually organized the contracting section of the SPO, YZK, into sections along contractor lines, effectively one for P&W (YZKA) and one for GE (YZKB). In 1981, the Air Force reorganized the program side of the SPO matrix along similar lines, with a "tactical" engines office (YZF) to deal with P&W and a "strategic" engines office (YZY) to deal with GE. The engineering office was also split along similar lines (YZEF and YZEY). This structure allowed the SPO to bring considerable experience with these contractors to bear across programs that the contractors worked on. Discussions with SPO officials reflect an intense appreciation of differences in the cultures of these two contractors, an appreciation that transcends and informs the two developments we examine.

Looking beyond the formal matrix for the SPO, the Air Force engine development community also included the Arnold Engineering Development Center (AEDC) and the Flight Test Center (AFFTC) at Edwards Air Force Base. The SPO maintained long-term relationships with those centers and had well-established procedures for dealing with them. During the developments we study, problems occasionally arose between the SPO and these centers, but the problems were exceptional and were solved quickly. Contractual material and interviews suggest that such experience is typical; the SPO had a smooth-running relationship with the principal government facilities it used for testing. The Navy and NASA also conducted tests during our developments. Although those tests, too, appear to have gone smoothly, the SPO did not typically work closely with these centers.

The final link in the Propulsion SPO's experience base was the rapidly developing formal development doctrine that it used to support its general risk-management goals and its goals in the two developments. The SPO was already using accelerated mission tests in the late 1970s to bring empirical evidence to bear on the durability issue. It was using the four-step process to extend the development cycle to further emphasize durability, operability, and supportability and to reduce concurrency between development and production. And it was formalizing a set of technical insights into the engineering structural integrity program (ENSIP), a set of tools that found their first application in the F100-PW-220 and F110-GE-100 developments.¹⁰ These analytic devices provided a formal approach to risk management that helped structure the derivative developments we study.

¹⁰For details, see Section 3.

Standard Procedures

As a standing SPO that remains in place as developments come and go, the Propulsion SPO has developed many standard operating procedures. A number of them appear to have been especially important during the developments we study: program business/technical review, independent propulsion review teams, the test-analyze-fix approach to development, contracting procedures, and general procedures derived from the CIP approach to development.

The program business/technical review (PB/TR) every other month reviewed progress against key contractual, control, engineering, and test milestones for each development. By surfacing potential problems and considering potential solutions that cut across functional areas, it facilitated the SPO's execution of integrated system development in a matrix setting. A standard management device unlikely to be unique to the Propulsion SPO, the PB/TR was designed to pass a thorough overview of each development above the program office on a regular basis. It also played the critical role in a matrix organization of ensuring that all parts of the organization were current on the status and needs of each development in progress. Managers of each three-digit office (the offices shown in Table 5.1) attended. Hence, the reviews ensured that all functional offices saw the development programs in a similar light and understood constraints imposed by each of the functional capabilities; that different program offices involved with the developments maintained a common image of the developments, facilitating when appropriate hand-off of tasks and personnel from one office to another; and that related programs, such as the F101 and F110 programs, had some formal interaction even if they were not coordinated on a day-to-day basis. They also added cumulative knowledge on the SPO's experience with each of the key contractors.

To complement the regular internal review of issues in the program business/technical review, the Propulsion SPO used ad hoc independent propulsion review teams or groups to examine material developed by the SPO and its contractors before major decisions were made. Such a team included a highly respected chairman and members from outside the primary development team. The SPO regularly used such teams before committing to and starting a flight-test program. It also used them when major problems arose in a development and the SPO did not feel confident resolving them on its own. During the developments, such teams rarely found significant problems in SPO plans. They did raise lesser issues that the SPO and its contractors could then manage before an accident resulted. And they provided political cover for the SPO commander in case anything serious did occur. As luck would have it, the SPO never required such cover during the two engine developments.

The development process itself was seen as highly empirical and pragmatic. The test-analyze-fix (TAF) approach was well accepted and established when the developments began, and the SPO maintained it throughout the development.¹¹ Formal weekly activity reports, command assessment reviews, and SPO office reports produced during the developments reflect this cumulative approach by characterizing the developments in terms of week after week, month after month of almost tedious test sequences to locate and fix problems. This approach takes time: Weapon system developers typically expect an engine development to take longer—two to three years longer for a centerline engine—than that for a matched airframe development, in part because of this data-intensive, progressive approach to development. By its very nature, however, the TAF approach tends to yield robust results. It tests and fixes an engine until the engine stabilizes in a design that the Air Force can use. As long as the TAF approach applies tests relevant to the expected usage pattern for the engine, the approach identifies and resolves most risks relevant to design, development, and final product verification.

We should not conclude from this description of a rough-and-ready, robust test regime that it was crude or clumsy in any way. On the contrary, each development routinely ran series of tests in parallel, often at several different test facilities, and regularly coordinated the activities in response to unexpected events.

A good example on the engine's implementation is a test failure that several participants identify as a major event in the F101 DFE development. During the fifth test flight for the F101 DFE in an F-16 at Edwards Air Force Base, California, on 7 January 1981, the pilot and a chase plane detected what appeared to be a fuel leak. Following an emergency landing, inspectors found that a 90-deg aluminum elbow fuel tube that connected the engine to the aircraft fuel-supply system had cracked. The damaged part was at the GE facility in Evendale, Ohio, the following day to allow an engineering team from ASD to inspect it.¹²

Within a week, GE had determined that the tube experienced higher-than-anticipated loads, duplicated the failure on a fuel-system rig, and verified that a support link would reduce those loads. Developers decided to add a support link and to replace the aluminum tube with a stainless-steel tube to add strength. Following tests of the proposed fix in an engine cell at Evendale, the F101-DFE-powered F-16 resumed flight at Edwards (on 31 January) with a restriction to nonaugmented flight. Work continued to reduce pressure

¹¹Section 3 discusses this approach in the context of the Air Force's risk management doctrine.

