The F-16 Multinational Staged Improvement Program: A Case Study of Risk Assessment and Risk Management

Frank Camm

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The research reported here was sponsored by the United States Air Force under Contract F49620-91-C-0003. Further information may be obtained from the Strategic Planning Division, Directorate of Plans, Hq USAF.

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A RAND NOTE

N-3619-AF

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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 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 a derivative fighter, the F-16C/D. That fighter uses as subsystems many of the other systems studied in this project. This Note examines the risks associated with integrating those systems into the F-16C/D. 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 Development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of Risk Assessment and Risk Management*, RAND, N-3618-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 related unpublished papers 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.

SUMMARY

The F-16 Multinational Staged Improvement Program (MSIP) is the development program that the F-16 program has used to move beyond the F-16A/B. Its primary product has been the F-16C/D, an aircraft whose design evolves over time as new technological capabilities become available or attractive to incorporate in its design. MSIP is the program that F-16C/D developers have used to introduce these capabilities over time. The prime contractor for the F-16, General Dynamics, and the F-16 System Program Office (SPO) formally initiated the program in 1980. It continues today.

MSIP provides a derivative approach to development, an approach the Air Force may want to use more broadly in the future for several reasons. The environment in which the Air Force does business is changing rapidly. The external threat that it must engage is far less well defined than it had been in the past and is likely to change fairly rapidly over time. The Air Force will not have the resources it has today to face such an uncertain threat. A development process that allows fairly rapid response to changes in threat at a moderate cost would appear to be very attractive. MSIP offers such a process.

This study examines MSIP, giving special attention to means of assessing and managing the risks associated with system development. It is one of seven case studies conducted by RAND for the Air Force to examine the Air Force's management of risk in development programs during the 1980s. Other case studies address the Alternate Fighter Engine, AMRAAM, B-1B, Global Positioning System (GPS), JSTARS, and LANTIRN systems. MSIP has integrated a number of these subsystems into the F-16C/D.

When we speak of *risk*, we mean a situation in which a manager can be surprised in a negative way. The higher the probability of a negative outcome from an activity is, the riskier that activity is. Development managers clearly try to limit the probability of negative outcomes from their highly uncertain development efforts. Development programs effectively set a number of minimum acceptable outcomes relating to system performance and the cost and schedule of the development. Over the course of a development, its managers attempt to eliminate the possibility that the minimum outcomes will not be met. In this sense, their management of risk is difficult to distinguish from their management of development in general. Development managers do not make a strong distinction. Hence, this study views risk assessment and risk management in rather broad terms.

MSIP is called "multinational" because it includes the European Participating Governments (EPG)—Belgium, Denmark, The Netherlands, and Norway—in planning and

decisionmaking. In this process, the United States is the dominant partner. For the most part, MSIP has developed new versions of the F-16C/D for the U.S. Air Force and then offered variations to the EPG and to other foreign air forces not represented in the process. This approach limits both risks associated with setting new system specifications and risks associated with implementing designs for foreign air forces. It also affirms the U.S. Air Force's strong continuing interest in the F-16C/D, assuring foreign governments that the U.S. Air Force will continue to support the aircraft designs they buy.

MSIP is called "staged" because it incorporates new capabilities in increments. It is an approach that allows MSIP to incorporate new capabilities in the F-16C/D as technology or requirements change; to use a retrofit program to control production costs (MSIP incorporates provisions in aircraft produced in an early stage that reduce the cost of retrofitting subsystems that will be incorporated in aircraft produced in a later stage); and to resolve the risks associated with the subsystems integrated during one stage before moving on to engage the risks associated with subsystems to be integrated in the next stage. The program was initially conceived with three stages. General Dynamics proposed a fourth stage to implement a follow-on to the F-16C/D; it was rejected in 1989.

MSIP is essentially a management device for coordinating many concurrent efforts to integrate subsystems with one another and an F-16 airframe. That is, in each stage, new designs of the F-16C/D are conceived that integrate many new subsystems to create a coherent aircraft with new combat capabilities. To do so, MSIP relies on the F-16 Falcon Century program to survey new capabilities and consider matches of technological capabilities and missions that might be used to define new aircraft designs. When it discovers a new subsystem program that might be attractive to integrate in the future, MSIP establishes a relationship with the program as early as possible. MSIP works with the program to provide test assets, influence design specifications that affect the subsystem's compatibility with the F-16, and ultimately coordinate the integration of the subsystem with the other subsystems that it will join in a new F-16C/D design.

To this integration task, MSIP brings a test-analyze-fix approach, which emphasizes the need for extensive, iterative testing to yield quickly empirical information on problems. As the process reveals integration problems, MSIP developers can analyze and fix them and then test again for success of fix. When it attempts to integrate many subsystems at once, this approach is demanding because subsystem integrations proceed at different rates. It is difficult to maintain an up-to-date and coherent configuration against which to test simultaneously each of the subsystems being integrated. To support the test effort, MSIP has employed a Systems Integration Laboratory and F-16C/D simulator at General

Dynamics to great effect. But the process is still challenging. MSIP managers expected that the greatest risk in their program would arise from problems associated with integrating many subsystems at once, and they were right.

MSIP, then, presents a program in which planners can anticipate that many changes will occur in the future. Some changes will occur simply because the program is developing new aircraft designs for implementation. Others will occur because the planned integrations do not proceed as expected. To prepare for such changes, MSIP has done two important things. First, it has established a flexible management strategy and contractual environment that plan for change to occur and respond to individual changes as they occur. The strategy and contractual environment affect the F-16 SPO, General Dynamics, all the SPOs and prime contractors associated with subsystems being integrated through MSIP, and the many test facilities that support MSIP efforts. They focus as much on establishing and maintaining good relationships among these organizations as they do on controlling individual changes. Second, MSIP has assembled an experienced management staff to handle changes as they occur. Staff quality is more important to MSIP than it is to more traditional developments precisely because its flexibility cannot be effective unless MSIP managers respond effectively as MSIP's development tasks change over time.

While MSIP has overseen the F-16C/D program's development activities, a series of three multiyear production contracts have governed its production activities. Those contracts signal a strong consensus between the Congress and Air Force, both approvers of the contracts, that the F-16 program would remain healthy and continue in a fairly predictable way. Such consensus must have relieved MSIP managers about one major risk that developers must typically address—the risk that their programs will not continue. MSIP managers could presumably give greater attention to other risks associated with developing the F-16C/D.

Although a derivative development program, MSIP has incurred substantial costs: about $1 billion to date. But it has successfully handled the risks associated with sophisticated new capabilities. In particular, it has successfully managed the risks associated with integrating many subsystems at once. Its ability to do so allows it to design and implement new variations on the F-16 quickly. MSIP has successfully fielded a series of effective F-16C/D designs. It has also set the stage for developing F-16 variations outside the F-16C/D program.

In the end, MSIP is as much a general approach to system development as it is a formal F-16 program. The F-16 program has used this general approach to upgrade the F-16A/B fleet, extend the F-16C/D over time, and design new F-16 variations based on the two basic designs. Such variations include an enhanced air defense fighter for the Air National Guard, a new reconnaissance aircraft, an aircraft that emulates Soviet fighters for the Navy, and the potential for a new aircraft to provide close air support. For each variation, the F-16 program has selected subsystems like those used in MSIP and integrated them using methods similar to those used in MSIP. For each, the F-16 program generated a design and implemented it quickly at a reasonable cost. Such a capability could prove useful in the future on a broader basis, outside the F-16 program, to enhance the Air Force's ability to adjust to a changing world.

ACKNOWLEDGMENTS

I thank especially Albert Misenko, chief of the U.S. Air Force Aeronautical Systems Division History Office, and his staff. Without their cooperation in providing access to official documents and other historical material on the F-16 program, this study would not have been possible. I also thank the officials in the Aeronautical Systems Command who gave generously of their time for interviews that facilitated this study. 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 helpful review of an earlier draft. I retain responsibility, of course, for any errors in fact or interpretation.

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GLOSSARY

A-16	A variant of the F-16C/D proposed as a CAS aircraft.
ACIU	Advanced control interface unit, a device developed as a result of problems identified during MSIP to facilitate the integration of the AMRAAM with other systems.
ADF	Air Defense Fighter, a variation of the F-16 developed using an approach like that in MSIP.
AFE	Alternate Fighter Engines, F100-PW-220 and F110-GE-100, developed to compete with one another on a continuing basis as engines for the F-16 and F-15.
AFFTC	Air Force Flight Test Center at Edwards Air Force Base. Home of the F-16 and LANTIRN combined test forces.
AFOTEC	Air Force Operational Test and Evaluation Command.
AFSC	Air Force Systems Command, parent command for the F-16 SPO.
AFTI	Advanced Fighter Technology Integration program, a development program for testing advanced subsystems in an F-16 testbed.
AGM-65D	Maverick air-to-ground missile.
AIBU	Advanced interference blanking unit, a device developed as a result of problems identified during MSIP, to mitigate electromagnetic incompatibilities among F-16 subsystems.
ALQ-131	An electronic warfare pod considered as an alternative to ASPJ.
ALR-74	The initial radar warning receiver considered for MSIP. Later replaced, as a result of MSIP activities, by the ALR-56M.
AMRAAM	Advanced medium range air-to-air missile, a critical element in the Block 40 upgrade.
APG-68	The fire-control radar used in a series of variations in MSIP. It began as the improved or advanced APG-66 and then evolved into the APG-68M, a lower cost version, and APG-68V, a more reliable version.
ASD	Aeronautical Systems Division, the immediate parent organization for the F-16 SPO.
ASPJ	Airborne self-protection jammer, a key element of MSIP that never worked as expected.
ATA	Advanced terrain avoidance, a capability developed during MSIP to enhance LANTIRN's capability to support low-altitude flight.
ATDL	Adaptive target data link, a system developed in response to problems identified during MSIP to integrate GPS, PLSS, and JSTARS.
ATF	Advanced tactical fighter.
ATHS	Automatic target hand-off system.
BPS	Battery power supply.
CARA	Combined altitude radar altimeter, a key subsystem integrated during MSIP.
CAS	Close air support, a combat function served by a series of proposed F-16 variants.
CCP	Contract-change proposal, the principal management device used to organize and control new development and integration tasks under MSIP.

CEB	Common or configured engine bay, a device developed as a response to problems identified during MSIP, to enable the F-16C/D to accept easily either AFE engine.
CNI	Communications/Navigation/Identification system.
CTF	Combined test forces.
DFLCS	Digital flight control system, a critical system introduced during MSIP and central to realization of LANTIRN-related capabilities.
DMT	Dual-mode transmitter, a line replaceable unit in the APG-68 that experienced serious, unexpected development and producibility problems.
DoD	Department of Defense.
ECP	Engineering-change proposal, the principal management device used to transform capabilities developed through CCPs into actual capabilities incorporated on production aircraft.
E^2GS	Enhanced envelope gun sight.
EJS	Enhanced JTIDS.
EPA	Economic price adjustment clauses.
EPG	European Participating Governments of Belgium, Denmark, The Netherlands, and Norway.
F-16A/B	The first production version of the F-16, upon which the F-16C/D is based.
F-16ADF	An air defense version of the F-16 developed as an upgrade of the F-16A/B.
F-16C/D	The version of the F-16 developed during MSIP.
F-16N	A version of the F-16 developed for the Navy to emulate Soviet fighters.
FANG	Fast Action Negotiating Group procedure, established by CCP 9101 as means of quickly definitizing all contract changes under $10 million.
FIM	Forward inlet module, a device developed as a response to problems identified in MSIP to customize airflow for the AFE engines used in the F-16.
FLIR	Forward-looking infrared sensor, the basic sensor technology embodied in LANTIRN.
FPI	Fixed-price incentive contract, the key type of contract for MSIP.
FSD	Full-scale development.
FSX	A new Mitsubishi fighter derived in part from the F-16C/D.
FYDP	Fiscal-year defense plan, a DoD document specifying expected future resource flows for defense systems and activities.
GPS	Global Positioning System, a device introduced during MSIP to enhance navigation and other location-related activities.
HARM	High-speed antiradiation missile.
HUD	Head-up display, a display introduced during MSIP to show FLIR images and data on the status of the aircraft, its stores, and its targets.
IFF	Identification, friend-or-foe system.
IOC	Initial operational capability.
ISPR	Integrated System Performance Responsibility, a contractual device assigning specific integration responsibilities to the prime contractor, General Dynamics.
JPO	Joint program office.
JSPO	Joint system program office.
JSTARS	Joint surveillance, target acquisition, and reconnaissance system, an airborne radar sensor that could potentially communicate with an F-16 through the ATDL developed during MSIP.
JTIDS	Joint Tactical Information Distribution System.

LANTIRN	Low Altitude Navigation and Targeting Infrared at Night system, a sensor and laser designator around which MSIP built its Block 40 design.
LAU-129	The final modular rail launcher developed for the AMRAAM.
MCID	Modular common inlet duct, a device developed in response to problems identified during MSIP, to facilitate customizing air flow to the AFE engines.
MFTBMA	Mean flight time between maintenance actions, a logistics measure relevant to the development of the APG-68(V).
MSIP	Multinational Staged Improvement Program, the program responsible for developing the F-16C/D.
NTE	Not to exceed, a contractual term that, during the period before the task is definitized, defines the maximum amount that a contractor can spend on the task.
OCU	Operational Capability Upgrade, a counterpart to MSIP that develops and implements upgrade programs for the F-16A/B.
OSD	Office of the Secretary of Defense.
PLSS	Precision location strike system, a sensor initially scheduled for integration though MSIP, but later dropped.
PSP	Programmable signal processor, a key line replaceable unit in the APG-68 that caused serious development problems during MSIP.
QA	Quality assurance.
RDT&E	Research, development, test, and evaluation, a DoD funding category.
RF-16	A reconnaissance variation of the F-16 design to carry a conformal, centerline sensor pod.
SAFPAR	Secretary of the Air Force program assessment report, a regular, periodic briefing to the secretary on the state of a program.
SIL	Systems Integration Laboratory, a development resource at General Dynamics that has played a key role in MSIP.
SOL	Statute of limitations.
SPO	System program office.
TA	Test article.
TAC	Tactical Air Command, the principal user of F-16s in the U.S. Air Force and the principal incremental source of test aircraft.
TAF	Test-analyze-fix, an iterative approach to development that places heavy emphasis on repeated development of empirical measures on systems in development.
TBD	To be determined.
TEMP	Test and evaluation master plan.
VHF	Very high frequency.
VHSIC	Very high-speed integrated circuits, an advanced form of microelectronic technology.
VNS	Vehicle navigation system, a subsystem in PLSS that provided the basis for the ATDL.
WAC	Wide-angle conventional, a type of HUD.
WAR	Wide-angle raster, a type of HUD.
YP	F-16 SPO.
YPA	F-16 directorate of acquisition planning, closed during MSIP.
YPC	F-16 directorate of configuration management.

YPD	F-16 directorate of deployment and test and later development and integration; under the latter name, responsible for managing MSIP.
YPE	F-16 directorate of engineering, the principal functional office supporting MSIP.
YPF	F-16 directorate of test and deployment, created during MSIP.
YPK	F-16 directorate of contracting.
YPL	F-16 directorate of logistics planning and later, when integrated with YPA, of logistics.
YPM	F-16 directorate of manufacturing and later of manufacturing/quality assurance.
YPO	F-16 directorate of operations management.
YPP	F-16 directorate of program control.
YPR	F-16 directorate of projects and later of development programs; under the latter name, responsible for managing MSIP until integrated into YPD.
YPS	F-16 directorate of system safety.
YPX	F-16 directorate of multinational programs.

1. INTRODUCTION

Risk management is a central part of programs to develop new technology. By its very nature, the development of new technology requires identification and reduction of uncertainties about a product's performance to the point where the product can be successful in actual use. Potential risks stem from, among other things, the nature of the continuing demand for the services provided by the new product, the ability of the product to provide such services when it is mature enough to produce, and the ability of developers to achieve timely and cost-effective system maturity.

For weapon system developments, risk management can be approached in many ways. A derivative approach allows a weapon system to evolve over time, incorporating new technological capabilities as they present themselves or as new system requirements emerge. Such an approach limits the "jumps" that can occur in capabilities, but it also enables fairly quick, low-risk adoption of changes once it becomes clear that change is desirable. By limiting risk, it also limits the cost of developing such an improvement. Whereas a mainstream development might easily require 10 to 15 years to move from a concept to an operable system in the field and cost billions of dollars, a derivative development can field selected capabilities in a fraction of that time for a fraction of that cost.