¹²U.S. Air Force, Aeronautical Systems Division, "Deputy for Propulsion Weekly Activity Report," 8 January 1981.

spikes from afterburner pump initiation by releasing fuel more slowly to fill the engine afterburner pump and modifying the aircraft fuel inlet pipeline. This second change required coordination with General Dynamics, the airframe manufacturer. Ground tests on the new configuration were completed at Evendale on 24 February. Following review, of the generated data, by the Propulsion and F-16 SPOs and ASD's Engineering Office, the aircraft was released for one unrestricted flight, to be followed by further analysis. By 10 March, the aircraft had returned to normal flight-test activities.¹³ Two months after a serious, unexpected test incident, the developers had coordinated two contractors, two SPOs, two test facilities, and additional ASD personnel to design, test, and implement a robust solution that could be used in the final engine configuration if necessary and that kept the test program on schedule.

In a similar manner, the Propulsion SPO was successful in coordinating development activities across programs within the SPO and even across the services. Informal interaction and devices such as the program business/technical review handled routine coordination. The SPO also stood ready to manage less predictable and often serious problems.

For example, the failure of an F404 turbine disk made of René 95 caused the crash of a Navy F-18 in September 1980. The F101 DFE had several parts, including disks and shafts, made of René 95. Before flight-testing the F101 DFE in an F-16, the SPO used the available F404 data to conduct an ENSIP-based risk assessment to determine the expected time to failure in the relevant components in its test engines. It concluded that "all F101 DFE R'95 part life predictions exceed the planned flight test usage," and subsequently proceeded with the test. New Navy data on the F404 surfaced on 11 May 1981, prompting the SPO to stand down F-16/F101 DFE flight operations while it reassessed the safe operating life for the F101 DFE. The SPO completed the analysis within four days, allowing flight tests to resume on 15 May.¹⁴ No formal channels existed to coordinate and act on such information with the Navy; the Propulsion SPO handled the situation calmly and efficiently.

Such coordination was routine on F100 development programs, which regularly exchanged engines in a way that would only be possible with close coordination across individual development efforts. Coordination did not work as well on the F110 side of the house. The F101 DFE program set up a common-issues program with the F101 program, but interaction was limited. The SPO set up a liaison function between the F101 and F110

¹³U.S. Air Force, Aeronautical Systems Division, "Deputy for Propulsion Weekly Activity Report," 15 January 1981, 5 February 1981, 12 February 1981, 19 February 1981, 26 February 1981, 12 March 1981.

¹⁴U.S. Air Force, Aeronautical Systems Division, "Deputy for Propulsion Weekly Activity Report," 26 February 1981, 14 May 1981, 21 May 1981.

programs during the early years of F110 production; the liaison function closed down shortly thereafter. When the B-1B program restarted, it did so under such tight schedule and cost constraints that the Propulsion SPO elected to isolate the F101-GE-102 engine being developed for the B-1B from related programs to simplify the engine's management. This action may have simplified the management of the closely related F101 DFE and F110-GE-100 as well, but it also sacrificed significant opportunities for coordinating what could have been complementary test programs. Coordination might have increased the external risk that each development faced, but should ultimately have reduced the joint risk that the two programs faced after spending any given level of time and resources; that is, the decision not to coordinate, for better or worse, ultimately increased the risk to the SPO as a whole.

Similarly, GE developed the F118 engine for the B-2 from a core common to the F101 DFE and F110. Because F118 development proceeded in a "black" program, little coordination was possible, in the SPO or at GE. More generally, coordination at GE among military engine programs worked well in the absence of explicit restrictions. Coordination between the military F101, F110, and F118 programs and the technologically related civilian CFM-56 program remained weak despite some SPO effort to enhance it.¹⁵ This problem apparently persisted when the Air Force began to buy CFM-56 engines itself for the C-135.

Even within a development program, significant coordination was required as development passed from one contract to another. Such passages were most common in the CIP, for which new contracts began each year in the early part of the developments we examine. The contracts smoothly transferred development tasks and test assets from one contract to the next. The absence of significant modifications and the smooth administration of the award-fee process point to a process that functioned well during the period. Similar transfers from EMDP to full-scale development contracts point to a similarly smooth process being in place.

The SPO staff generally believes that the Defense Acquisition Regulations (DAR), the contract law that it uses to administer its relationship with its contractors, were (and are) more than adequate for the task. One manager noted that continual reforms in that law typically create more turbulence and risk than they resolve by muddying the precedents and the informal relational contract that the SPO uses to manage its relationship with its contractors.¹⁶ During the developments we examine, such turbulence appears to have

¹⁵We did not determine the reason for this weakness. It deserves further attention.

¹⁶A similar complaint is heard with regard to change in civil law in general. Many of the arguments offered about civil law apply to the DAR without difficulty.

created only one small problem, a problem that the SPO and P&W satisfactorily resolved without serious difficulty.