A development approach that can respond quickly to change, for a reasonable cost, is likely to become more important in the near future. Declining real defense budgets will limit the resources available to develop and produce new weapon systems. And the exact nature of the threat will be more elusive than it has been. The threat is likely to change over time as the situation changes. Because such a development approach is designed to deal with continuing change, it is also likely to offer attractive, more general insights into risk management in the development of new technologies.

With these perspectives in mind, this Note examines the approach used to upgrade the F-16 fighter over time as new technological capabilities have become available and as new threats have presented themselves. The multimission, multinational fighter, the F-16 Fighting Falcon, completed its initial full-scale-development (FSD) effort and achieved initial operational capability (IOC) in the U.S. Air Force in 1979.[1] Since then, this General Dynamics aircraft program has continued to upgrade the F-16 and has used it as the basis for a series of models specially tailored to a variety of separate missions and the needs of 19

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[1]U.S. Air Force, Aeronautical Systems Division, F-16 System Program Office, "Management Information Notebook," Wright-Patterson Air Force Base, Ohio, 30 April 1984.

individual nations. As a result, the program has prospered. By 1990, it was committed to producing almost 2,500 aircraft for the U.S. Air Force and Navy and 1,300 aircraft for other governments.[2]

Much of the aircraft's continuing success can be attributed specifically to its ability to mature over time as technologies and threats change. Over the last decade, General Dynamics has performed a variety of development activities that maintain the flexibility of this fighter and continue its maturation. This Note examines the central development activity during the 1980s, the Multinational Staged Improvement Program (MSIP). This activity is responsible primarily for developing the modifications of the F-16A/B that led to the higher-performance F-16C/D in the mid-1980s.[3] It continues to this day as more capable F-16C/Ds emerge from development.

The approach to managing MSIP used by the U.S. Air Force and General Dynamics illustrates their more general approach to developing derivative aircraft from an established and successful design. Hence, it offers lessons about how such development might occur elsewhere in the future. This Note focuses on a development program that has generally been viewed as highly successful in the hope that it can offer lessons for managing the risks of system development as the world situation continues to change.

THE F-16 MULTINATIONAL STAGED IMPROVEMENT PROGRAM

To begin, let us review briefly what MSIP is. Section 5 will return to this question in greater detail. MSIP is a development plan managed by the U.S. Air Force, Aeronautical Systems Division F-16 System Program Office (F-16 SPO), and General Dynamics to coordinate improvements added to the F-16 over time. It began formally in 1980 as an effort to synchronize the introduction of a series of enhancements to the F-16 as new capabilities became available to be incorporated on the platform. At that time, an F-16 SPO official said:

> Looking ahead, two major factors will dominate the future course of the F-16 program: MSIP and the realization of foreign military sales. These two factors directly impinge on the length of the production run and thereby determine the lifespan of the F-16 program.[4]

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[2] General Dynamics, 1990.

[3] The A and C models have only one pilot. The B and D models facilitate training by providing space for two pilots. Otherwise, the A and B models are very close to being functionally equivalent, as are the C and D models.

[4] U.S. Air Force, Aeronautical Systems Division F-16 SPO, "Semiannual Historical Report, 1 July–31 December 1980," Wright-Patterson Air Force Base, Ohio.

Two considerations were important in the design of MSIP: compatibility of capabilities and planning for potential new systems. The first consideration, to ensure that new capabilities were compatible with one another, required compatibility checks at all levels. At the simplest level, all components anticipated on the aircraft had to fit and had to be compatible with the airframe's basic aerodynamics. Computers, radars, jammers, and weapons had to work together to ensure their effective incorporation on new weaponry. New components also had to avoid interfering with one another's electromagnetic frequencies. Cockpit controls and displays were needed for each new capability; even as the aircraft became complex, controls and displays had to remain as simple as possible to avoid overwhelming the aircraft's single pilot. And the aircraft had to provide adequate power and environmental-control services to support all new systems and adequate thrust to lift those new systems into combat.

Second, installation of the structure and wiring to support the new systems could be cheaper if it were done during the manufacture of an airframe rather than being retrofitted when a capability became available. This insight suggested introducing so-called Group A provisions on new aircraft, which were basically wiring and structures to support Group B hardware and software that would be installed in new aircraft and retrofit into aircraft with the appropriate Group A fittings. Designers had to weigh against the potential savings the possibility that, for technical or budget reasons, Group B add-ons might not occur in the future and, even if they did, the added weight of Group A provisions would impede aircraft performance until Group B provisions were added.

That is, MSIP has essentially been a development program aimed at incorporating many disparate capabilities in a coherent way. Whereas development as separate, modular systems is the key to the new capabilities, integrating such modules and incorporating them into the production of new F-16s to realize their capabilities is the key to MSIP. Although MSIP planning and testing activities for a particular component typically occur in parallel with the full-scale development and final product verification for that component, MSIP remains distinct from the latter, subsystem-specific activities. MSIP focuses on integration. Even when integration activities reveal the need for new capabilities in a component or for new components, development activities relevant to subsystem-specific activities generally remain separate. Distinguishing MSIP from the individual development programs is often difficult, particularly when the F-16 SPO provides aircraft as testbeds for new technologies and other inputs into individual developments meant to enhance integration in the future. But the distinction is important and real.

The distinction is clarified by stating that the F-16 SPO and General Dynamics organize their integration activities around blocks of new aircraft. Each block of aircraft has an identifiable constellation of systems that must be integrated. Blocks 5, 10, and 15 involved improvements in the reliability, supportability, and producibility of the F-16A/B design. Blocks 25, 30/32, 40/42, 50/52, and higher involved extensive enough changes to call for a designation change from F-16A/B to F-16C/D.[5] The systems to be included in a block change over time as more information accumulates about their availability and capability. The F-16 SPO and General Dynamics have created an extremely flexible management environment in which contract-change proposals constantly adjust the MSIP activities associated with new systems, and engineering-change proposals incorporate the new systems in new F-16s or retrofit them in existing F-16s as MSIP completes its integration tasks.

MSIP conceived blocks from Block 15 and higher as part of a three-stage program, accounting for the name, MSIP. Table 1.1 summarizes these stages as they were described in 1990; as noted above, they changed somewhat as MSIP proceeded.

Stage I required little development or design and called primarily for the installation of new structures and wiring in Block 15. Such installation was achieved primarily through a single engineering-change proposal. The second and third stages required new contracts, and many contract- and engineering-change proposals. Stage II incorporated improved radar and engines, enhanced munition capabilities, and power and cooling capabilities to accommodate future changes in Blocks 25 and 30/32. This stage initiated the development of the F-16C/D per se. Stage III built a new kind of fighter around the night/all-weather capabilities allowed by LANTIRN in Block 40/42. It added many advances in avionics and new engines in Block 50/52, which is not to use the LANTIRN system. As new capabilities are added to new blocks of production, many will also be retrofitted into blocks of existing aircraft.

These stages are useful as planning constructs; however, administration of the changes made possible through MSIP has focused on the specific blocks of aircraft involved. As a result, for most of its history, MSIP has included activities managed by more than one program office in the F-16 SPO. And budgets that distinguish MSIP from non-MSIP activities are difficult to define.

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[5]Blocks 30 and 32 differ only in their engines: Whereas Block 30 uses the General Electric F110-GE-100 engine, Block 32 uses the Pratt and Whitney F100-PW-220 engine. The same applies to Blocks 40/42 and 50/52. Block names changed over the course of MSIP. For example, Blocks 40/42 and 50/52 were initially known as Blocks 30G and 30P.

Table 1.1

Basic Stages of the Multinational Staged Improvement Program

Stage (Date[a])	Block	Major Changes Included
Stage I (1980)	Block 15	Structure and wiring provisions for future systems Increased-area horizontal tail
Stage II (1981)	Block 25	AGM-65D Maverick APG-68 fire-control radar Enhanced avionics and cockpit Wide-angle conventional head-up display (HUD) Increased-capacity electrical power and cooling
	Block 30/32	AMRAAM provisions Shrike Alternate Fighter Engines (AFE) with configured engine bay (CEB) Memory expansion Seal-bond tanks
Stage III (1985)	Block 40/42	Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) pods LANTIRN HUD Global Positioning System (GPS) High-speed Antiradiation Missile (HARM) II APG-68V fire control radar Expanded computers Digital flight control system (DFLCS) Automatic Terrain Following
	Block 50/52	Additional changes in weapons, radars and other avionics, cockpit, engines, and reliability and maintainability

SOURCE: General Dynamics, 1990, pp. 28, 85.

[a]Date when development and integration for the stage began.

Throughout MSIP, the U.S. Air Force has coordinated development, integration, and production incorporation planning with the so-called European Participating Governments (EPG) of Belgium, Denmark, The Netherlands, and Norway, which were involved in the multinational F-16A/B program. A quick review of the relative numbers of aircraft procured by these governments (527) and the United States (2485) reveals that the United States has been the dominant partner in this effort, which has been true throughout MSIP. Nonetheless, MSIP has proceeded on the understanding that the participating governments would probably want access to the capabilities being developed and that much of the work required to produce the F-16C/Ds, resulting from MSIP, would in fact be performed by companies located in those countries. Hence, although U.S. Air Force priorities have dominated MSIP from the beginning, multinational participation in the program has also been important.

What began as a formal three-stage plan has, more and more, become viewed as almost synonymous with continuing development efforts for the F-16, more an approach to development, integration, and production incorporation than a formal program in its own right. So it is not surprising that when the Air Force began to contemplate further changes radical enough to call for another designation change to an F-16E from an F-16C/D, many began to refer to the development program for the Agile Falcon follow-on to the F-16C/D as MSIP IV, the fourth stage of the continuing development program. As events unfolded, efforts to initiate this new activity failed.

But MSIP itself continues as the F-16C/D continues to mature in new capabilities that can be installed on new aircraft or retrofit on existing F-16C/Ds. Viewed more broadly, MSIP epitomizes the development of other aircraft derived from the F-16, efforts to retrofit existing F-16A/Bs to incorporate new capabilities, and efforts to customize aircraft for the needs of the many non-U.S. governments that continue to buy new F-16A/Bs and F-16C/Ds.

ANALYTIC APPROACH

MSIP, then, is a structured means of coordinating the introduction of many new capabilities—the general approach itself, a top-down entity that transcends the individual components managed by MSIP. Viewed from the bottom up, MSIP is simply the sum of the myriad improvements. We can understand the success of MSIP only by understanding each improvement and its incorporation in the F-16 through MSIP. In fact, both top-down and bottom-up perspectives are valid; they simply offer different ways to look at the way MSIP works. Both perspectives are reflected in this document. The material presented here is based primarily on management documents and historical reports prepared by General Dynamics and the F-16 SPO during the period and on interviews with individuals associated with MSIP during the 1980s.

The Note focuses almost entirely on events and circumstances within the program and, in particular, on events and circumstances relevant to U.S. versions of the F-16. Further work is needed to examine the external circumstances—in the Air Force and the contractors most directly involved in the development—in which this development proceeded and the international dimensions of the development; time and resource constraints did not permit us to examine these topics carefully in this study.

Following a brief description of our approach to risk and risk management, in Section 2, Section 3 describes the F-16 SPO and explains the SPO's management of MSIP over the past 10 years. As MSIP proceeded, the SPO reorganized to reflect the growing maturity of the F-16C/D; Section 3 discusses these changes as well. Section 4 explains in greater detail the F-16 development program during the 1980s, when MSIP was active. It emphasizes that MSIP operated in a broader setting and that it exemplifies the type of development activities occurring elsewhere in the SPO. Then Section 5 describes MSIP itself in greater detail, explaining the major technological changes it has effected, the management strategy it has used to effect those changes, and the contracts used by the F-16 SPO and General Dynamics to govern their relationship during MSIP. These sections provide what is essentially a top-down discussion of MSIP, treating it as a unified process that is greater than the sum of its parts.

The Appendix adopts a view from the bottom by describing six subsystems introduced in MSIP II and III and using them to illustrate important aspects of MSIP and its management of risk. Table 1.2 summarizes pertinent information about these subsystems. Each subsystem has a distinctive, and sometimes turbulent, development history separate from MSIP.[6] Each system was prominent in the concerns of the managers responsible for MSIP. As Table 1.2 shows, the subsystems also span a range of factors relevant to MSIP: the major functional capabilities represented in MSIP—cockpit, avionics, munitions, and other major components—and three blocks of MSIP Stages II and III, changes in two components across blocks help illustrate the degree of flexibility in MSIP. The F-16 SPO oversaw the development of some but not most of the changes. All but one are important

Table 1.2

Selected Subsystems Studied in Greater Detail

Subsystem	Type of System	Block Introduced	Developing SPO	Government or Contractor Furnished
APG-68 fire-control radar	Avionics	25, 40[a]	F-16	Government
AMRAAM and launcher	Munition	30	AMRAAM, F-16[b]	Government
LANTIRN pods	External avionics	40	LANTIRN	Government
Head-up display (HUD)	Cockpit display	30, 40[c]	F-16	Contractor[d]
Global Positioning System (GPS)	Avionics	40	GPS	Government
Alternate Fighter Engine (AFE)	Propulsion	30	Propulsion, F-16[e]	Government

[a]Improved version (V) of APG-68 introduced at Block 40.
[b]F-16 SPO oversaw redesign of launcher.
[c]C/D HUD introduced at Block 30, LANTIRN HUD at Block 40.
[d]Changed to contractor furnished during MSIP to facilitate integration.
[e]F-16 SPO oversaw development of common or configured engine bay.

[6]For more detail on the AMRAAM, LANTIRN, GPS, and engine programs, see this Note's companion case studies.

enough to be government furnished. The exception was changed from government- to contractor-provided equipment to promote the integration task of MSIP. In sum, we cannot say that these examples tell all of the stories important to risk management in MSIP, but they provide useful illustrations that relate to many of the MSIP-affected factors.

Section 6 closes the Note with general policy conclusions and suggestions for future work.

2. RISK ASSESSMENT AND RISK MANAGEMENT[1]

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 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 true 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 give up some aspect of unpredictability. It is difficult—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 the view by development managers of 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

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

[2]After 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.

[3]Many 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.

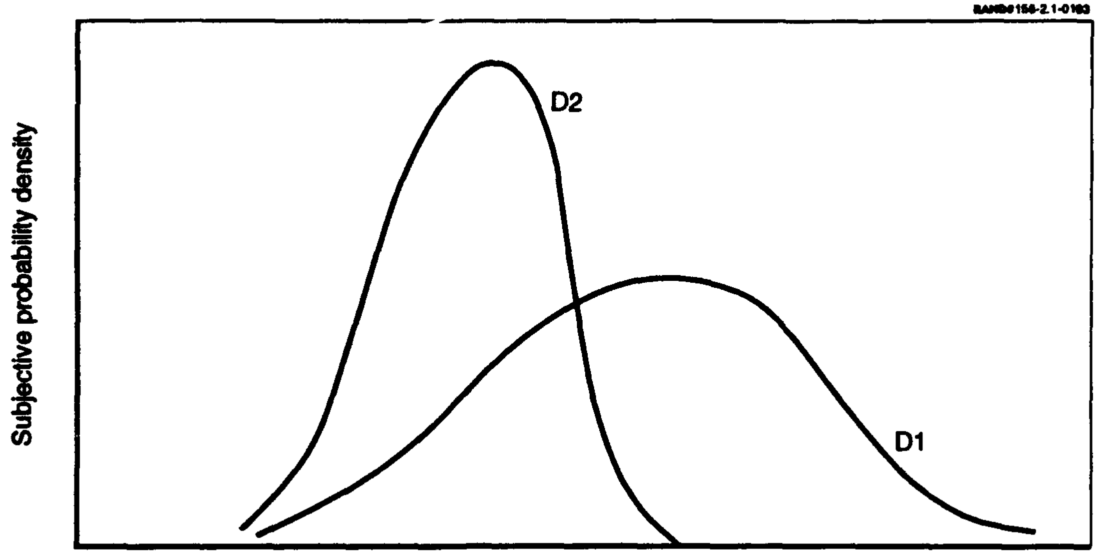

Figure 2.1—Subjective Probability Density Distributions D1 and D2 for Two Programs

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 expected outcomes of two different approaches to developing a weapon system. The metric of performance might be the probability that a fighter aircraft prevails in a standardized air-to-air engagement with the enemy. 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 probability of success S for the aircraft 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 re-creates 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 aircraft designed by each process failed to meet the set standard.

[4]That 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.