The CIP, which predated the Propulsion SPO by many years, created a set of standard procedures that were well developed and functioning smoothly by the time the subject developments began. At the center of these procedures was (and is) the Resolution of Operational Problems (ROP) clause, which stated that "it is recognized by the parties hereto that the . . . Component Improvement Program is dynamic and—therefore—it is anticipated that tasks will be added and cancelled during the course of the contract."¹⁷ The CIP contract identifies clear priorities and procedures for adding and removing tasks as development proceeds or as external events change funding or priorities within the CIP. Using these procedures, the Air Force can expedite the administration of changes in a development program. The net result is an orderly process that reduces many of the risks often associated with flexible program administration and hence encourages flexibility. The process is not risk-free. Both the Air Force and its contractors have yielded to the temptation to exploit this flexibility in inappropriate ways. But over the long run, the program has been quite successful at allowing timely resolution of development issues.

The CIP played an important but limited direct role in the developments we study. But it provides a tradition for the Propulsion SPO, with effects that extend well beyond the CIP itself. All SPO personnel are familiar with the CIP and value the flexibility that it allows. It provides a model for administering development that cannot be transferred wholesale to the rest of the SPO, but does color the way the SPO approaches development. In the end, the CIP also serves as a useful metaphor for the Propulsion SPO's general approach to managing development. Both the CIP and the Propulsion SPO have accumulated experience in managing engine development over numerous engine designs. Both use well-conceived standard procedures for monitoring and reacting to unexpected events. As a result, managers in both the CIP and the Propulsion SPO have the confidence and tools required to pursue a fairly flexible and creative approach to development. The next subsection considers some examples that illustrate this point.

Illustrations of Flexibility and Creativity

The F100 EMDP was initially set up to introduce demonstrated advanced component technologies into the F100 production engine design. One of the two key components initially

¹⁷U.S. Air Force, Aeronautical Systems Division, Contract F33657-81-C-0001, Wright-Patterson Air Force Base, Ohio, 14 October 1980, Section H, Clause 10, p. 22. Similar language exists in all CIP contracts.

considered was a partial swirl augmentor. Within four months of the F100 EMDP's initiation, altitude tests at the NASA Lewis ground engine test facility had failed to substantiate any of the operability benefits claimed for this "previously demonstrated" and hence presumably low-risk component. For lack of funds, the Air Force could not begin its own tests at AELC until March 1980, and foreign-object damage to a test engine delayed the tests still further. The Air Force completed a preliminary design review of the partial swirl augmentor by June 1980, but later Air Force tests produced results similar to the NASA results. By the end of 1980, P&W and the SPO had reacted by replacing the partial swirl augmentor with another advanced design, a ducted flameholder configuration. Despite these difficulties, the failure of the partial swirl augmentor ultimately had no negative effects on the program because an alternative was readily available to replace even this fairly low-risk item.¹⁸

The beginning of the F101 DFE EMDP demonstrates a remarkable degree of creativity. With no funding of its own to commit, the Air Force located unused funds that Congress had appropriated for the Navy. Despite considerable difficulties following the Navy's untimely earlier withdrawal from the F100 development, a withdrawal that required major readjustments in that program, the two services were able to reach agreement over an arrangement that would transfer \$33 million of \$41 million to the Air Force and give the Air Force effective control over the development so funded. Funding remained tenuous throughout this EMDP, but this first step initiated a process that ultimately yielded all the funds required for the development without significantly affecting the progress of the development effort itself. In the last step of this EMDP process, the developers established a new type of program, a Transition to Engineering Development, that allowed GE engineers to continue the development process beyond the initial EMDP plan while the Air Force built support for a full-scale development. This effort kept the GE design team together and allowed a smooth transition from the initial demonstration into a final product-verification program.

The F101 DFE EMDP was set up as a "success-oriented" program, meaning that it had less than the normal amount of slack allowed in a development program to deal with unanticipated events. Its managers perceived that any major failure in the program could kill it. The Air Force was willing to use this approach in part because killing the program

¹⁸Our description relies in part on official Air Force histories of various Aeronautical Systems Division development programs written by C. J. Geiger during 1979-1980. Because those unclassified histories are chapters in classified Air Force documents, we cannot provide explicit citations in this document. Unpublished history reports of the Propulsion SPO New Engines Program Office, January-June 1980, p. H-5, and July-December 1980, p. H-6.

would not threaten major Air Force goals and because GE, to ensure that the program as a whole succeeded, had very strong incentives to back up the program in case of test failures. But the Air Force did not rely on GE alone to ensure success. The SPO used unusually close oversight of the ongoing test program and continually informed its superiors about the program's successes and failures. The SPO worked hard to prevent the development of rumors that could magnify routine difficulties out of proportion. This approach is reflected in the SPO commander's weekly activity reports to the ASD commander. These reports gave the F101 DFE EMDP disproportionate attention and often provided minutely detailed coverage of problems and efforts to resolve them from one week to the next. These reports also make clear that frequent communication of important information on problems was common.

The environment for the F110 full-scale development was more comfortable and forgiving. The development managers were able to build important slack into the program that allowed successful adaptation to a number of surprises.

For example, as the development proceeded, GE fell farther and farther behind in its test schedule, completion of nontest activities, and delivery of data items to the Air Force. GE proposed a number of solutions that it could not execute. It also became apparent, as product-verification activities fell behind their schedule, that the schedule for such activities at AEDC was unrealistic. The SPO sought ways to intervene at GE and increased the priority of F110 test activities at AEDC. In the end, the SPO could not avoid slipping the deadline for product verification from 30 September 1984 to 31 January 1985. This was a significant slip, since the product-verification milestone was mutually set at the start of full-scale development only nine months earlier. But it did not affect GE's scheduled delivery of engines to the airframe manufacturer.¹⁹

The SPO and GE absorbed the slip by using a shorter interval to review the results of the product-verification process in anticipation of production. To make the planned production schedule, the developers could not slip the date for decision on long-lead items, a date initially planned to succeed the product-verification milestone. Following the GE schedule slips, the SPO approved long-lead procurement before final product verification was complete. This decision potentially increased concurrency between development and

¹⁹Unpublished history report of the Propulsion SPO Strategic Engines Program Office, July-December 1983; "F110-GE-100 Program Business/Technical Review," ASD Deputy for Propulsion, unpublished briefing charts, Wright-Patterson Air Force Base, 11 April 1984; J. R. Nelson, "Command Agreement Review," unpublished briefing charts, Deputy for Propulsion, Wright-Patterson Air Force Base, 16 April 1984; unpublished history report of the Propulsion SPO Engineering Office, January-June 1984.

production, something the four-step process sought to reduce. But sufficient slack allowed a decision without a significant increase in risk. Product verification occurs over a long time, and the items most critical to long-lead procurement had been verified early enough to allow a long-lead decision without delay.

Slack in the product design allowed satisfactory adaptation to another unexpected event. Late in the development, testers identified a problem with "screech" in the F110 augmentor, a dynamic oscillation of flame that, in a small part of the flight envelope, could break spraybars in the augmentor, cause engine fires, and endanger the engine and its aircraft. Pilots rarely fly in the affected region, but consultations with future users in the Tactical Air Command (TAC) determined that screech remained important to the engine specifications when engines were deployed.

The developers employed a three-part response to this unexpected problem. First, they cut the air/fuel ratio in the augmentor, reducing thrust somewhat. Second, they then reoptimized the operation of the engine. Test data suggested that sufficient slack existed in the design so that they could reduce the stall margin by increasing the pressure ratio in the compressor to compensate for some of the loss of thrust in the augmentor. Third, they developed a refinement in the augmentor spraybar. This third step took a great deal of effort and, in fact, continued beyond the deployment date for engines. While this was happening, the Propulsion SPO continued to work with TAC to ensure that performance changes associated with these changes were satisfactory from the user's point of view.

In the end, it is unclear why the development process did not catch this problem earlier. But when it was identified, the developers used an orderly, flexible system to respond in a way that satisfied the final engine users.

The F100 DEEC/pump/valve/EMS full-scale development that yielded the -220 was a much more complex undertaking than the F110-GE-100 full-scale development. Here, P&W and the SPO coordinated three different contracts and funding sources: the full-scale development itself, the supporting CIP, and the continuing EMDP. Each had well-defined tasks that, in the end, created the capability required to draw up specifications for and verify the production version of the -220. The success of this effort clearly illustrated the synergy between SPO and contractor and their proficiency in working with several programs to produce a final product that was delivered to the field six months before expected.

Summary

The Propulsion SPO is different from most SPOs because it remains in place as development and production programs pass through it. Therefore, the SPO can build

experience and capability in a well-designed and familiar decision-making environment. The tradition that exists today was still young when the F100-PW-220 and F110-GE-100 developments occurred, but important elements of it were in place. The managers of these developments were experienced and familiar with the underlying technology. The basic matrix was in place to support several developments at once. All the standard procedures now used by the SPO to explain its longer term success were in place. With experienced managers, the SPO was able to use those procedures to deal confidently with unexpected events in a flexible and often creative way. With its contractors, it developed creative ways to maintain funding for their efforts. It used close oversight and good communication to manage the developments in their riskiest, formative days. It reacted smoothly to test failures with alternative technologies and development changes that ultimately enabled the developments to meet the expected performance specifications on time and without a cost overrun.

CONTRACTS

Much of the discussion of risk management in acquisition policy has emphasized the importance of contracts, and contract type in particular. Contracts did play a key role in the management of risk in the two developments, but not necessarily in the way that we might expect based on the traditional view of acquisition policy. Contract type is only one of several aspects of risk management in the contracts used to implement these developments. The writing of the statements of work and special clauses in the development contracts and in the warranties in the follow-on production contracts was also important.

Contract Type and the Statement of Work

The EMDP and full-scale-development contracts for the engine developments were all firm-fixed-price contracts. The F100 CiP used cost-plus-award-fee contracts throughout these developments.²⁰ The common wisdom today strongly frowns on the use of firm-fixed-price contracts in development efforts, although they appear to have worked satisfactorily in the two developments. In fact, the use of firm-fixed-price contracts per se does not appear to have been the key contracting issue in these developments.

Most observers today now reject firm-fixed-price contracts for development programs because of the risk involved. It is extremely difficult to predict precisely what a development program will yield or what the effort will cost. Hence, observers often argue that specifying a

²⁰F100 CiP Increment VIII in 1981 used firm-fixed-price level-of-effort terms for its flight-testing tasks. These terms played a very limited role in the developments we examine here. P&W strongly resisted the use of a firm-fixed-price approach and it was dropped after this contract.

firm fixed price typically imposes unacceptable risk on the contractor. The contractors in these developments did not balk at using firm-fixed-price contracts, partly because of the low expected technological risk in these developments. But a contract type is only one of several elements that determine the risk associated with a contract.

At least as important, the goals of these developments were stated in terms that controlled the risks involved in the developments. The EMDPs especially placed very heavy emphasis on how development would proceed, rather than on what it would produce. The statements of work for both the F100 and the F101 DFE EMDPs gave substantial attention to levels of inputs expected—for example, numbers of test engines and numbers of hours or flights for testing. Final system requirements were more clearly stated in the FSD contracts; but even there, the development process received considerably more attention than the development product. All contracts included an order-of-precedence clause that essentially stated which parts of the contract took priority when different parts conflicted with one another. In that clause, the contracts gave specifications lower priority than anything else, effectively emphasizing the way the development was conducted over what it produced when questions arose. This emphasis is typical of development contracts; specifications typically receive much greater relative emphasis in production contracts.