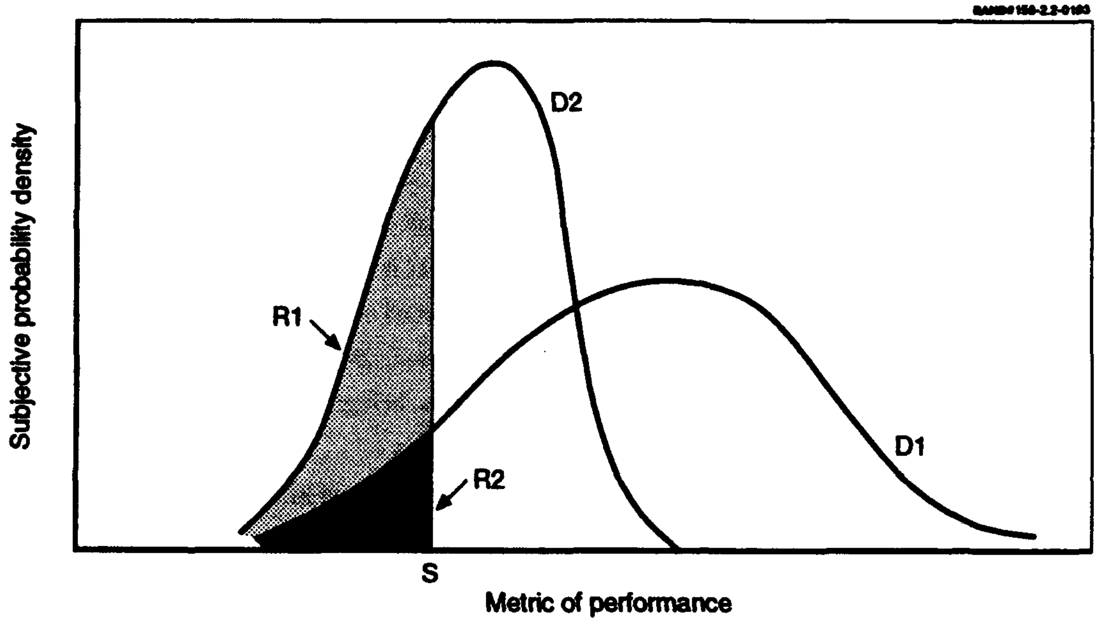

Figure 2.2—Risks R1 and R2 Associated with Two Weapon System Development Programs and Occurring Below the Set Standard for Performance S

Development managers would find this view of their decision environment grossly oversimplified. For example, such managers do not generally attempt to estimate, even 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 decisionmaking 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 a variety of sources. They affect a development program in many 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, he or she can reduce their effects, generally 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." Such logistics-oriented factors as reliability, availability, maintainability, and operating and support costs are increasingly considered important parts of system performance. Traditional measures of system performance emphasize combat capability and can normally be measured in a variety of ways specific to each system. 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 exist on those processes. Hence, it is most likely to support design of selected parts of the

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[5]Such 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.

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 hurt. 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 approach 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 established custom. In all cases, more than one perspective on the risks associated with a

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

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 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 those functions. In fact, the primary value of a good staff may well lie not in planning *for* the future but in its ability to react confidently and creatively when things go wrong.

The importance of good people is a point that development managers emphasize repeatedly. 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 so is, the better is the response and the less managers must rely on the blunter rules that an acquisition plan or contract might use to manage surprise. A well-organized, competent staff offers an additional benefit in the face of uncertainty. Because surprises 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 extensive 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 view risk this way 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 to understand better how managers have assessed and managed risk in the F-16 MSIP.

3. THE F-16 SYSTEM PROGRAM OFFICE AND ITS MANAGEMENT

By the time MSIP began, the F-16 SPO was a large, well-organized activity. The F-16 program began in 1971. As the SPO and General Dynamics began to plan MSIP in 1979, they were completing full-scale development of the F-16A/B, freeing management resources for further development work. The management techniques and experience developed during the 1970s provided a good basis for a continuing development program. This section describes the SPO that managed MSIP during the 1980s. It briefly reviews the changes in that organization over time and how that change related to MSIP itself. It also examines the continuity of leadership most relevant to MSIP.

INITIAL ORGANIZATION

Table 3.1 shows the basic organization for the SPO when planning began for MSIP. The SPO used a matrix organization with three project offices for production—for the U.S.

Table 3.1

Organization of the F-16 SPO During MSIP

Office Symbol	Organization in 1979: Directorate Name	Organization in 1979: Assigned Personnel	Organization in 1988: Directorate Name	Organization in 1988: Assigned Personnel
YP	Deputy for F-16	35	Deputy for F-16	9
		Project Directorates		
YPD	Deployment and test	28	Development and integration	28
YPF			Test and deployment	22
YPR	Projects	23		
YPX	Multinational programs	21	Multinational programs	36
		Functional Directorates		
YPA	Acquisition logistics	46		
YPC	Configuration management	35	Configuration management	28
YPE	Engineering	65	Engineering	102
YPK	Procurement	41	Contracting	55
YPL	Logistics planning	51	Logistics	50
YPM	Manufacturing	27	Manufacturing/QA	18
YPO	Management operations	19	Management operations	13
YPP	Program control	55	Program control	40
YPS			System safety	2

SOURCE: U.S. Air Force, Aeronautical Systems Division, F-16 Directorate of Management Operations, "Semiannual Historical Report," Wright-Patterson Air Force Base, Ohio, January–June 1979 and July–December 1988.

Air Force (YPD), for foreign sales (YPX), and for new development programs (YPR)—and functional offices typically found in a SPO. It was commanded by a major general. The SPO was assigned 170 people and had an additional 281 collocated, for a total of 451. Of these, 178 were officers, 22 were airmen, and 251 were civilians.

Primary planning for the MSIP occurred in the directorate for projects, YPR, which had responsibility for integrating new subsystems with the F-16 as they became available. Before MSIP existed, this directorate planned integration subsystem by subsystem. For example, individual efforts were under way on the APG-68, AMRAAM, LANTIRN, head-up display, GPS, and many other subsystems that would subsequently be associated with MSIP. With the advent of MSIP, this directorate continued to manage subsystem integrations individually, but MSIP allowed the directorate to do so within a broader framework. As MSIP became active, YPR managed it as a separable entity, with its own goals and milestones. By 1981, this management task manifested itself organizationally in a growth-management group (YPR-1) within YPR that was responsible only for MSIP.

During the formative stages of MSIP, the directorate for projects was run by a lieutenant colonel and dominated by military personnel—18 officers to six civilians, four of whom were secretaries.

Offices on the functional side of the matrix supported the directorate for projects. Those offices were typically directed by officers but dominated by civilians. The directorate for engineering played a special role for the subsystems that became associated with MSIP: Directed by a civilian, it provided the in-house technical expertise required to oversee the integration and production incorporation of those subsystems.

ORGANIZATIONAL CHANGES DURING THE 1980s

During the 1980s, the SPO underwent a number of changes. Table 3.2 provides a quick overview of this period, showing number of personnel assigned to the SPO as a whole and to three directorates associated with MSIP. MSIP accounted for a significantly higher proportion of those directorates' management interest during the 1980s than in other directorates.[1] The table shows that total staffing declined gradually until 1981, when it stabilized and began a gradual rise. The increase continued into the mid-1980s. Budget cuts beginning in 1987 required significant cuts that, as we shall see, affected SPO management of MSIP activities.

[1]This judgment is based on a review of directorate historical reports from the period.

Table 3.2

Assigned Personnel in the F-16 SPO

Six-Month Date	Total	YPD	YPE	YPR
		Directorate Symbol		
July 1979	451	28	65	23[a]
January 1980	442	28	71	22[a]
June 1980	434	26	69	19[a]
January 1981		— missing —		
June 1981	399	27	74	19[a]
December 1981	401	31	72	20[a]
June 1982	425	37	75	21[a]
December 1982	437	36	78	25[a]
June 1983	419	34[a]	80	17[a]
December 1983	445	41[a]	86	21[a]
June 1984		— missing —		
December 1984	465	33[a]	111	21[a]
June 1985	473	38[a]	106	20[a]
December 1985	480	37[a]	111	23[a]
June 1986	472	40[a]	112	20[a]
December 1986	478	41[a]	111	23[a]
June 1987	440	36[a]	109	0
December 1987	414	33[a]	102	0
June 1988	417	31[a]	104	0
December 1988	404	28[a]	102	0

SOURCE: U.S. Air Force, Aeronautical Systems Division, F-16 SPO Directorate of Management Operations, "Semiannual Historical Report," Wright-Patterson Air Force Base, various dates.

[a]MSIP activities occurred primarily in these project offices.

During this period, the first major MSIP-related organizational change occurred, in 1983. The SPO reorganized to transfer responsibility for MSIP from the directorate for projects to a new directorate built around the old directorate of deployment and test:

> As the [MSIP] program moved out of the realm of a future program and more into the area of a production aircraft, the decision was made to move the program into a division more adept at handling integration, testing, and deployment.[2]

This new directorate, which would become known as the directorate of integration and test, effectively became the project office for the F-16C/D. A new directorate of field operations (YPF) took on responsibility for the F-16A/B.

The old directorate of projects, now the directorate of development plans, retained responsibility for selected subsystems relevant to MSIP, including the Alternate Fighter Engine and GPS. It continued to oversee new technologies that might be integrated into the

[2]U.S. Air Force, Aeronautical Systems Division, F-16 SPO Directorate for Development Plans, "Semiannual Historical Report, 1 January–30 June 1983," Wright-Patterson Air Force Base, Ohio.

F-16 through MSIP in future configurations. And it continued to oversee the development of variations on the F-16 other than the F-16C/D. Meanwhile, the directorate of integration and test took over responsibility for the subsystems formally configured as part of forthcoming blocks of the F-16C/D, including the APG-68, AMRAAM, LANTIRN, HUD, and many other subsystems. About half of the staff from the old directorate of projects moved to the new directorate of integration and test during this reorganization, ensuring a fair degree of continuity despite the change. Nonetheless, the change meant that subsystems relevant to MSIP would be managed by two separate project offices within the F-16 SPO for the next several years.

The directorate of integration and test continued to be led by the original director, a colonel. Officers exceeded civilians, 22 to 11. A lieutenant colonel continued to lead the directorate of development plans, where officers continued to exceed civilians, 14 to three.

The second major MSIP-related change occurred in 1987, when the directorates of integration and test (YPD) and development plans (YPR) merged to become the directorate of development and integration (YPD). Unlike the first change, this change resulted from a budget cut that forced the F-16 to reduce its staffing and consolidate activities. But like the first change, this one maintained continuity by transferring personnel with their associated tasks from one office to another. The old YPR simply disappeared. Test activities in the directorate of integration and test migrated to the directorate of field operations, leaving the new YPD essentially as a program management directorate, overseeing the F-16C/D program, integration of government-furnished subsystems associated with MSIP, and development of new derivative engines. MSIP-related staffing in the project offices decreased proportionately more than staffing in the SPO as a whole, requiring the managers responsible for MSIP activities to relinquish significant responsibilities to the functional directorates on the other side of the matrix. Since 1987, all MSIP-related activities have been managed through the YPD office, with the continuing support of the functional directorates.

Table 3.1 displays the structure of the SPO at an important milestone near the end of the 1980s: General Dynamics' delivery of the first MSIP III, Block 40 F-16C, in December 1988. When that occurred, the F-16 SPO had 404 personnel assigned, including 132 officers and 258 civilians. Despite the predominance of civilians, officers ran all but two directorates. One of the two was the directorate of engineering, where civilians exceeded officers, 79 to 23. Officers continued to predominate the project directorate responsible for MSIP, the directorate of development and integration, 21 to seven. The SPO continued to be commanded by a major general.

CONTINUITY OF PERSONNEL

Short tours of duty tend to hamper continuity over the course of a long development program. The predominance of military personnel in leadership positions and in the project directorates with greatest responsibility for MSIP raises questions about continuity in the SPO. Table 3.3 summarizes information on the principal managers relevant to MSIP.

Although the table is not complete, the data available tell a fairly clear story. Recall from Table 3.2 that YPD did not actually become relevant to MSIP until 1983 and that YPR disappeared after 1986. The SPC commanders appear to have served standard three-year tours. Their deputies were also military, limiting the institutional memory developed at the top of the organization. Perhaps the most important source of continuity at the top of the organization has been Mr. John Brailey, the technical director for the SPO since 1983 and the director of engineering for a short time before that.

Military managers have also run YPD and YPR, where, for the most part, they appear to have served two- to three-year tours. Their deputies and most of their professional staffs have also been military, suggesting that any institutional memory about activities in these

Table 3.3

Managers Relevant to MSIP

Year	Commanders F-16 SPO	Directors YPD	Directors YPE	Directors YPR
1979	Abrahamson	Belinne	Bair	Packin
1980	Abrahamson/ Monahan	Wolff	Bair	?
1981	Monahan	Wolff	Madden?	?
1982	Monahan	Wolff/Sabo	Brailey	Boyd/ Westover
1983	Monahan/Yates	Sabo	Brailey/Culp?	Westover
1984	Yates	Sabo	LeMaster	Westover/Tucker
1985	Yates	Sabo/Hayashi	LeMaster	Tucker/Cathey
1986	Yates/Eaglet	Hayashi	LeMaster	Cathey
1987	Eaglet	Hayashi/Hogstrom	LeMaster	
1988	Eaglet	Hogstrom	LeMaster/ Smithers	

SOURCES: U.S. Air Force, Aeronautical Systems Division, assorted F-16 organization charts, Wright-Patterson Air Force Base, Ohio, and SAFPAR briefings from the period shown.

areas would lie in the functional directorates that supported those activities. The directorate of engineering, YPE, might be a logical place to turn for such knowledge about the technical aspects of the development.

This final directorate, YPE, has usually been run by a civilian with a military deputy and has used a predominantly civilian staff. The directorate of engineering achieved considerable stability in management from 1984 on. For several years before 1984, during the formative years of MSIP, leadership of this directorate experienced much more rapid turnover.

As a working hypothesis, we might postulate that institutional memory in the SPO is limited. The SPO's leadership has stabilized in recent years, but we would have to seek stability in the early years of MSIP farther down in the civilian parts of the organization, presumably on the functional side of the matrix.

SUMMARY

MSIP is only one activity among many in the mature F-16 SPO. In the face of dramatic changes in MSIP, the SPO as a whole has fluctuated in size only about 20 percent, sometimes in response to MSIP-related changes, more often in response to totally unrelated factors. The SPO was already well organized and experienced as an organization by the time MSIP began in 1979. The predominance of the military in the SPO's leadership and in its project offices probably hampered accumulation of knowledge about the system at a high level. But the SPO appears to have accommodated MSIP comfortably as a new activity as MSIP matured.

MSIP began as a development concept in the part of the SPO devoted to such work, the directorate of projects. As MSIP matured and approached the point of being embodied in a major new F-16 variation, the F-16C/D aircraft, the SPO reorganized to accommodate that change. In 1983, a new project directorate was effectively set up to house the new F-16C/D. As portions of MSIP matured enough to be incorporated in production, they came to be managed in the new directorate. MSIP-related subsystems at a more developmental stage remained in the directorate of developmental plans. This approach presents MSIP more as a concept or plan than as a formal program; it allowed the SPO to handle individual activities associated with MSIP much as it would have handled other, similar activities unrelated to MSIP.

Large budget cuts in 1987 forced an end to this approach. To accommodate reductions in staffing, the SPO reorganized again and placed all MSIP-related work in one directorate, where it remains today. The SPO also significantly increased its reliance on its civilian-dominated functional directorates as a result of the change.

In sum, MSIP is one activity among many in the F-16 SPO. It has been important enough to change the SPO as a whole. But it was conceived in and continues to operate in the broader context of the F-16 program as a whole.

4. F-16 DEVELOPMENT PROGRAMS DURING THE 1980s

Even after the close of the initial full-scale-development program for the F-16 in 1979, the F-16 SPO maintained an active research-and-development program. Table 4.1 presents the program's spending on activities related directly to research and development. Although the bulk of real spending occurred during the 1970s, a substantial effort has continued to the present.