Even when a final deliverable was defined, the terms were often broad. For example, the F101 DFE EMDP envisioned "a derivative design of the F101 engine, using the F101 core engine design to the maximum extent possible. The engine design shall be satisfactory for use in fighter aircraft applications. . . . The engine shall be capable of producing at least 28,000 pounds of thrust at sea level static standard day conditions. The engine design and performance will conform to the detailed requirements of the Engine Specification;" the contract indicates elsewhere that the contractor will provide this specification as part of the development effort.²¹ The F100 EMDP set a long list of development goals and then stated that "These Program Goals are for planning and management purposes and are not to be considered criteria for successful contract completion."²² Discussions of the development tasks (as opposed to products) that dominate these contracts are equally general.

The risk presented in a development contract depends at least as much on the way the statement of work is defined as on the contract type itself. Observers suggest that the statements of work used in the engine developments are not unusual. They reflect an

²¹U.S. Air Force Contract F33657-79-C-0178, Modification PZ0003, 16 July 1979, Attachment 1, pp. 2, 4-5

²²U.S. Air Force Contract F33657-79-C-0641, Modification PZ0001, 6 May 1980, Attachment 1, pp. 2-3. Table 4.3 excerpts some of these goals.

important feature of a relational contract, the importance of watching the progress of the work closely in a relationship that is expected to persist over the long term. All the development contracts allow the Air Force to remain intimately involved in the process of development itself. They provide access that ensures that the Air Force will learn about problems quickly as the developments proceed and that the Air Force can react quickly to surprises to control their effect on the program as a whole. Participants in the development emphasize that this monitoring function played a larger role in these developments than the general type of contract. And, as noted above, the presence of competition simplified this monitoring role: It made it harder for either contractor to exploit the general language used to specify the statements of work in the contracts.

Some students of contracting suggest that the difference between fixed-price- and cost-plus-type contracts is overstated because contractors can use contract modifications in a firm-fixed-price contract to recover their costs if they are higher than expected. All the engine contracts experienced substantial contract changes over their lifetimes. Without a detailed audit of those changes, we cannot state that they were not used to cover unexpected costs earlier in a program. But numerous auditors who examined the programs found no evidence of such a problem. On the face of them, the modifications of these contracts appear to have been driven by reasonable changes in work scope required to let the developments continue in fruitful directions. The number of changes and the ease with which they were implemented appear to reflect a well-functioning system that promoted the kind of flexibility the changes made possible. Perhaps more to the point, GE and P&W have both shown a strong preference for cost-based contracting when offered the choice, which suggests that both experience a greater degree of freedom under cost-based contracts than under fixed-price contracts.

The simultaneous use of cost-plus and fixed-price contracts in the F100-PW-220 development created a small problem in that development. Because CIP tasks cannot be known far in advance, P&W traditionally accumulated an inventory of components under the CIP that could support a wide range of tasks in the future. The CIP is flexible enough to allow this practice and, although it does impose perhaps unexpected inventory costs on the U.S. government, it contributes to the flexibility that the CIP is meant to maintain. When paired with fixed-price contracts, however, accumulation of inventory under CIP can allow more flexibility than intended. All of the contracts in the two developments were fairly flexible. In particular, they allowed certain transfers of government-owned equipment among specified, closely related programs. Under such circumstances, a strong temptation existed to buy components under the cost-based CIP, where the contractor could recover the

costs of these assets from the government, and use them in the EMDP or full-scale-development program, both firm-fixed-price, and for which the contractor could not recover costs from the government. The Air Force had to tighten control on the acquisition and use of inventories under the CIP to avoid this kind of problem. The problem is a direct result of the type of contracts chosen for the development programs.

Special Clauses

The contract type and statement of work are not the only parts of a contract that provide information on the risk in a development program and the developers' approach to it. Special clauses provide additional information.²³

In the subject fixed-price contracts, the most important special clause was the limitation-of-government-obligation (LOGO) clause. Each contract had it.²⁴ The clause was required because, unlike production contracts, development contracts need not be fully funded. This clause limits the government's obligation under a contract to the level of funding explicitly obligated to the contract, thereby eliminating the risk that the Air Force might be required to pay for services with funds that it does not have. In all of these contracts, the most common contract modification increased the level of funding available, effectively increasing the amount of work that could be performed under the contract. Over their lifetimes, the developments were rarely fully funded. As a result, the contracts often used the level of funds obligated instead of the contract price as the best measure of the contract size. This clause clearly limited the Air Force's risk in the event that insufficient funds were available. In the end, all the contracts were fully funded and, with the exception of later CIP contracts, the availability of funding had no effect on the actual activities of development. The developers had an understanding with the Air Force comptroller, often in writing, about when funds would arrive, and they generally arrived as scheduled. Systematic delays in annual congressional funding decisions for the program made this understanding more difficult to sustain in later CIP contracts.

The F100 DEEC/pump/valve/EMS full-scale-development contract provided another clause to deal with more fundamental uncertainty about funding. It listed five options with not-to-exceed quantities, exercise dates, and incremental statements of work.²⁵ As funding became available, the Air Force exercised these options and effectively expanded the scope of

²³For a discussion of use of special clauses to promote fairly detailed risk assessment in Air Force contracts, see Bodilly, Camm, and Pei, 1991.

²⁴Cost-based contracts such as the CIP contracts used an equivalent device called a limitation-of-funds clause.

²⁵U.S. Air Force Contract F33657-82-C-2199, Section H, Clause 11, pp. 21B-21C and Attachment 1, Addenda 1-5.

the effort. Merely structuring such options helps structure the development effort in a way that accommodates uncertainty about funding; exercising them or not provides a well-structured way to share risk about funding. The Propulsion SPO has used such an approach in other development contracts. The CIP resolution-of-problems clause offers a standardized means of managing such risk within the CIP itself.

To manage another form of major risk, the F100-GE-100 full-scale-development contract had a clause saying that "the prices and the delivery provisions of this contract do not include provisions for major repair, replacement or retesting of the engine, components, and/or special test equipment due to loss, destruction, or damage incurred as the result of a catastrophic failure during the testing . . . [or for] . . . any individual repair, replacement, or retesting of which the agreed allocable costs shall exceed \$1,000,000 and which are not compensated by insurance. . . . Any such major repair, replacement or retesting shall be the subject of separate negotiation." At this stage in development, such a risk was perhaps the largest risk internal to the development effort itself. This clause significantly reduced its importance in the context of a firm-fixed-price contract.

Other specialized clauses dealt with specific concerns in each contract. For example, while a legal issue of how to allocate a particular form of corporate overhead costs remained before an arbiter, the F100 DEEC/pump/valve/EMS contract used a clause to bound the outcomes that were mutually acceptable to P&W and the Air Force.²⁶ The F110-GE-100 full-scale-development contract contained a similar clause to characterize the treatment of independent research and development, bid and proposal, and related fuel and tax costs.²⁷

Warranties

Final performance on each full-scale-development effort was judged by comparing actual engine specifications with the over one thousand pages of specifications in the contract that described the engine contracted for. A warranty offers one way to reduce these thousand-plus pages to a few key criteria to facilitate ongoing oversight of the engine and its promised performance after it is deployed. Knowing that production contracts will contain such contractual devices potentially motivates developers to adjust their designs in anticipation.

Formal warranties did not exist until the production contracts became effective. In this sense, their effect on development is very much like that of the formal competition

²⁶U.S. Air Force Contract F33657-82-C-2199, 30 September 1982, Section H, Clause 12, p. 21D.

²⁷U.S. Air Force Contract F33657-82-C-0257, 15 November 1982, Section H, Clause 23, p. 38.

embodied in these same contracts; although warranties did not exist earlier, observers and participants widely anticipated their use early in the developments.

GE in particular expected to use warranties to promote its entry into the fighter market. The Air Force was most concerned about operability and the long-term cost of engine ownership. GE believed that it could best demonstrate its responsiveness to these concerns by offering warranties that made guarantees about these concerns. Hence, early in the development of the F101 DFE, GE developed an operating-and-support-cost model, based on its existing commercial engines, to estimate the likely costs of the engine that resulted from the DFE development. It used this model, which incorporated many of the new techniques emerging under ENSIP, to estimate a reasonable price for a warranty at that time.

The request for proposal for the first production competition, released in December 1982, included explicit provision for a warranty that the Air Force expected to²⁸

- motivate/ give incentive to the contractor
 - influence design, manufacturing, test, and support activities
 - deliver a quality product initially and consistently
 - stabilize the engine support system early
 - retain thrust, operability, availability, and reliability
- satisfy the 1983 3,000-TAC-cycle warranty statute.²⁹

Figure 5.1 summarizes the terms of the proposed warranty. The Air Force would have the option of repairing failures under the first two parts and receiving compensation from the contractor based on a specified schedule of costs. The first portion of Part I is essentially a standard warranty covering the early part of the engines' lives. The remaining parts look farther into the future, aiming directly at the development goals of ensuring operability, durability, and performance retention.

The Air Force released these terms at about the same time that the full-scale developments began. As indicated above, the Air Force expected the warranties to influence the design of the engines. What influence did they, and earlier expectations about warranties, have on the developments themselves?

²⁸U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1984.

²⁹Section 797 of the FY 1983 DoD Appropriation Act states that no money shall go to an alternate or new model fighter engine without a warranty guaranteeing 3,000 tactical cycles.

Part I: To assure quality, avoid infant mortality, assure consistency, retain performance

For 3 years or 1,000 engine flight hours (EFH):

engines, modules, components, parts	
defects in materials and workmanship	parts and labor
unusable/unserviceable conditions	parts
operation outside tech order limits	parts
support equipment defects in materials and workmanship or function	
or operations outside required limits	parts and labor

For 3,000 TAC cycles or 8 years:

performance retention	
more than 98% intermediate thrust	parts and labor
less than 105% intermediate SFC	parts and labor

Part II: To emphasize high cost/maintenance drivers, assure quality, and avoid major support destabilizers

For 3,000 TAC cycles or 8 years:

combustor and high-pressure turbine	
unusable/unserviceable conditions	parts
operation outside tech order limits	parts

Part III: To assure long-term stability in fleet support, incentivize contractor, and share risk

3,000 TAC cycle demonstration:

- engine fleetwide combined UER and SER/1000 EFH
- contractor-designated rate for F-15, F-16
- first demonstration period, 1987-88, with assessment in 1989
- annual demonstrations through 1994, with assessment a year following
- contract adjustment for rate better/worse: \pm \$25,000/removal

SOURCE: U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1984.

Figure 5.1—Summary Terms of Warranty Called for in Request for Proposals

Participants in the developments discount the effects of the warranty on the developments themselves. They emphasize the role of warranties to define and explicitly share risk after the engines reached the field. The prices demanded for warranties provided useful information on the maintenance costs that each developer expected for its design, *given* the design chosen. Participants believe that the designs of the engines that actually reached the field would have been of about the same quality with or without the warranties.