MSIP accounts for part of that effort. But MSIP is only one of a family of related programs to upgrade new production F-16s, retrofit new capabilities into existing F-16s, and develop new variations based on the F-16. These programs use research-and-development funds, but they rely primarily on production funds to pay for the nonrecurring costs associated with production. Hence, the figures in Table 4.1 offer only a lower bound on development spending, because all these programs share the common characteristic that

Table 4.1

RDT&E Expenditures in the F-16 Program

Fiscal	*Expenditures ($ millions)*	
Year	Then-Year Dollars	1980 Dollars
1975	32.0	48.0
1976	214.7	290.2
1977	69.0	88.5
1977T	256.4	322.0
1978	162.3	192.5
1979	93.6	102.4
1980	27.6	27.6
1981	43.1	38.5
1982	57.9	47.4
1983	70.9	55.3
1984	93.1	70.0
1985	90.6	65.8
1986	61.1	43.2
1987	52.0	35.8
1988	21.7	14.5
1989	24.4	15.6
1990	18.0	11.1

SOURCE: Then-year dollar expenditures are reported in the U.S. Air Force, Aeronautical Systems Division, F-16 SPO, *F-16 Selected Acquisition Report*, Wright-Patterson Air Force Base, Ohio, 31 December 1990. Dollar expenditures for 1980 are based on then-year dollar expenditures and escalation rates reported in the same document.

T = Transition quarter (July–September 1977).

they upgrade the F-16 primarily by adding new capabilities essentially off the shelf from development programs conducted elsewhere. MSIP development work concerns itself primarily with integrating the new systems with a baseline version of the F-16 and ensuring that all systems integrated at the same time are compatible with one another. Seeing MSIP in the context of a family of similar programs reminds us that the development approach provided by MSIP is as much a way of life in the F-16 SPO as it is a formal program aimed only at bringing the F-16C/D on-line.

This section briefly reviews a series of programs from the 1980s that created new aircraft derived from the F-16, upgraded the F-16A/B, and sought to provide an aircraft design that could meet the Army's needs for a new close-air-support aircraft. Table 4.2 capsulizes relevant program activities.[1]

Table 4.2

F-16 Development Programs During the 1980s

Name	Date Begun	Brief Summary
	New Variations on the F-16 Aircraft	
Agile Falcon	1988	Would have enlarged the wing and improved aerodynamics, avionics, and other internal systems. Canceled by the secretary of defense.
RF-16 Reconnaissance Aircraft	1986	Would add a sensor pod and software to support reconnaissance functions.
F-16N Navy Adversary Training Aircraft	1987	Emulates Soviet fighter characteristics; Navy bought 26 and considered more.
FSX Joint Development Program with Japan	1987	F-16 provides the baseline for major Japanese improvements in airframe, avionics, weaponry, and radar cross section.
	Operational Upgrades for the F-16A/B	
First Operational Upgrade	1987	Added selected F-16C/D capabilities to Blocks 10 and 15 F-16A/Bs sold to EPG air forces.
F-16ADF Air Defense Fighter	1986	Modified 270 F-16As for use in the Air National Guard.
Mid-Life Upgrade	1989	Would upgrade existing U.S. and EPG F-16A/Bs to have capabilities similar to F-16C/Ds.

[1]The discussions below are based on interviews as well as General Dynamics, 1990; Richardson, 1990; and Wolf, January 1986–December 1989. Our description also relies on official Air Force histories of various Aeronautical Systems Division development programs written by C. J. Geiger during October 1982–December 1985. Because that discussion is from an unclassified history in a classified Air Force document, we cannot provide an explicit citation in this document.

NEW VARIATIONS ON F-16 AIRCRAFT

Agile Falcon, Successor to the F-16C/D

The new variation most closely related to MSIP was Agile Falcon, which General Dynamics marketed as MSIP IV, a designation that could be viewed as an attempt to minimize the degree of change in moving from the F-16C/D to a new aircraft designed to replace it. It is also an indication of the extent to which MSIP has become a way of doing business in the F-16 SPO. The management techniques used in the original three stages of MSIP that yielded the F-16C/D naturally carried over into the design of a successor aircraft.

Agile Falcon was the product of a three-year design effort at General Dynamics. It provided the basis for a response to a 1987 request from the secretary of defense to develop an upgraded version of the F-16 that could replace the F-16C/D and complement the advanced tactical fighter that would replace the F-15. The new design offered a larger wing and aerodynamic improvements in addition to the changes in avionics and other systems internal to the airframe that characterized the first three stages of MSIP.

In 1988, the deputy secretary of defense approved a two-year pre-development program, with full-scale development to begin in FY 90, pending approval by the Defense Acquisition Board, and production deliveries to the Air Force to begin around 1995. With the deputy secretary's support, the F-16 SPO reached an agreement with the advanced tactical fighter SPO to transfer engine and avionics technology from the new fighter for use in the design of Agile Falcon. Institutional arrangements were also established with the European Participating Governments to facilitate their participation in the multinational F-16 program. The new secretary of defense canceled the program in 1989.

RF-16 Reconnaissance Aircraft

This variation adds a sensor pod with multiple capabilities to a standard F-16C/D in much the same way that MSIP added individual subsystems. As a point of reference, the Dutch have been using a modified F-16A since the early 1980s as a platform for a variety of European sensor pods.

The RF-16 variation retains all the air-to-air and air-to-ground combat capabilities of a standard F-16C/D. Like LANTIRN, the sensor pod has a modular design optimized for F-16 aerodynamics, maintainability, and fit. Even with the pod in place, the aircraft retains its full flight envelope. The variation affects primarily pod integration and control and an expansion of F-16 software to support reconnaissance functions. The pod is integrated with the F-16 HUD and other displays and with cockpit controls that allow man-in-the-loop sensor control to improve target acquisition and enable in-flight changes in sensor missions. The system supports real-time viewing in the cockpit and near-real-time viewing on the ground.

General Dynamics developed the pod, simplifying the integration process. Concept validation occurred in 1986. Flight simulations were used to verify the cockpit arrangements. The U.S. Air Force selected the RF-16 as a successor for the RF-4C in 1989. The aircraft entered the DoD approval cycle in 1990, with full-scale development expected to begin in FY 92. MSIP has not required formal OSD approval. But the general approach to conceiving and developing the RF-16 is similar to activities for a block change in MSIP.

F-16N Navy Adversary Training Aircraft

General Dynamics developed and produced this aircraft for the Navy, using an approach similar to that for developing Air Force variations on the F-16. The Navy sought an aircraft that could emulate fourth-generation Soviet fighter performance, system capabilities, and tactics. It modified a Block 30 F-16C/D to provide those characteristics. For the most part, it simply selected from the same set of subsystems for developing Air Force variations. The Navy bought 22 single-seat and four two-seat versions in 1987–88 and has considered additional purchases of the same design. This development illustrates the feasibility of using an MSIP-like approach for a very small block size.

FSX Joint Development Program with Japan

The F-16 airframe provides the starting point for a new Japanese-U.S. fighter that will replace the Japan Air Self-Defense Force F-1, developed by Mitsubishi Heavy Industries. The design and development processes for this derivative differ substantially from those for MSIP. Although both programs are multinational, the Japanese will clearly dominate the FSX development, just as the U.S. dominates the F-16 MSIP. Mitsubishi Heavy Industries will be the prime contractor; General Dynamics will serve as a subcontractor, along with many other U.S. and Japanese firms. The U.S. Air Force SPO's role will be commensurately limited. And the FSX will look quite different from the F-16 on which it is based: Only 20–30 percent of the original airframe will remain unchanged, and the design will incorporate Japanese radar-absorbing materials to reduce the radar cross-section, primarily Japanese avionics, and Japanese weaponry.

The Japanese selected the F-16 as the basis for its FSX in 1987 and completed a memorandum of understanding to that effect a year later. The agreement stirred great political controversy. The U.S. government finally agreed to the arrangement in 1989, allowing a joint design team to begin work in 1990. First flight of a prototype is expected in 1993, with production to occur around the turn of the century.

In sum, MSIP does not offer the only model available for developing F-16 derivatives. This high-visibility alternative, effectively controlled by a foreign government and prime contractor, and relying primarily on subsystems not traditionally associated with the F-16 program, represents a very different model of multinational development.

THE OPERATIONAL CAPABILITY UPGRADE PROGRAM FOR THE F-16A/B

From the beginning, MSIP was conceived as a program that would be implemented in part by retrofitting capabilities into existing aircraft as new capabilities became available. Although such retrofits were carefully planned into the designs of new F-16C/Ds, many could also prove useful in the F-16A/B. In fact, as the U.S. Air Force moved toward the F-16C/D model, foreign sales of the F-16A/B were threatened by a concern that the U.S. would lose interest in and provide less support for the less-capable F-16A/B model. One way to avert such concerns was to upgrade F-16A/Bs using capabilities brought to the F-16 program through MSIP. The F-16 program developed the Operational Capability Upgrade (OCU) program to do just that. Like MSIP, it proceeded under limited oversight from DoD.

MSIP provided two important resources for the OCU: a database of available capabilities that could be considered for incorporation in various versions of the F-16A/B, and management techniques and capabilities in the F-16 SPO and General Dynamics that facilitated such upgrades.

Upgrades provided through the OCU program produced three separate versions of the F-16A/B.

First Operational Capability Upgrade

In 1987, the first OCU changes affected existing Block 10 and Block 15 F-16A/Bs and new Block 15 F-16A/Bs sold to the European Participating Governments. Much like those in a block change of MSIP, the changes include expansion of computer capacity; provisions for beyond-visual-range missiles; and additions of a radar altimeter, the wide-angle HUD used in the F-16C/D, and the new F100-PW-220 Alternate Fighter Engine. MSIP had previously integrated each of these modifications into F-16 variants, simplifying the task of implementing them on F-16A/B aircraft.

The F-16ADF Air Defense Fighter

The F-16ADF, or F-16A (ADF), was a response to a 1986 U.S. Air Force proposal to develop a new aircraft to replace F-4s and F-106s as air defense interceptors in the Air National Guard. The Air Force favored an aircraft designed as a modification of an existing fighter, but considered a range of alternatives. The Aeronautical Systems Division (ASD), in coordination with the Tactical Air Command and Headquarters, U.S. Air Force, developed acquisition and source-selection plans that ultimately yielded a decision later in the year in favor of modifying the F-16A. The primary competitor was the Northrop F-20. After the award of a contract to modify 270 F-16As already in the inventory, ASD transferred control of the program to the F-16 SPO. Production deliveries of modified aircraft were scheduled for 1989–91.

This derivative development program began very differently than the first OCU program (or MSIP) by using a competition to discipline the designers. General Dynamics was able to respond quickly to the Air Force's expressed interest because the OCU program was in place. The F-16ADF simply offered an additional application of the system that yielded the first OCU changes described above. Hence, General Dynamics was already familiar with the subsystem integrations that it proposed for transforming an F-16A into an F-16ADF. For example, the F-16ADF upgrade would modify the APG-66 fire-control radar to accept AMRAAM data. It improved the F-16A's electronic counter-countermeasures, high-frequency radio, identification, friend-or-foe (IFF) system, and flight data recorder, and added Group A provisions for GPS. MSIP had included each of these improvements in earlier F-16 variants.

Mid-Life Update Program for the F-16A/B

This program is essentially to retrofit existing F-16A/B aircraft in the U.S. and the European Participating Governments so that their avionics are very close to those in an F-16C/D. To allow transfer of certain technologies, this program has required a change in the security agreements in place for the governments involved. The F-16 SPO advanced this multinational program in conjunction with the Agile Falcon. Unlike Agile Falcon, this program continues to survive.

This program's connection to MSIP is quite direct. It makes a series of changes already engineered for the F-16C/D under MSIP, many of which are at a similar stage of development in the MSIP effort to incorporate them in later parts of F-16C/D Block 50. The mid-life update also improves the reliability and operability of the APG-66 fire-control computer in the same way that MSIP improved the APG-68 radar for the F-16C/D. And the update integrates these changes with one another as they were integrated for the F-16C/D under MSIP.

Predevelopment continued through 1989. Full-scale development, which is scheduled to occur during 1991–95, will cover initial fabrication and assembly of test retrofit kits, flight test of those kits, and Lead-the-Fleet operational testing at a number of installations.

Delivery of production kits is expected in 1996. Until this program is executed, we cannot know how similar it is to MSIP; current plans suggest strong parallels.

PROPOSALS FOR A CLOSE-AIR-SUPPORT AIRCRAFT

General Dynamics and the Air Force have studied a close-air-support (CAS) role for the F-16. They have developed a number of CAS concepts that take advantage of the F-16's ability to fly close to the earth at night and designate targets with a laser, capabilities that could be improved by advances in digital terrain data, terrain-following and -avoidance systems, night vision, and target-definition systems. General Dynamics has used its own funds to develop and validate these advances. Since 1987, the Air Force has tested and demonstrated several of them on its Advanced Fighter Technology Integration (AFTI) F-16 testbed.

Proposals differ. In 1988, the Air Force developed plans to buy 150 Block 50 F-16C/Ds a year modified to serve the CAS role. In 1989, the NATO commander and the Air Force and Army Chiefs of Staff all expressed support for a CAS-oriented F-16 as a near-term solution to NATO's perceived need for CAS aircraft. That version would have added several subsystems to new Block 40 F-16C/Ds, including an improved fire control radar, GPS, an improved gunsight, and the potential for carrying HARM missiles. A variation, considered in 1989, would have upgraded 146 Block 30 F-16s to the CAS role by adding digital terrain-following, ground-collision avoidance, an automatic target hand-off system (ATHS), a 30mm gun pod, a PAVE PENNY laser tracking pod, and armor. In 1990, the Air Force proposed the A-16, a variation on the F-16C/D, to the Defense Acquisition Board. The A-16 would look similar to a Block 50 F-16C/D developed under MSIP, and it could potentially be managed as one more block in the current program, effectively bringing it into the same management system as MSIP. If approved, it would presumably continue as part of MSIP, without further OSD oversight.

All these proposals share a common feature: use of an MSIP configuration as a baseline, with a discrete set of changes to achieve a CAS capability. In that sense, all of them look like a new block in MSIP. Any one of them could be managed in a similar way. This pattern of proposal is testimony to the power of MSIP in the development program for the F-16.

SUMMARY

The F-16 development program remained active after the close of its initial full-scale development. MSIP was the dominant development effort, but other programs played important roles and took advantage of subsystems tested and integrated in MSIP and of management techniques developed in MSIP. As a result, all such efforts share common elements.

Placing MSIP in the context of these other efforts helps us understand that the MSIP approach had much broader implications for the F-16 program. All these programs essentially add subsystems developed in other programs to a baseline F-16 configuration. The programs integrate each subsystem with the baseline configuration and with all other subsystems being added, as follows: They simulate the performance of new subsystems in the F-16 environment, fabricate and assemble test subsystems, flight test them, conduct operational tests, and, finally, incorporate the subsystems into the production of a new F-16 variation. The upgrade approach can be applied to new aircraft or, through retrofit, to existing aircraft.

These activities emphasize the usefulness and feasibility of modular design for subsystems and, at the same time, the effort required to adapt modular systems to a new configuration. Although such efforts are clearly development, test, and evaluation activities, they are often funded with production funds as nonrecurring costs. Therefore, the ongoing development effort in the F-16 program has been much larger than a simple review of research-and-development funds would suggest.

5. DETAILS ON THE F-16 MSIP

The preceding sections explain that, although MSIP was a distinct program, it was only part of the F-16 program's continuing development efforts. The F-16 SPO used its normal structure to manage MSIP as part of those broader efforts. The summary of milestones in Table 5.1 places MSIP in the broader context of the F-16 program.

With this perspective, we can now look more closely at the management goals of the F-16 MSIP and program organization by the F-16 SPO and General Dynamics to achieve those goals.

In particular, we want to answer the following questions: What specific technological changes did MSIP effect in the F-16? What risks did those changes present? How did the F-16 SPO and General Dynamics manage the process that realized those changes? What was their basic management strategy and how did it relate to the risks expected in MSIP? What kinds of contracts did the F-16 SPO and General Dynamics write to coordinate their

Table 5.1

Key Events Relevant to the F-16 MSIP

Year	Key Events in MSIP	Key MSIP-Related Events
1979	MSIP planning begins	F-16A/B FSD complete
1980	MSIP Stage I begins	F-16A/B achieves IOC
1981	MSIP Stage II begins First MSIP I aircraft delivered	500th F-16 delivery
1982		F-16 Multiyear I awarded Falcon Century begins
1983		1000th F-16 delivery
1984	First F-16C (MSIP II) aircraft delivered	
1985	MSIP Stage III begins	1500th F-16 delivery
1986		F-16 Multiyear II signed F-16 selected for ADF
1987		First F-16N delivered. Operational Capability Upgrade begins
1988		
	First MSIP III (Block 40) aircraft delivered	First F-16ADF delivered
1989		F-16 Multiyear III signed
1990		Joint FSX design team begins
1991		F-16A/B Mid-Life Update FSD begins
	First MSIP Block 50 aircraft delivered	
1992		RF-16 FSD begins

PRIMARY SOURCE: U.S. Air Force, Aeronautical Systems Division, F-16 SPO, "Management Information Notebook, FY86–2," Wright-Patterson Air Force Base, 1986, p. G-3.

activities? How did those contracts address the risks that MSIP presented? How did the contracts change as MSIP matured?[1] This section addresses each of these questions in turn.

THE TECHNOLOGICAL CONTENT OF CHANGES EFFECTED THROUGH MSIP

As explained in Section 1, MSIP has proceeded in three stages, in a series of aircraft blocks associated with these stages. The program is set up to allow flexible improvement of the F-16 as enhanced subsystems become available. This subsection briefly describes the improvements incorporated in Blocks 15 to 40 to date and improvements anticipated in the early years of Block 50. It also describes briefly the level of risk that MSIP managers have associated with each set of improvements.

Stage I

MSIP began formally in February 1980, when detailed work on Stage I was authorized to begin. Because that work required little new design or development effort, it was envisioned that the changes implemented during Stage I would be incorporated in F-16A/B aircraft Nos. 330 through 785 in Block 15, to be produced starting November 1981. New U.S. Air Force aircraft were affected first; changes in aircraft destined for the European Participating Governments began in May 1982.

Despite such short lead times between the beginning of the program and production delivery, it took time following the initiation of the program for the Air Force and General Dynamics to agree on the set of changes to be included. A highly interactive process rapidly increased the number of changes to be included over the period. In the end, those changes included essential structure, wiring, and interface provisions to support future aircraft avionics changes and a number of growth systems. Figure 5.1 summarizes the changes included.

These changes added no immediate combat capability to the F-16. They were essentially designed to reduce the cost of retrofitting future systems that would add such capability. Because little design work was required, developers viewed this stage as presenting little technical risk; rather, the main risk associated with this stage was whether provisions made for future systems were the right ones. If future needs differed from those anticipated during Stage I, rework would be required to retrofit future systems. Any

[1]This section draws heavily on the U.S. Air Force, Aeronautical Systems Division, F-16 System Program Office, 1987 [hereinafter, F-16 *Program Management Plan*]; General Dynamics, 1990; and Jane's Information Group Limited, various dates. Risk assessments in particular draw heavily on the discussion of individual MSIP blocks in the F-16 *Program Management Plan*.

- Wing structure and partial wiring provisions for beyond-visual-range air-to-air missiles
- Engine inlet structure and wiring provisions for various electro-optical and target-acquisition pod systems
- Cockpit structure and wiring provisions for a wide-field-of-view raster HUD, multifunction display set, data transfer unit, and Up Front Communications/Navigation/Identification (CNI) system
- Wiring provisions for an expanded-capacity fire-control computer, advanced weapons central interface unit, and radar altimeter
- Early structure and wiring provisions for internal electronic countermeasures systems
- Increased-capacity environmental control and electric power systems

Figure 5.1—Modifications Included in Stage I

surprises associated with such a risk would obviously occur in future stages as the retrofits actually implemented as part of MSIP were finalized.

Stage II

Plans for the second stage of MSIP were presented to the F-16 Multinational Configuration Steering Group in October 1980. They were formally authorized in May 1981, with initial production deliveries of Block 25 aircraft expected in December 1984. The first Block 25 F-16C was delivered to the Air Force in July 1984, and a production version of the F-16C/D baseline aircraft was realized in December 1984. Production of increasingly capable Block 25 and 30/32 versions of Stage II aircraft continued into 1989. The changes included during this stage occurred at a series of discrete points over the course of the stage as "miniblocks" within Blocks 25 and 30 were delivered to the field. These pre-planned miniblocks allowed for continuing introduction of planned changes and for updates, particularly in software, that were found to be desirable as MSIP II proceeded.

This stage began to move beyond the existing technological base, advancing the F-16 program from the F-16A/B to the F-16C/D. The F-16 SPO and General Dynamics chose to structure MSIP as a coordinating environment in which many parallel development, integration, and production incorporation activities for individual subsystems would proceed. The subsections below on management strategy and contracts say more about this approach.

The second stage of MSIP provided additional aircraft avionics and subsystem improvements required to support future growth. In particular, it incorporated subsystems that would enable a single pilot to perform complex tasks associated with simultaneously flying the aircraft, choosing targets, and delivering weapons against them in a high-threat environment. Figure 5.2 shows the expanded systems that were included. These changes effectively began to fill spaces planned for in Stage I and to continue adding capability to add more. They substantially increased the amount of information available to the pilot and the ease with which that information was used in combat. By the end of Block 30, they also added new weapon capabilities.

- Wide-field-of-view raster head-up display
- Multifunction display set and software-programmable display generator to replace the then-current stores control panel, radar display, and radar symbol generator
- Data transfer unit that allowed the use of a cartridge to enter mission data before a flight
- Up-front CNI system
- Enhanced fire-control computer
- Advanced central interface unit
- Radar altimeter
- AN/APG-68 radar incorporating a programmable signal processor (PSP) and dual-mode transmitter (DMT) that increased the range and resolution of the radar, and the number of radar modes available; improved electronic counter-countermeasure capability; and increased flexibility in the use and addition of modes in the future
- Shrike antiradiation missiles
- Software changes that allow full level-IV multitarget compatibility with AMRAAM
- Configured engine bay and F100-PW-220 and F110-GE-100 Alternate Fighter Engines, either of which could fit in the bay
- Modular common inlet duct/large forward inlet module to increase airflow to, and therefore full available thrust from, the F110-GE-100 engine
- Structure and wiring provisions and later the hardware for a crash survivable flight data recorder
- Improved environmental-control-system turbine assembly, compatible with the Stage I environmental system, to provide added cooling air capacity

Figure 5.2—Modifications Included in Stage II

MSIP managers viewed the risk associated with this stage as low to moderate. Most of the changes were evolutionary; for example, the greatest management attention among these changes was received by the APG-68 radar, which "simply" added the programmable signal processor and dual-mode transmitter to the APG-66 radar already in service on F-16A/Bs. Similarly, the new head-up displays evolved from a head-up display already in service on F-16 A/Bs. The Alternate Fighter Engines were derived from engines already in service on the F-15, F-16A/B, and B-1B. In addition, the military standards used to plan MSIP were essentially those used to plan development of the F-16A/B or standards that had evolved from them.

MSIP's approach to managing Stages II and III introduced an additional risk during Stage II. For reasons discussed in the subsection "Management Strategy" below, MSIP managers placed a higher priority on meeting the schedules of Stage III than those of Stage II. As a result, those managers expected problems in Stage II resulting from its relatively low-priority access to manpower, simulation, and test assets. Although this management approach might have increased risk in Stage II of MSIP, it was not expected to adversely affect the level of risk in the program as a whole.

Stage III

Stage III continued to use the development-and-integration approach begun in Stage II, including the continual introduction of pre-planned changes and updates in miniblocks within Blocks 40/42 and 50/52, which currently constitute this third stage of MSIP. Other blocks have been considered; for example, Block 50 is a scaled-back version of an earlier Block 70. The budget cuts that led the F-16 SPO to reorganize in early 1987 also forced the F-16 program to restructure Block 70 into a less ambitious Block 50 in early 1987. Blocks 40/42 and 50/52 are the final products of a continuing process to define the structure of MSIP III. Authority to begin Block 40/42 was given in June 1985, with production deliveries of Block 40/42 aircraft expected to begin in December 1988. In fact, MSIP achieved this milestone on schedule. Block 40/42 production deliveries are scheduled to continue into 1992. Preliminary design go-ahead for Block 50/52 came in September 1986, with initial aircraft delivery anticipated in June 1991. Block 50 production deliveries are now expected in October 1991.

Stage III provides for installation and retrofit of specific growth systems to meet future mission needs. The systems included have changed repeatedly as information has accumulated on the technological maturity of the systems considered. Systems included in Block 40 were structured around the LANTIRN system, which would give the F-16C/D new terrain-following and -targeting capabilities at night. Figure 5.3 shows the systems introduced to date. Other systems will be added as the block matures; most of them will also appear in Block 50/52 aircraft. The important exceptions are the LANTIRN pods and HUD, which effectively define Block 40/42 as a special breed of F-16C/D.

Figure 5.4 lists modifications expected to be included in early versions of Block 50/52 aircraft. These additions illustrate how the development approach introduced in Stage II is

- LANTIRN navigation and targeting pods
- LANTIRN diffractive optics HUD
- APG-68V fire-control radar, an increased-reliability modification of the APG-68
- Aft-seat HUD monitor in the F-16D
- Four-channel digital flight-control system
- Enhanced-envelope gun sight
- Global Positioning System (GPS) receiver and antennas
- Structural strengthening
- Provisions for advanced electronic warfare and identification-friend-or-foe (IFF) equipment

Figure 5.3—Modifications Included in Stage III, Block 40/42

- Improved-performance engines, F110-PW-229 or F100-GE-129, derived from the current Alternate Fighter Engines
- Advanced programmable signal processor using VHSIC technology in an improved APG-68V5 fire-control radar
- HAVE QUICK IIA VHF radio
- ALR-56M advanced radar warning receiver
- Provisions for the automatic target hand-off system and HAVE SYNC VHF antijam radio and, later, installation of these systems
- Full integration of HARM/Shrike antiradiation missiles
- Upgraded programmable display generator with digital terrain system provisions and scope for digital map capability
- ALE-47 chaff dispenser

Figure 5.4—Modifications Included in Stage III, Block 50/52

continuing. As new capabilities become available, they are programmed for integration and production incorporation. Where they are likely to reduce the cost of retrofit without unduly increasing risks of incompatibility with future systems, structure and wiring provisions enter the aircraft in one miniblock in anticipation of full incorporation of the related hardware in a future miniblock. And where possible, subsystems already incorporated in the F-16C/D are allowed to improve through additional subsystem-specific development effort.

MSIP managers associate a moderate level of risk with Stage III. They associate low risk with the integration of most single subsystems taken alone, but expect problems with the coordination of concurrent efforts to integrate subsystems with the baseline airframe and to integrate many developing subsystems with one another as they mature. The "Management Strategy" subsection below returns to this problem and explains why these managers believed that risk associated with schedule could be high for many of these subsystems and for MSIP III as a whole.

Discussion

MSIP provides for progressive enhancement of the F-16. Looked at solely from the technology "supply side," this approach allows the F-16 to benefit from new capabilities as they become available. Promotional material on the program emphasizes this aspect of MSIP and its principal product to date, the F-16C/D. For example, in its F-16 program overview, General Dynamics spends its opening pages on the F-16C/D listing all the subsystems being added over time and, in its first direct statement about the aircraft, says

- F-16C Incorporates Latest Technology
  —Provides Increased Tactical Capability
  —Allows Incorporation of Emerging Weapons and Sensor Systems.[2]

But MSIP's progressive approach to improvement also offers an important benefit from the designer's "demand-side" perspective. Even if all new capabilities were available at once, a progressive series of introductions enables the designer to sort through selected sets of unknowns at a time. As information accumulates on subsystems introduced early and the way they work together, problems with these subsystems and their interaction can be sorted out.

MSIP's miniblock system encouraged such an approach by allowing multiple points at which to introduce improvements. As the design for an integrated set of subsystems stabilized, more could be added, beginning the process of information collection and

[2]General Dynamics, 1990, p. 29.

improvement again. We see this approach most directly in the incremental development of the software that played such a vital role in integrating subsystems with the airframe and one another. We see it from a different perspective in the APG-68, which was reintroduced in a new and improved form in almost every new block of MSIP.

This approach may have had its greatest payoff to date in the successful development and introduction of Block 40. As noted above, Block 40 was specially designed around the capabilities provided by the LANTIRN system, which required extensive integration of the navigation and targeting pods with controls and displays, the radar altimeter, terrain-avoidance and terrain-following systems, the digital flight-control system, and air-to-ground weapons on the aircraft. (The Appendix details this integration.) The blocks preceding Block 40 introduced subsystems required to support these new capabilities, although these earlier blocks would not necessarily be retrofitted with LANTIRN equipment. The thorough testing of supporting subsystems in earlier blocks limited the risk associated with them, setting the stage for Block 40, in which risk reduction efforts could focus on the LANTIRN and the subsystems most closely allied with it.

That is not to say that the supporting subsystems introduced before Block 40 benefited only Block 40. In fact, they also set the stage for Block 50, with its different set of subsystems to integrate, and for integrating additional capabilities into earlier blocks by means of retrofit.

MSIP has the appearance of introducing myriad improvements as individual integrations, and, in fact, most of MSIP has been organized around the integration of specific, individual subsystems. At the same time, MSIP itself must be regarded as a carefully planned and coordinated environment in which to effect such integrations. The integrations required to realize Block 40 were carefully structured around the LANTIRN system. And each set of integrations has built on the sets of integrations completed earlier. Although MSIP is designed to allow continuing improvement in the design of the F-16 by integrating additional new systems, it is successful in doing so because it structures the way the integrations complement one another.

MANAGEMENT STRATEGY

The idea that informs MSIP is the development of a highly capable aircraft by adding selected incremental capabilities to an existing high-performance design. The demand for the F-16 has been well established and maintained by a series of three multiyear contracts that significantly relieved risks associated with support for the F-16 program as a whole. Those contracts helped free the F-16 SPO and General Dynamics to focus, in MSIP, on managing the risks associated with adding capabilities to the F-16 in the context of the broader, stable demand for the F-16 system. Because the fighter was being developed and produced for many users, the F-16 SPO and General Dynamics had to determine a process of selecting designs for new, improved F-16s. And because capabilities could be added only by adding new systems developed elsewhere, they had to determine how to manage the risk associated with subsystem designs over which they had only limited control. Given that any new design would incorporate many changes, they also had to manage the risk that the systems would not work well together. And because MSIP would necessarily be handling many tasks at once, they had to determine how to manage risk associated with the concurrency inherent in such a development approach (even if no concurrency existed between development and production). This subsection discusses the approach that the F-16 SPO and General Dynamics chose for handling these basic management issues.

The Stability Associated with Multiyear Production Contracts

When the F-16 SPO and General Dynamics conceived MSIP in 1979, the kind of multiyear production contract that has become familiar was not feasible. Such contracts became feasible only following policy changes in 1981;[3] therefore, a multiyear contract per se clearly played no role in the early planning for MSIP.

But the F-16 became one of the first systems to adopt multiyear contracting. Its first multiyear contract covered FYs 82–85; the second, FYs 86–89; and a third, FYs 90–93. These contracts point to a stable production plan in a healthy, ongoing weapon program. One of the key risks associated with a development program—the risk that the program will not survive—is likely to be limited in such an environment.

The process that Congress uses to approve production programs for multiyear contracts highlights a variety of risks and approves a program only if those risks are limited. It seeks stability in the production rate, procurement rate, and total quantities expected, continued funding over the course of the contract, system design for the portion of the system covered by the contract, and estimates of expected cost. The fact that the F-16 program has exhibited the stability required to maintain multiyear contracts ever since they became available suggests that similar stability was present even beforehand, during early discussion of MSIP, and that demand for F-16s was highly likely to continue over the course of MSIP.[4]

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[3]For details, see Bodilly, Camm, and Pei, 1991.

[4]One might argue that the presence of the multiyear contracts itself directly improved the stability of the F-16 program. While that may be, such a contract by itself can have only limited effects on the stability of a manufacturing program. For example, even with a multiyear contract in place,

Given such stability, the challenge for MSIP managers is to design a way to build a development program on it. The solution that MSIP managers reached was to assume that production of F-16s would continue regardless of progress under MSIP and to absorb much of the risk associated with MSIP by changing the dates at which new capabilities entered the F-16 fleet. So, for example, if a new avionics box was ready for incorporation a year later than expected, such tardiness need not delay production of the system as a whole. Instead, it could be introduced a year later than expected and potentially retrofitted into aircraft produced in the meantime. If it was to be retrofitted, structural and wiring provisions, or even a partially complete version of the final hardware or software, could be implemented on the production line, limiting the cost of retrofit when it did occur. Such an arrangement was especially attractive when hardware was ready on time but software was late. In many cases, software could be updated without requiring much adjustment to the hardware in place.