We cannot prove or disprove this assertion by looking at only one case. But it seems to defy common sense, particularly if we view the warranties in the context of competition. GE effectively proposed a warranty as a way to market its new capability. Given the Air Force's priorities in the competition, P&W had to recognize that, to be competitive, this warranty would enforce a similar requirement on P&W. If P&W was to meet GE's threat effectively, it had to design an engine good enough to allow P&W to offer a competitive warranty. And once committed to a competition defined in part by warranties, both developers had incentives to design engines compatible with such a competition. Perhaps the exact terms of the warranty were finalized too late to influence the exact design of the two engines. Perhaps the role of competition in this scenario is so large as to overwhelm the role of warranties. Most observers agree that we cannot separate the warranties from the competition—the competition could not have been as successful without warranties and the Air Force could not ultimately have negotiated as satisfactory terms on the warranties without competition.³⁰ The issue bears additional attention.

Summary

Discussions of risk management in acquisition contracts tend to emphasize contract type. While contract type is not unimportant, other aspects of contracts also play an important role. The development contracts we examine used statements of work that addressed not just the final product of development, but the process of development, focusing primarily on development tasks that are easier to understand in advance than development products. They also employed special clauses to deal with major risks related to funding and test events. Perhaps as a result, P&W and GE appear to have had little objection to conducting development activities under firm-fixed-price contracts. The low inherent risk in the developments, of course, was also a factor. The production contracts that followed the

³⁰In fact, P&W demanded a very high price for its warranty in the first competition if the Air Force split its buy. A successful competition effectively increased P&W's risks, and P&W found one way to express that increase by demanding a higher price for bearing the risk of the warranty if competition continued than if the Air Force foreclosed the GE alternative. The Congress refused to pay this high price following the first production competition; P&W relented, and the price of P&W's warranty closely matched GE's price in future competitions.

developments included detailed warranties designed to define and manage risk following deployment. Whether anticipation of those warranties helped define and manage risk during development is unclear.

SECTION SUMMARY

Participants in the derivative engine developments did not ever perceive them as presenting high risks. As derivative engines, the F100-PW-220 and F110-GE-100 presented low technological risks. And because the developments were small and unlikely to affect any other higher profile programs, officials above the Air Force imposed few risks on them other than balking initially about funding.

Such low risks significantly contributed to the success of these developments. But other factors contributed as well. Active, if informal, competition significantly increased the Air Force's power in its long-term relationships with P&W and GE. Competition increased P&W and GE's responsiveness, simplified the Air Force's need to monitor them, and made it easier for the Air Force to respond flexibly to unexpected events during the developments. An experienced SPO, with well-developed standard procedures and a rapidly expanding formal doctrine on risk management also contributed to the developments' flexibility. The SPO and its contractors repeatedly managed unexpected events in the developments with skill and confidence. Low risk facilitated the use of firm-fixed-price contracts in the developments, but other contractual factors enriched those contracts' ability to reduce and share risk. The statements of work reduced risk by emphasizing process over product; special clauses managed concerns about specific uncertainties about funding, the cost of catastrophic test failures, and other factors. Warranties clearly helped manage risk during the production and deployment of engines that the development programs created; their effects on risk management during the developments are less clear.

6. CONCLUSIONS

We conducted this study as one of seven case studies designed, when taken together, to yield useful insights about Air Force development practices and the assessment and management of risk in those practices. We must be cautious drawing firm conclusions from the one case presented here. Nonetheless, this case develops suggestive information that we can present in the form of six hypotheses. These hypotheses suggest information to look for in the other cases as well as ideas for future policy and policy analysis.

1. Derivative development can reduce risk in limited circumstances. The Air Force uses derivative engine development when they allow such development to achieve its goals. But derivative developments do not allow large advances in system performance, broadly conceived. Large advances require more traditional, centerline engine developments, which inherently entail more technological risk than that observed here.

This view of derivative development finesses the question of whether larger advances are worth the risk or whether the current mix of derivative and centerline developments found in the Air Force is appropriate today or would be appropriate in the rapidly changing environment of the near future. We can expect that environment to increase the external risk experienced in most developments; greater emphasis on derivative development may offer one way to offset that risk increase. We cannot say more about this possibility without giving the question additional attention.

2. Continuity in SPO management significantly enhances risk management. As a standing SPO that does not come and go with individual development programs, the Propulsion SPO has accumulated experience, doctrine, procedures, and knowledge about its contractors, all of which contribute significantly to its ability to anticipate and manage problems. These sources of order and stability, perhaps ironically, gave the SPO the skill and confidence required to react flexibly and creatively to unexpected events in the subject developments. Analogous statements apply to the contractors themselves.

It is, of course, easy to say that more continuity is better. What is the cost of increasing continuity? For engines, continuity is possible because engines are all managed by a standing, collective staff instead of being placed in aircraft SPOs, as they were before the Propulsion SPO formed in 1977. Total system management of new aircraft emphasizes the importance of integrating the management of all subsystems of an aircraft in one place. ASD turned back toward this approach with the B-2 development, which integrated development of the F118 engine with development of the airframe to facilitate security goals.

ASD has also placed responsibility for developing the engine for the advanced tactical fighter (ATF) with the airframe SPO, not the propulsion SPO, to ensure proper integration.

Placing all engine development in one SPO makes it more difficult to manage system integration and security, but giving these goals too much emphasis poses a serious risk. The Air Force formed the Propulsion SPO to solve some serious problems. The story of the subject developments is part of the story of how the SPO solved those problems. With the problems apparently solved, it may be easy to forget their importance and their solution. An important lesson of these developments is that continuity in a SPO makes it easier for lessons learned not to be lost, including lessons about continuity.