Such a strategy obviously has limits. MSIP was a response to perceived changes in threat, and MSIP managers could not respond effectively to that threat if the capabilities they were developing were delayed too long. To reflect this concern, managers picked a key milestone, the date for which they would try hard to maintain. That milestone was the introduction of Block 40, the first installment of major new capabilities made possible through MSIP. MSIP managers considered that maintaining the date for initial production of Block 40 aircraft at December 1988 was their most critical risk in the MSIP test plan:

> The goal of meeting the directed F-16 operational capability associated with the [Block 40] aircraft . . . is critical. This milestone cannot slip without potentially significant impact to expected operational capability and retrofit costs. Schedules and technical risk interact heavily in meeting this milestone—both within the individual, often parallel, development efforts and the final integration task on the newly configured production aircraft.[5]

Introduction of selected systems could slip, but the basic capabilities required for Block 40 would be held to that date. As things turned out, MSIP could not quite realize this goal. At the December 1988 milestone, hardware development and testing met program requirements, but software development remained incomplete, and delivery of a production-quality software tape would not be made until the next year. Avionics problems caused by

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General Dynamics and the Air Force recently agreed to a major reduction, from 600 to 300 aircraft, in the production quantity expected for the contract. The underlying stability of the program as a whole appears to be more important than the presence of one specific contractual device.

[5]F-16 *Program Management Plan*, p. 5-8.

electromagnetic interference from several avionics boxes persisted.[6] And although Block 40 aircraft were capable of *accepting* LANTIRN pods on December 1988, LANTIRN pods were not ready for installation by that time. They were installed soon afterward, however.

Therefore, although individual improvements could slip without affecting the preset production rate for the underlying F-16 airframes, MSIP would be set up to work around that rate. Stability in the production program, of course, could not guarantee stability in the development program. And, in fact, MSIP went through many changes during its first decade. Flexibility is a central characteristic of the program. But a stable production program could limit risks that might endanger the development program in the absence of stable production.

One Development Program for Many Users

General Dynamics has sold the F-16 to 19 different governments. Each typically wants a somewhat different design, and some want more than one design. Even if the general production rate is expected to be stable, MSIP must adapt its planning process to meet the needs of so many users, especially when those needs are likely to change over time.

The key to this problem is the predominance of the U.S. Air Force among General Dynamics' customers. MSIP has effectively served the U.S. Air Force first, testing and delivering U.S. configurations first. When budget cuts or shortages of test assets have threatened the program, MSIP has tended to place priority on U.S. interests. And in the end, MSIP developed a large set of capabilities that the U.S. Air Force wanted, essentially creating a menu that other countries could choose from when customizing their own designs. The basic MSIP plan covered all the work required to integrate a new system with the baseline F-16 and most of the work required to integrate any set of subsystems with one another. Additional work required to complete integration on a customized version was small relative to the program as a whole. Hence, the U.S. Air Force could take primary responsibility for MSIP without seriously compromising the interests of potential foreign buyers.

This is not to minimize the role foreign buyers played in MSIP. On the contrary, designs routinely went through the Multinational Configuration Steering Group for approval, effectively involving the European Participating Governments—Belgium, Denmark, The Netherlands, and Norway. Security restrictions limited transfer of some information and delayed release of other information in the process. But the multinational partners in the original F-16 program remained active throughout the process. And

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[6]Wolf, 1988, pp. 184–185.

individual members received changes not included on U.S. designs. For example, to accommodate needs imposed by short Norwegian runways, Norwegian F-16s were modified to add a fairing for a braking parachute to the base of the vertical fin.

In addition, Israel maintained a development program of its own that coordinated testing with MSIP. The program enabled Israel to add capabilities to the MSIP-generated F-16s it received that were not available elsewhere in the fleet. But Israel's commitment to a serious complementary development program is unique among F-16 users.

The dominant pattern, then, was for the U.S. Air Force to create a menu of new capabilities that other nations could choose from. The success of this approach may help explain foreign buyers' concern that the U.S. Air Force would lose interest in the F-16A/B and thereby reduce the benefits the Air Force created by playing a central role there. It played such a role throughout the MSIP.

Capitalizing on Capabilities Developed Elsewhere

The heart of the MSIP approach is the incorporation of new capabilities into the F-16 design as they become available. With a few exceptions, contractors other than General Dynamics or its subcontractors developed the major subsystems used in MSIP, and SPOs other than the F-16 SPO oversaw the development of those subsystems. Relying on technology sources beyond the immediate reach of the F-16 SPO–General Dynamics nexus raises a number of risks.

The first challenge is knowing what capabilities exist and what risks might be associated with them. The F-16 SPO set up the Falcon Century Program in 1982 to assess technologies that might be incorporated in MSIP in the future. The Falcon Century Program evaluates future development and production alternatives and links the availability of evolving technologies to required mission capabilities. It evaluates alternative design configurations against such identified requirements as weapon system performance, production and retrofit feasibility, cost, and mission effectiveness. Falcon Century serves all programs in the SPO, not just MSIP, but it has played an important part in long-term planning on later blocks of MSIP.

Once subsystems are identified for a potential role in MSIP, relationships must be established. To open communication with the relevant groups, the F-16 SPO generated many memoranda of agreement. Figure 5.5 lists those in place in 1987. The organizations involved include a large number of other SPOs, government laboratories and other government agencies. Table 5.2 summarizes the F-16 SPO's sharing of responsibility with other SPOs for the major subsystems included in MSIP. Other SPOs generally retain

F-16 DET33, AFCMC CASEUR, Brussels
4950 Test Wing, Non-Flight Test Support
GSP JPO (SD/YE)
Life Support SPO (ACES II)
ALR-74 Radar Warning Receiver
General Dynamics/Ft Worth AFPRO
Deputy for Propulsion (ASD/YZ)
Simulator SPO (ASD/YW)
Preprosal Review System
Precision Location Strike SPO
Airborne Self-Protection Jammer (ASPJ)
AIS EET
Modular Integrated Communication, Navigation and Identification Avionics (ASD/AE)
B-1B AND F-16
ATC/AFSC Cockpit Familiarization Trainers/Egress Procedures Trainers
Inertial Navigation System (INU)
F-16 Cockpit Information Requirements, AFWAL
AMRAAM
Joint AFTI/F-16 Technology Demonstrations, AFWAL and ASD/YP
AFWAL Materials Lab
AFWAL Avionics for Have Wine
Multinational Staged Improvement Program Software Verification and Validation (OO-ALC)
GD Adaptation of F-16 Automatic Text Equipment to Modular Automatic Test Equipment Guidelines
AGM-65 SPO
AFCMD/AC, AFSC/PQ, ASD/YP
R&D Civil Engineering/ASD
ASD/AE Breakout Items Acquisition of Selected Component Reciprocal Funding for Radar Programs
Avionics Intermediate Shop (AIS) Service Reports F-16 and OO-ALC
Program Management Transfer of the F-16 Centralized Data System
Integration and Test of ASPJ
RADC (F-16 Parts Control Board)
ASD/RWN LANTIRN SPO
F-16 Fire Control Radar, AFPRO Westinghouse
ASD, AFSC, ALD, AFCC, NAVAIR, ASPJ NAVMAC
F-16 Depot C/D Automatic Test Equipment System Test Specification Independent Assessment Plan
ESD Electronic Systems Div. for SEEK TALK/Aircraft Integration
FALCON RALLY Aircraft Modification and Flight Testing
ASD/AFWAL Development Planning Activity
F-16 SPO and 6510 MSUG, AFPRO/GD on Class II Mods
Foreign Disclosure Following PMRT
F-16 and 3246 TESTW
H. G. Armstrong Aerospace Medical Research Lab—Have Wine
System C Integration into Peace Marble Aircraft

SOURCE: F-16 *Program Management Plan*, p. B-1.

Figure 5.5—Memoranda of Agreement Maintained by the F-16 SPO in 1987

Table 5.2

Funding and Management Responsibilities Under MSIP

Systems	Development Tasks: Growth System Dev/Test (Class II Mod)	Development Tasks: F-16-Peculiar MSIP Integration	Dev for Interm & Depot Support Equipment	Production Tasks: Group A	Production Tasks: Group B	Production Tasks: Group B Support	Retrofit: Group A/B
Core/MSIP II	N/A	F-16	F-16	F-16	F-16	F-16	F-16
Radar Altimeter	N/A	F-16	F-16	F-16	F-16	F-16	N/A
Adv. Radar	F-16	F-16	F-16	F-16	F-16	F-16	F-16
LANTIRN (L)							
Pod	L	L	L	F-16	L	L	N/A
HUD	L	L	L/F-16[a]	F-16	F-16(L)	F-16	N/A
Pylon	L	L	N/A	F-16	F-16	F-16	N/A
Auto TA (A/C Changes)	F-16	F-16	F-16	F-16	F-16	F-16	F-16
AMRAAM (A)							
Missile	A	F-16	A	N/A	A	A	N/A
Launcher	A	F-16	A	F-16	F-16 (A)	F-16 (A)	F-16 (A)
AMRIU	F-16	F-16	F-16	F-16	F-16	F-16	F-16
A/C Changes	A	F-16	F-16	F-16	F-16	F-16	F-16
Launcher Adapter	A	F-16	F-16	F-16	F-16	F-16	F-16
HAVE QUICK (HQ)	HQ	F-16	HQ	F-16	F-16 (HQ)	F-16[b]	F-16 (HQ)
GPS (G)	G	G/F-16[c]	F-16	F-16	G	G	F-16/G
ASPJ (ASPJ)	ASPJ	F-16	ASPJ (F-16)	F-16	F-16 (ASPJ)	F-16	F-16 (ASPJ)
PLSS VNS	F-16	F-16	F-16	F-16	F-16 (PLSS)	F-16	N/A
ALR-74	74	F-16	F-16	F-16	F-16	F-16	F-16 (74)
EJS	EJS	F-16	F-16	F-16	F-16	F-16	F-16

SOURCE: U.S. Air Force, Headquarters, 1984, Attachment 1.

NOTE: Parentheses indicate management responsibility when different from funding responsibilities.

[a] LANTIRN will fund only non-AIS O&I-level development.

[b] F-16 funds peculiar F-16 support requirements, and HAVE QUICK funds common support only.

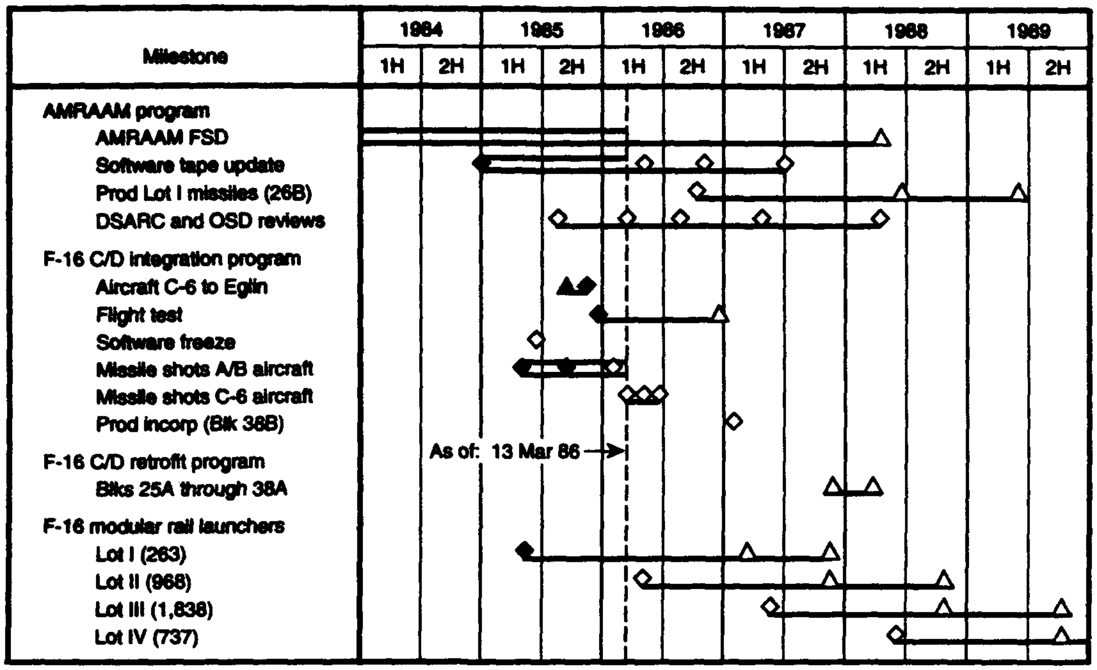
[c] GPS will fund in 1984; the F-16 SPO will fund 1985 and out years.

responsibility for the development and test of each subsystem. Many also retain responsibility for production and support of Group B items (the subsystems without the parts required to integrate them with the F-16, which appear in Group A). The F-16 SPO takes responsibility for most other activities. General Dynamics has similarly signed associate contractor agreements with firms planning to provide government-furnished equipment that MSIP would integrate into the F-16C/D. To coordinate the activities of the major contractors involved, interface-control working groups also exist for each major subsystem.

The next challenge is technical compatibility. Modular design maintains flexibility, for the designer and the potential user, but a subsystem must ultimately be integrated with the systems of which it will become a part. The F-16 SPO and General Dynamics faced this problem by trying to get involved early in development programs for the subsystems of interest. At the very least, through the agreements above, they exchanged information on an ongoing basis. They often sought a more active role. The F-16 SPO played an active role in defining the performance requirements for a number of new systems as early as their concept-validation stages. The F-16 SPO provided aircraft as testbeds for selected systems, fortuitously allowing them to begin preliminary integration with an F-16 system early in their full-scale development and sometimes earlier. Similarly, General Dynamics permitted access to its principal simulators, the Systems Integration Laboratory (SIL) and MSIP simulator. Developers could test software in the complex information environment in which it would have to operate well before hardware was ready for testing in other than a simulated environment. The Appendix illustrates many such activities.

Of course, integration and testing would continue after the subsystem itself was fully developed. The subsystem would be checked in the Systems Integration Laboratory, undergo functional hardware and software tests, and then undergo flight tests. Such tests rarely proceeded successfully the first time. MSIP managers routinely used such testing to isolate problems that required further development. Repeated testing and development pursued a TAF cycle that played an important part in bringing all subsystems into the broader F-16 environment.

Given the applicability of a test-analyze-fix approach, it is useful to find ways to integrate the subsystem and an F-16 surrogate of some kind as early as possible. One way to do so is to seek coordination early in the development of the subsystem and use the F-16 actively in the testing of the system. This obviously creates a high degree of concurrency between the development of the subsystem and integration efforts in MSIP. Such concurrency has been common in MSIP. Figure 5.6 illustrates this approach by showing MSIP's view of the AMRAAM program in 1986, which indicates MSIP flight tests, missile



SOURCE: F-16 "Management Information Notebook" FY 86-2, p. D18.

Figure 5.6—MSIP Master Schedule for AMRAAM Integration with the F-16C/D

shots, and production incorporation of the system are occurring well before full-scale development (FSD) for AMRAAM itself was scheduled to end in 1988. That MSIP did not realize this schedule with AMRAAM does not negate the fact that it was attempted. MSIP executed similarly concurrent schedules with many other developing subsystems.

Relying on subsystems still in development, of course, presents risks of its own. There is no guarantee that developing subsystems will achieve their stated goals or achieve those goals on a schedule compatible with that for MSIP. MSIP often balanced risks by seeking subsystems being derived from other subsystems with known performance characteristics, so that MSIP could influence those systems during their development to improve compatibility with the F-16 and to take advantage of recent improvements in technology without accepting the risks associated with major new developments. That is, just as MSIP was itself a derivative development, it often sought subsystems that were derivative developments themselves. Combined with the test-analyze-fix approach, this strategy allowed MSIP to exploit apparently modular developments while ameliorating the risk that they would yield final systems incompatible with the F-16. And when a subsystem program was unexpectedly delayed, particularly a software program, MSIP could often absorb such a delay without endangering the key December 1988 milestone for its total Block 40 system.

Integrating Several New Capabilities Simultaneously

For the most part, MSIP managers expected the integration of individual subsystems to present little difficulty. They associated a low risk with most subsystems and rarely more than a moderate risk with selected subsystems. Integrating all of them at the same time introduces additional risks that led some managers to judge the schedule risk as high for MSIP as a whole.[7] The simultaneous-integration problem has two components: having a flight-tested, final configuration available at all times to meet the production schedule; and testing each subsystem in a final configuration still under development, a configuration that will still be incomplete until each subsystem is finalized.

Unless a final configuration has a constellation of subsystems that allows safe flight, it cannot be delivered and fielded. If all subsystems complete their development and integration programs on schedule, the final configuration can be delivered as planned. If even one subsystem is unavailable, the final configuration must be delayed or a substitute must be found for the missing subsystem so that a substitute final configuration, presumably missing some desired capability, can be delivered. To maintain the production rate dictated by the underlying production contracts, MSIP has not wanted to delay delivery under any circumstances. Hence, it has sought ways to provide substitutes for subsystems that have not completed development. As a final configuration attempts to integrate more new subsystems at a time, the probability of this problem occurring rises. And the probability that more than one subsystem will be missing, yielding a delivered F-16 with still less capability than expected, also rises.

MSIP plans for this problem in three ways. First, it tries to get involved early in individual subsystem programs to establish the status of those programs and the performance requirements for each subsystem. The earlier the performance requirements can be established for each subsystem, the easier it is to test other systems and the F-16 as a whole to ensure that all other parts of the system are compatible with those requirements. When several subsystems develop simultaneously, early requirements definition for each of them specifies a nominal total system that all can move toward as they mature. It reduces uncertainty about the environment that each will encounter at maturity and, even when not

[7]MSIP managers, for example, judged Blocks 40 and 50 to present moderate to high risks, primarily because of such concurrency. F-16 *Program Management Plan*, pp. 15-2, 15-3.

all requirements are met, limits the final adjustments required to bring all individual subsystems together.

Second, if a test-analyze-fix cycle makes sense for individual subsystems, it makes even more sense for groups of them. Simulation and modeling have improved a developer's ability to predict and resolve problems associated with well-understood processes. As more subsystems must be coordinated, however, their joint performance becomes increasingly difficult to model analytically. Hence, the empirical tests in a test-analyze-fix cycle are indispensable to integration efforts. MSIP reflects this insight by anticipating a need to iterate attempts at integration. At preset times, MSIP tests those aspects of individual subsystems that can be tested then for their fit with other subsystems. The Systems Integration Laboratory plays an integral part in this process because it can test important aspects of new systems fairly early in the integration process. Early iterations invariably identify integration problems that may require adjustment in the subsystem being added or in some other part of the system that might initially have appeared to have no connection to the subsystem in question. Early iteration also helps identify serious integration problems early, giving developers more flexibility in finding a solution.[8]

One solution may be to replace a subsystem. This is the third way developers plan for the problem of a poorly performing subsystem. As problems emerge in the integration process, developers begin to seek alternatives. The alternative may be the subsystem currently in the baseline F-16; an improved version of the failing subsystem, i.e., the subsystem has experienced further development; or another subsystem entirely. In some cases, developers have used one subsystem as a short-term fix while continuing development to get the performance that they really want from a subsystem at a later introduction date. Until such a subsystem is introduced, however, a substitute must be found to allow any final configuration to fly. This aspect of the integration process emphasizes the importance of ties between MSIP and the development programs for the subsystems that it uses. It also emphasizes the importance to maintaining contacts with other development programs well into the integration process. On more than one occasion, MSIP reopened the development process for a subsystem by sending the failing subsystem back into a full-scale-development competition with an alternative subsystem. In at least one case, that for the radar warning receiver, the alternative ALR-56M replaced the ALR-74 originally included in MSIP through a renewed competition and fly-off.

[8] MSIP focuses on integration activities, not the testing of subsystems per se. But tests to integrate, say, a jammer into the F-16 could simplify future efforts to integrate that same jammer into other aircraft. In this way, MSIP could be seen as supporting underlying subsystem development programs.

All these problems address the need to integrate subsystems to allow delivery of a final configuration. This is the most visible multisystem integration problem that MSIP has faced. But another, closely related problem has also presented serious difficulties. If a subsystem is not available to complete a final configuration, it is also not available to test other subsystems in the configuration. The unavailability of subsystems for use as test assets has repeatedly delayed test and integration of other subsystems. MSIP developers have reacted by using every means available to maintain schedules. For example, they have pressured the developers of the missing assets to deliver them, tested features that could be tested in the absence of the missing assets, used simulation or analysis to infer what tests might have revealed if they could have been conducted, and substituted alternative assets with similar features to make other inferences. This type of problem repeatedly has tested the imagination of a creative manager. The Appendix provides examples of this problem.

The F-16 SPO and General Dynamics obviously cannot do all these testing and integration tasks by themselves. Active involvement of other SPOs and contractors is vital. Memoranda of agreement and associate contractor agreements facilitate coordination. By early 1981, an F-16 Integration Executive Committee was established, with membership from the AMRAAM, ASPJ, LANTIRN, GPS, PLSS, JTIDS, and SEEK TALK SPOs, as well as Headquarters, Air Force, the Air Force Systems and Logistics Commands, and the Tactical Air Command. It would later become the MSIP Executive Committee. It set up five working groups to cover technical integration, test planning, logistics, production planning, and finance. By the same time, meetings were being held with representatives of the LANTIRN, PLSS, GPS, AMRAAM, ASPJ, SEEK TALK, and JTIDS SPOs to establish master development and integration test schedules, optimize use of F-16 test aircraft, and identify test hardware shortfalls.

No matter how much interaction occurred, however, General Dynamics retained the standard total-system-performance responsibility that one would expect of a prime contractor. And given the nature of MSIP, the Air Force required that definitized production contracts contain an Integrated System Performance Responsibility (ISPR) provision as well. This provision states that General Dynamics is responsible for ensuring that selected major integrated systems, including government-furnished equipment, meet the performance requirements defined by the Air Vehicle Specification, provided that all government-furnished MSIP subsystems meet their individual performance requirements.

To perform its role in overseeing integration efforts, the F-16 SPO turns to its directorate of engineering for technical expertise. This directorate has established special procedures for addressing integration problems associated with the following subsystem and engineering programs:[9]

- environmental control systems
- electrical power system
- aircraft structural integrity program
- corrosion control program
- aircraft weight summary and maximum gross weight
- volume/equipment locations
- landing gear
- aircraft performance
- radio frequency/electromagnetic compatibility.

Many subsystems are clearly in direct competition for the services of the aircraft's central environmental control and power systems and for the limited space and weight available on the aircraft. Many also compete for use of a limited set of radio frequencies. Subsystems can have unexpected effects on the structural integrity or effective lifetime of other subsystems; corrosion control presents a similar problem.

Managing Multiple Demands on Test Resources

MSIP would ultimately have to address the concerns above in a concrete test program. MSIP managed its test program through the standard structure of the F-16 SPO and related organizations. The SPO directorate responsible for testing, which changed over time, had primary responsibility. Its most difficult time during MSIP began in 1987, when budget cuts severely reduced its test management expertise. This directorate worked closely with the 3246th Test Wing at Eglin Air Force Base, the F-16 Combined Testing Force maintained by the Air Force Flight Test Command at Edwards Air Force Base, and General Dynamics. Together with the Air Force Operational Test and Evaluation Command (AFOTEC) and the Tactical Air Command (TAC), these organizations composed the Test Management Council that met quarterly to coordinate test-related interaction among these organizations. TAC played a special role in this organization, both as a source of aircraft to be used in flight tests and as the source of priorities on what aspects of system performance deserved emphasis when not all testing goals could be realized.

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[9] F-16 *Program Management Plan*, pp. 4-8–4-10.

For MSIP, these organizations coordinated a test program and an associated test and evaluation master plan (TEMP) to identify risks and structure a test plan to address those risks. To obtain OSD approval for the Block 40 test plan, they also assembled a baseline correlation matrix that documented relationships between mission requirements and evaluation criteria to ensure coordination between development and testing. Within MSIP, testing affected the integration of individual subsystems and assessment of full F-16C/D configurations. Each system-integration program maintained its own TEMP. MSIP then maintained a test program separate from these individual efforts that focused on the F-16C/D aircraft itself and tested it as a system to qualify new configurations for production. This test program focused on the carriage and separation envelope for all MSIP-related stores and munitions loadings and on the effect of MSIP equipment on F-16 performance, flying qualities, and structural considerations.[10] Such a test program obviously had to rely heavily on the tests run on individual subsystems and their individual integrations into the F-16C/D. To facilitate coordination among all the test programs, the MSIP Executive Committee set up an MSIP Test Planning Subgroup composed of "key test and support equipment managers from the various program offices, test centers, the users, AFOTEC, and contractors."[11] Table 5.3 lists the key participating organizations in this group in the mid-1980s. Membership changed over time as the key systems included in MSIP changed. This subgroup identified a set of testing issues and risks specifically relevant to MSIP. Concern about maintaining the December 1988 milestone for initial Block 40 delivery, mentioned above, was their primary concern. Other concerns dealt more with the coordination of resources used in testing and of data generated by testing; they included:

Table 5.3

Key Member Organizations in the MSIP Test Planning Subgroup

Program	SPO	RTO/PTO	Contractor
F-16	ASD/YPD	AFFTC/AD	General Dynamics
LANTIRN	ASD/RWN	AFFTC/TBD	Martin Marietta, Marconi
AMRAAM	AD/YM	AD/AFFTC	Hughes
ASPJ	NAVAIR/PMA-272	AD/AFFTC	Westinghouse/ITT
GPS	SD/YE	AFFTC/ATBD	Magnavox, Rockwell Collins
ALR-74/ALR-56M	ASD/YPD	AD/TBD	Applied Technology/Loral

SOURCE: F-16 *Program Management Plan*, p. 5-7.

[10]F-16 *Program Management Plan*, p. 5-11.
[11]F-16 *Program Management Plan*, p. 5-7.

- co-use of scarce, high cost test assets for both development and integration tasks;
- adequate funding for test and evaluation assets, including contractor support where required;
- adequate and consistent priorities at the various test sites and within the various test programs; and
- cooperative development of integrated test objectives and the co-use of related test data.[12]

Among these concerns, access to F-16 test aircraft, coordination of the available F-16 test aircraft, access to the General Dynamics Systems Integration Laboratory, and access to prototype subsystems that could be used in test configurations presented the greatest challenges in the development. Budget shortfalls in the late 1980s also created difficulties. The Appendix presents examples specific to these concerns.

Discussion

As a successful program perceived to present limited risks in its production program, the F-16 program was attractive for conducting a development program like MSIP. The MSIP management strategy limited risks associated with the program as a whole and made it easier for developers to plan for and react to risks associated with development itself. Within that strategy, developers dealt with the problem of having potentially many users by giving a single user, the U.S. Air Force, priority, and essentially offering other users variations that could be constructed from options included in the U.S. Air Force program. They dealt with risks associated with integrating individual subsystems developed elsewhere by getting involved in the development of derivative subsystems early, learning about their capabilities, and shaping their development to promote integration with the F-16. Early involvement enabled them to use a test-analyze-fix cycle to promote integration. They used similar techniques to deal with risks associated with integrating several subsystems at once. Such risks were more difficult to plan for and required especially creative reactions by managers to keep the program on track.

The concurrency MSIP managers experienced as they coordinated early with the development p grams for subsystems and integrated several subsystems simultaneously imposed the most severe residual risk in the program, a risk important enough for some managers to believe that the MSIP faced a high-risk schedule. Such risks existed in part because the developers chose to meet shortfalls by letting the schedule for final production

[12] F-16 *Program Management Plan*, p. 5-8.

incorporations slip. Such an approach was compatible with the underlying production program. But to ensure timely delivery of the key system in the MSIP, the fully capable Stage III F-16C/D, MSIP tried to hold fast to the first delivery of Stage III F-16C/Ds. These F-16s were delivered without all the anticipated capabilities, but an orderly program of retrofits has restored those capabilities as they have become available to MSIP.

CONTRACTS

Although many organizations have contributed significantly to MSIP, the key relationship in the F-16 MSIP, as noted above, has been that between the F-16 SPO and the F-16 contractor, General Dynamics. The relationship between the two organizations has governed the planning and execution of the MSIP development. To define that relationship during MSIP, the F-16 SPO and General Dynamics used a series of contracts. Those contracts, listed in Table 5.4, give the very strong sense of having evolved from one into the other as the program itself matured. That is, as the program became increasingly well defined, contracts better tailored to the needs of the program could be devised.

MSIP began as an add-on to the existing full-scale-development and production contracts in place for the F-16A/B. Those contracts provided the basis for Stage I of MSIP and preliminary work on Stage II. Stage II marked a significant "jump," however, from the F-16A/B to the F-16C/D. To accommodate that jump, the F-16 SPO and General Dynamics negotiated a new development contract. The contract defined the terms under which MSIP-related design changes were developed and translated into engineering change proposals that could be implemented in the standing multiyear production contracts for the F-16. It facilitated the development of Blocks 30 and 40 for the F-16C/D. The F-16 SPO and General Dynamics used it also to initiate Block 50, but ultimately returned to the negotiating table and initiated a new development contract to continue MSIP. This subsection explains these evolutionary events in more detail.

Table 5.4

Key Contracts in F-16 MSIP

Contract	Type	Brief Summary
F33657-75-C-0310	FPI	F-16 FSD contract provided basis for initial development work on Stages I and II
F33657-78-C-0669	FPI	F-16 production contract paid for ECPs in Stage I
F33657-82-C-2038	FPI	MSIP contract evolved from changes in F-16 FSD contract; provides new basis for expedited changes to effect Stages II and III.
F33657-89-C-0009	FPI	MSIP follow-on evolved from changes in MSIP contract to provide basis for Stage III—Block 50 development

Stage I

The F-16 SPO authorized General Dynamics to proceed with Stage I long-lead arrangements in February 1980, for production delivery in May 1982, by preparing an engineering-change order, ECP 0350. The ECP added tasks to the existing full-scale-development and production contracts.[13] Over 1980, the Air Force added tasks to this ECP. By the end of the year, it had a not-to-exceed value of $68.2 million. Continuing adjustments in the tasks to be included delayed definitization until February 1982. The cumulative value (target price) of Stage I tasks at that time was $104.6 million, which included both development and production tasks. Modified aircraft were already completing production by this time. The first was delivered in November 1981.

Both contracts used to implement Stage I were fixed-price-incentive firm contracts. The full-scale-development contract had a 90/10 share line, making it close to a cost-plus contract up to its ceiling at 130 percent of the target price. The production contract had a much more moderate share line and lower ceiling relative to its target price.

Stages II and III

The F-16 SPO had developed an acquisition plan for Stage II by early 1981. The plan would bring new tasks into the program as individual contract-change proposals. To facilitate its implementation, General Dynamics asked that changes be consolidated to include tasks with similar technical-design maturities and related production-incorporation dates. General Dynamics submitted its first contract-change proposal, CCP 9101, under this new system, in February 1981. It called for testing and integration of core avionics, the radar altimeter, the LANTIRN HUD, and what would become the APG-68 fire-control radar. The F-16 SPO gave General Dynamics until July to submit a firm Air Vehicle Specification and firm-price proposal. This proposed change to existing contracts marked the first step both beyond Stage I and into development of the F-16C/D itself.

Contract-change proposals cumulated quickly. General Dynamics had submitted a second proposed change, CCP 9103, concerning the avionics intermediate shop, the maintenance activity that would be required to support the F-16C/D in the field. By December 1981, the F-16 SPO had authorized $219.2 million for MSIP II contract-change proposals. Meanwhile, other change proposals, developed to integrate new subsystems into the F-16 before MSIP became a formal program, continued. They would provide input for the MSIP program in the future.

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[13]It was incorporated in full-scale-development contract F33657-75-C-0310 by modification P01385 and in production contract F33657-78-C-0669 by modification P00128.

CCP 9101 led to the initiation of a formal MSIP contract, F33657-82-C-2038, in June 1982, establishing the basic terms and conditions for all MSIP II change proposals. It effectively provided a contracting environment in which to add new tasks as they arose. The contract provided a pre-negotiated fixed-price-incentive firm arrangement with an 80/20 share line, a ceiling 125 percent above target price, and a 12-percent profit rate for new contract-change proposals. It established a Fast Action Negotiation Group (FANG) procedure to definitize quickly all contract changes under $10 million. The umbrella contract included correction of deficiencies and economic price-adjustment (EPA) clauses and provided for flexible progress payments. CCP 9101 effectively became the first of a "9000 series" of MSIP II and III changes definitized under this new contract.

By 1983, the MSIP contract had become one of the six largest contracts administered by the F-16 SPO. Table 5.5 charts its evolution through the 1980s. From an initial target price of $144.0 million, it grew progressively to well over $1.3 billion by 1988. Subsequent budget cuts and a new contract (see below) led to adjustments that eliminated tasks from this MSIP contract, leaving it with a (target price) value of $1 billion by the end of 1990. The substantial growth and subsequent contraction of the contract's value help illustrate the flexibility allowed by the contract. Because this contract was considered about 90 percent complete by the close of 1990, $1 billion is a reasonable estimate of the full value of the contract over its lifetime.