3. Formal risk assessment plays a limited but important role in general risk management. New concepts and methods developed in the 1970s, including the accelerated mission test, the four-step development process, and the Engine Structural Integrity Program, gave the developers of the two engines tools for managing numerous important risks. Without those tools, the developers could not have achieved the durability and supportability goals sought for the engines. But such methods do not help managers deal with broader, less-defined risks. Here, there remains no substitute for the judgment of experienced managers familiar with the routine management of risk in system developments.

Formal risk assessment is possible only when the risks involved are simple enough to be viewed in a simple analytic framework. And even then, the results of the assessment are no better than the inputs to the framework. The value of the methods mentioned above is twofold: they reflect major new insights into the reasons why engines and their components fail and the way in which they fail; and the Air Force and its contractors have been able to collect fairly objective empirical data to implement those methods. There will always be more room for improvement in our understanding of failure modes and of the data we use to quantify them, and future analysis should pursue both. But neither will ever replace the basic intuition of a manager acting in an unstructured setting. Making a decision in such a setting is essentially the *raison d'être* for a manager, and no amount of formal risk assessment will replace the manager's role. That said, we must accept that managers react to their incentives. And the problem of providing managers with incentives to "do the right thing" should benefit as much from additional analysis as from more precise questions raised by formal risk assessment.

4. Higher level interest in a program increases some program risks and reduces others. The general absence of higher level interest in the developments allowed their immediate managers to set realistic performance, schedule, and cost goals and

ultimately to meet those goals. In this sense, the lack of interest reduced the external risk experienced in the developments. But a lack of interest also left the developments without high-level advocates to protect the programs' funding, increasing external risk. Such risks must be balanced.

One way to reduce this conflict is to offer oversight well informed about the importance of setting and achieving realistic goals. Another way to say this is to encourage high-level policy makers to believe that, if a developer's promises look too good to be true, they probably are. Encouraging or even trying to force the developer to seek unrealistic goals is unlikely to be a successful strategy in the long run. To know whether promises are reasonable or not, of course, the policy maker must be well informed. A message offered over and over by participants in the developments is that the overseer's knowledge is critical to the success of a development because it is extremely difficult to create incentives that induce a developer to be fully open.

Perhaps the most difficult management problem in a development results from the fact that, even if a development goes poorly, it may continually seem to be rational to proceed. If the true path of the development had been known from the beginning, it might not have been rational to start. But, at each point along the way, what is past is sunk and it may appear that future benefits exceed future costs. Knowing this, a contractor has a strong incentive to get the government committed early and to continue ever hopeful that things will work out. The Air Force presumably has similar incentives relative to the Office of the Secretary of Defense and the Congress. Only a well-informed overseer can anticipate the problems of development and plan against them. This insight helps explain the Propulsion SPO's commitment to hands-on management and suggests that, properly understood, this insight has much broader application.

5. Competition redistributes risk in a development program. Competition increases the risk perceived by the contractors and reduces the risk perceived by the Air Force. At any point in time, the Air Force can change the market shares of its contractors, increasing their risks, and by so doing can reduce its dependence on the poorer performer, reducing its own risk. Competition also increases the risk that the Air Force can induce its contractors to bear at a given cost. These changes in risk result from a basic shift in relative power that increases the contractors' responsiveness and reduces the Air Force's cost of monitoring their contract compliance.

Using competition to get these benefits is not costless. Carrying two engines through full-scale development essentially doubled the cost of creating the technological capability offered by the derivative engines. Competition may have led to some economies during the

development phase that kept costs from fully doubling, but few would argue that such economies fully offset the cost of developing a second engine. Even all the added benefits of responsiveness and risk shifting during development are unlikely to justify such additional costs. The real benefits come over the life of the production of the engines. No good estimates exist for the benefits of competition over this period. In fact, the usual analytic view of competition, which does not examine the effects of power shifting in small-number relationships, has no widely accepted way to measure such benefits. The question deserves more attention.

It is instructive to note that, after two competitions touted by observers and participants in the Air Force acquisition community as highly successful, the Alternate Fighter Engine and improved performance engine competitions, the Air Force rejected the use of competition in its next major engine development, the full-scale development of the engine for the advanced tactical fighter. Apparently the Air Force found the cost of developing a second engine through product verification too high to support as its overall budget falls. Officials appear to believe that this cost would justify itself over the course of the full production run; but the initial cash flow expected for a second full-scale development would be too hard to justify to Congress in a period of uncertainty and retrenchment. Perhaps competition for derivative engines was so successful because the cost of developing a second engine through product verification was low enough not to attract undue attention to itself.

6. Other contractual terms are at least as important as contract type in risk management. The choice of contract type affects the business environment for development; contractors clearly prefer a cost-based to a fixed-price contract if both types are offered with similar terms. But a contract's statement of work and special clauses can be written to soften the risks implied by a fixed-price contract, potentially dominating the choice of contract type in their effects on contractor risk. And the techniques used by the SPO to monitor contract compliance can have far larger effects on risk management than the formal terms of the contract.

These conclusions are especially apropos in development contracts, the statements of work for which do not use the precision found in a typical production contract. And simple special clauses can be written to reduce dramatically the risk of large losses, which concern contractors the most. Such clauses may also be especially important in the near future as defense budgets shrink and the number of prime contractors involved in defense work shrinks. Longer term relationships between the government and individual development contractors could well become more important, emphasizing the need not just for clearly

written contracts and contract law but for a well-informed working relationship between the Air Force and its contractors that sustains the increasingly important relational contracts in defense system management.

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