Stage III began in the course of this formal MSIP contract. CCP 9226 to the MSIP contract initiated the basic program for Block 40 of the F-16C/D development program. It authorized, in July 1985, the studies and initial long-lead software development and

Table 5.5

Value of the MSIP Contract over Time

			Expected Value When Contract Is Complete	
Year	Target Price	Effective Ceiling Percentage	Contractor ($ million)	SPO ($ million)
1983	407.5	1.287	453.8	611.4
1984	500.4			488.4
1985	625.2	1.114	623.9	622.0
1986	843.6	1.114	838.1	833.1
1987	992.8	1.116	985.1	990.3
1988	1366.4	1.073	1367.0	1372.6
1989	1021.6	1.114	1038.0	1037.3
1990	1006.5	1.104	1030.5	1025.5

SOURCE: U.S. Air Force, Aeronautical Systems Division, F-16 SPO, *Selected Acquisition Reports* for 31 December of the years shown.

integration efforts in Block 40. Full authorization followed in April 1986. It was definitized in early 1987 for $296 million. Table 5.6, which presents the contract-change proposals associated with the Block 40 program, illustrates clearly how MSIP divided block programs into tasks associated with individual subsystems. Each of these tasks ultimately led to corresponding engineering-change proposals that were used to modify Multiyear Production Contract II, in effect for FYs 86–89. Hence, the tasks shown here and resources associated with them are primarily development tasks.

Block 50 of Stage III began in a similar manner. CCP 9903 to the MSIP contract, a preliminary design effort for Block 50 aircraft with initial production delivery in June 1991, received initial authorization in September 1986 and full authorization in January 1987. CCP 9903 would authorize full-scale integration efforts. CCP 9904 would authorize long-lead

Table 5.6

Contract-Change Proposals on MSIP Contract for Block 40

CCP Number	CCP Subject	Authorization Date
9211R1	Advanced IFF firm proposal	Dec 87*
9216C4	LANTIRN flight test support	Feb 87*
9226R1	Basic program for Block 40	Jan 86*
9226R1C1	Clarification of basic Block 40 program	Apr 86
9226R1C2	Additional changes within NTE of basic Block 40	Apr 86
9226R1C3	Additional changes and redirection within NTE	Sep 86
9226R1C4	AN/APG-68 radar	disapproved
9226R1C5	Support equipment schedule	disapproved
9226R1C6	Instrumentation changes	Jul 86
9226R1C7	Radio-frequency notch filter	Sep 86
9226R1C8	Increased-capacity battery	Sep 86
9226R1C9	LANTIRN navigation pod BPS	Sep 86
9226R1C10	Electronic warfare bus requirements	Sep 86
9226R1C11	Support equipment schedule	Jun 86
9226R1C12	Electronic countermeasures pod interface	Sep 86
9226R1C13	Aft-seat HUD monitor	Sep 86
9226R1C14	ALE-40 and AVTR	Sep 86
9226R1C15	AN/APG-68M radar	Sep 86
9226R1C16	Late government-furnished-equipment impacts	Jun 88*
9226R1C17	Special project	?
9226R1C18	IDR2 move	Mar 87*
9226R1C19	Additional items	Feb 87*
9226R1C20	SERD 75501 quantity	May 87*
9226R1C21	"No SOL" schedule impacts	Jun 87*
9227	Avionics intermediate shop impacts	Aug 86
9227R1	Avionics intermediate shop impacts update	Aug 87*
9235	Conduct additional LANTIRN flight tests	Mar 87
9236	Yuma Proving Grounds compatibility with test F-16Cs	May 87
9236C1	Additional GPS flight test	Feb 88*

SOURCE: F-16 *Program Management Plan*, pp. H-18–H-21.

NOTE: All authorization dates are actual unless marked by an asterisk (*), which indicates dates are planned.

activities in early 1987. These efforts led to a new contract, F33657-89-0009, signed in December 1988 and definitized in September 1990. It is a fixed-price-incentive firm contract with terms similar to its predecessor, -82-C-2038. And like the contracts before it, it has grown in value over time. With an initial target price of $76.4 million, it had grown to a target price of $162.7 million by the close of 1990, with a ceiling price only 6.8 percent higher. We can expect additional growth as the MSIP program continues to add tasks to this contract. Like its predecessor, this contract uses contract-change proposals that lead to engineering-change proposals in the current multiyear production contract.

Discussion

Taken together, these contracts indicate that, through 1990, the Air Force had agreed to pay General Dynamics about $1.3 billion in then-year dollars for development activities associated with MSIP. Discounting these *obligations* to 1980 dollars yields a base-year cost of about $980 million. (Because expenditures follow obligations in time, the base-year value of expenditures would be somewhat lower.[14]) This figure does not include the costs of integrating the LANTIRN system and GPS, which are covered by the budgets of other programs, or the government's own costs for test facilities, assets, activities, and general administration. On the other hand, we cannot allocate all of these costs to the development of one F-16C/D design. MSIP has conducted development activities for more than one type of F-16C/D and has also created the potential for improving the capabilities of Block 15 F-116A/Bs. As noted in Section 4, the program has also facilitated a series of other aircraft development activities in the F-16 SPO.

Viewed in this way, these contracts have successfully handled a rapidly evolving program and one that experienced considerable change within each block. The key to this success has been the decision to design the contracts effectively as contractual environments that enable rapid contractual revision as new information becomes available. Within these environments, the share lines distribute a substantial share of risk to the government. But moderate ceiling ratios have limited the government's exposure and have not been exercised in practice. These development contracts are backed up by provisions in the production contracts that give General Dynamics clear responsibility for integrated system performance. The potential obviously exists for abuse of the flexibility that such contracts provide. For example, definitization of individual contract-change orders has often taken longer than one

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[14]We discount using factors inferred from the F-16 *Selected Acquisition Report*, 31 December 1990. Assuming that average expenditure occurs two to three years following an obligation and that the average discount rate is 5 percent, the base-year value of expenditures would be about 10 to 15 percent lower.

might expect in a standard contract. But the history of the program offers little evidence that such abuse has occurred. Quite the contrary, the flexibility offered by the contracts has probably contributed substantially to the developers' ability to respond creatively and effectively to unexpected events.

SUMMARY

MSIP has introduced a series of technological improvements to the F-16 aircraft, moving the program beyond the F-16A/B to the F-16C/D and increasing the capability of the F-16C/D over time. MSIP has used a series of miniblocks to introduce improvements. This approach allows the F-16 to exploit the latest technology available and to resolve incrementally risks associated with the new capabilities, so that risk management for new-technology introduction builds on the findings of earlier test activities. The effort had cost about $1 billion through 1990.

Such a program requires coordination of a large number of parallel development and integration efforts. The simultaneity of those efforts creates the risks of greatest concern to MSIP managers. The stability of the F-16 program as a whole, reflected in a continuing series of multiyear production contracts over the course of MSIP, enabled MSIP managers to focus their concerns about risk on the development program itself. By keeping all parties affected by the development actively involved, assigning the U.S. Air Force priority in the design of new configurations, seeking derivative subsystem developments to coordinate with the MSIP effort, getting involved in subsystem development programs early and integrating them with an iterative testing procedure, using progressive introduction of new capabilities to limit simultaneity, and carefully managing the joint use of test resources and data, MSIP has satisfactorily managed the development-related risks associated with the program.

Maintaining a highly flexible management environment has been key to the MSIP approach. The contracts used to implement MSIP are essentially contracting environments that allow continual adjustment as information accumulates in the development effort. The fixed-price-incentive contracts shift much of the risk associated with such flexibility toward the Air Force for small, unexpected increases in cost. But they also cap the Air Force's risk with moderate ceiling ratios and a requirement that General Dynamics retain integrated system performance responsibility for the F-16 weapon system that results from MSIP efforts.

6. CONCLUSIONS

The F-16 Multinational Staged Improvement Program (MSIP) provides a useful example of a derivative aircraft development program that has essentially added capabilities developed elsewhere, in the form of modular subsystems, to an F-16 baseline system to create the F-16C/D. Such an approach offers one potential way to respond to the rapidly changing defense environment we face today. The threat is no longer as well defined as it was in the past. We can expect it to change quickly over time as new international contingencies develop, requiring the Air Force to refine its weapons and tactics in response. We can also expect that the Air Force will have fewer real resources with which to respond. MSIP offers a way to update a proven weapon system with specific new capabilities as technological advance makes them available or as the threat makes them more important to the Air Force. As we review the major findings of this study, let us also consider what they tell us about potential results of applying an approach similar to MSIP in other areas of Air Force acquisition.

MSIP is more an approach than a formal program. MSIP offers a way to think about derivative development. The F-16 SPO has used methods like those in MSIP to upgrade its F-16A/B fleet, to plan for successors to the F-16C/D, and to design variations on the F-16 that could meet specific new requirements. One variation emulates Soviet aircraft for the Navy. Another provides new reconnaissance capabilities. A third enhances air defense capability for the Air National Guard. A fourth, still under consideration, could provide enhanced close air support. Each variation was or could be designed and implemented quickly as new requirements were recognized. Development costs have been well below those associated with newly designed aircraft. Such a development capability should be attractive in an environment with an uncertain threat and limited resources.

It is not easy to integrate modular subsystems. It is difficult to maintain multiple subsystems on the shelf and integrate them into an effective new system whenever such a new system is required. MSIP has cost about $1 billion, "simply" to integrate capabilities developed elsewhere. And it would have cost a great deal more if MSIP had not become involved early in the development of those capabilities. MSIP has taken a proactive approach to identifying the new capabilities it might use, establishing relationships to bring those capabilities into a form it could use, and managing the final integration of many subsystems into a coherent system. In the end, an effective system must customize its subsystems to fit its weight, space, data, power, display and control, and specific system requirements, and customization requires time, resources, and expertise.

That said, integration efforts undertaken by MSIP to develop the F-16C/D have significantly eased the difficulty of integrating the same subsystems or constellations of subsystems into other aircraft variations. In particular, the integration of subsystems into U.S. versions of the F-16C/D has substantially reduced the difficulty of integrating them into foreign versions.

In the future, then, the Air Force should not try to respond to an uncertain threat by simply inventorying many subsystem capabilities on the shelf. MSIP suggests that it is best to develop those subsystems within some more focused context so that they reflect integration concerns and so that the Air Force establishes some experience in integrating them with other systems that it can apply quickly when it needs the subsystems in new contexts.

A test-analyze-fix (TAF) approach requires concurrent integration of subsystems. Concurrent integration efforts raised MSIP's greatest concerns about risk in its planning process, concerns that were realized in many of the subsystems examined in the Appendix. But concurrent integration is a response to yet another problem. MSIP exhibited a strong commitment to a TAF development approach that allowed many iterations of empirical testing to identify and resolve problems. Such an approach is especially important when integrating many subsystems because even the best analysis and modeling cannot predict the problems that will arise when complex subsystems interact. Empirical testing is necessary. Iterative testing is also necessary to ensure that solutions to problems associated with one interaction do not create problems with another interaction. To implement its TAF approach, MSIP has tried to get involved as early as possible in the development programs for its subsystems and begin looking at interactions between those subsystems and some useful F-16 configuration. Such an approach leads to heavy concurrency within the development process.

An alternative to this approach presumably uses iterative testing to integrate one system at a time. The flexible response needed to respond most effectively to problems discovered in such a process requires that earlier integrations continually be reopened and adjusted. Such an approach introduces its own risks and significantly increases the length of time required to achieve a complete system integration. One of the attractions of MSIP for future application is its ability to implement derivative designs quickly. It depends on concurrency to offer this benefit. Future users of an approach like MSIP should be prepared to accept the risks created by concurrency; they should also plan for them. We say more about concurrency below.

Introduction of new capabilities in stages ameliorates risks caused by concurrency. The desirability of concurrency is obviously not absolute. MSIP justifies its staged approach as a way to introduce new subsystem capabilities as they become available or attractive and as a way to limit the costs of retrofitting such capabilities by anticipating them and making provision for future subsystem incorporations on the production line. The approach also helps ameliorate risks associated with concurrency. In practice, MSIP has not found it necessary to reopen many decisions made in earlier stages when it reached later ones. So it has found a way to raise a limited set of integration risks at a time—in one stage or block—resolve them, then raise another set, resolve them, and so on. The delay imposed by such a staged approach is offset by the fact that interim stages actually produce aircraft with enhanced capabilities. Such technological capabilities—presumably those whose risks can be resolved quickly—become available early; others with more complex integration problems become available later.

Future developers could use a similar staged approach to limit some of the risk associated with concurrent subsystem integrations and to speed the introduction of new capabilities that pose fewer integration risks. Such a staged approach must, of course, consider the cost of retrofitting capabilities developed late into systems produced early and the operating and support costs of managing multiple variations of a system if retrofits do not ensure uniformity when the development is complete.

The cost savings of government-furnished equipment may be overstated during development. MSIP preferred developing most major subsystems as government-furnished equipment to save money. The F-16A/B had converted many subsystems to government-furnished equipment from contractor-furnished equipment to save money. MSIP continued that approach. There is no doubt that treating a major subsystem as government-furnished equipment during *production*, when its design is fairly stable, can save the Air Force substantial amounts of money by avoiding certain payments to the prime contractor. However, maintaining a system of government-furnished equipment during *development* may complicate integration efforts. If it does, resulting shortages of subsystem prototypes to be used as test assets for other subsystems and delays in upgrading these prototypes can significantly reduce the effectiveness of integration testing. Loss of effectiveness raises the cost of development in ways that a standard accounting system cannot easily capture: Subsystem assets standing idle for lack of adequate test assets can impose substantial opportunity costs that are never attributed to the missing test assets.[1] If maintaining a subsystem as government-furnished equipment contributes to test-asset shortage, doing so imposes costs that cannot easily be measured, but they are costs that could easily offset the apparent cost savings associated with government-furnished equipment.

Without a more detailed analysis of MSIP, we cannot say how important this problem has been. Surely, the Air Force required General Dynamics to assume integrated-system-performance responsibility for its key government-furnished subsystems to ameliorate the integration problems that might arise from maintaining those subsystems as government-furnished equipment. We cannot say how successful that gambit has been. Future developers contemplating an approach like MSIP should consider carefully the costs and benefits of government-furnished equipment, recognizing that standard cost accounts cannot provide the information needed to make the right decision. They should give closest attention to those major subsystems that will require the greatest integration effort.

The development risks presented by MSIP call for a flexible management and contracting structure. The types of risks that MSIP planners associated with concurrent integrations are precisely those that cannot be resolved at the beginning of a development in a management plan or by contractual arrangements. Although the planners knew that many surprises would arise, they could not know where they would arise or when, or what they would be. Any attempt to set up explicit arrangements for such surprises in advance would yield a fairly blunt, wooden development environment that could not respond well to the specific surprises that actually arose. This statement could probably be made about any development effort expecting to resolve significant uncertainties over its course; it is especially true of developments like MSIP, the risks for which arise from many integrations whose interactions simply cannot be foreseen.

Such a situation calls for a "relational contract" among the parties involved, a contracting environment that strives harder at defining and maintaining relationships among the parties than it does at resolving specific difficulties in advance.[2] Such an arrangement relies heavily on custom and historical relationships among the parties, but formal instruments can enhance it. The contracts, memoranda of agreement and understanding, working groups, and other management arrangements associated with MSIP exemplify the types of instruments required, the formats in which specific tasks can be

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[1]For a lucid and entertaining description of this problem in a production setting, see Goldratt and Cox, 1986.

[2]For an elaboration of this idea, see MacCaulay, 1969; Macneil, 1980; Williamson, 1979, 1985.

structured as the need arises. Such instruments impose close control on the tasks, if necessary, but maintain the flexibility to address new tasks in the best way possible for those involved.

Although disputes between organizations inevitably arose during MSIP and responsibilities were occasionally reassigned to deal with such problems, MSIP has been remarkably free of fundamental disagreements among the parties involved—all the more remarkable given the number of parties involved and the turbulence in the developments for many of the subsystems they represented. Future developers interested in using an approach like MSIP would benefit significantly from looking more closely at the specific arrangements established for sustaining organizational relationships.

Incentive contracts treat a limited set of risks. Much of the literature on defense contracting focuses on whether a contract is cost based or fixed price, on the share line that allocates risk between the buyer and supplier, and on the price ceiling that limits the buyer's risk. Although these factors are important, they address only part of the contracting problem, the specific set of risks associated with specific tasks' accounting costs. They do not deal with the major risks encountered in MSIP.

MSIP planners expected integration concurrency to contribute the largest risk to MSIP. When shortages of updated prototypes complicated MSIP, imposing costs not just on MSIP but on many of the development programs feeding into MSIP, the fixed-price-incentive MSIP contract in place could do nothing, by itself, about the costs that the Air Force (and its contractors) bore as a result. Among the histories presented in the Appendix, the APG-68 provides the most compelling illustration of this problem. After exceeding its price ceiling, Westinghouse bore the full burden of the costs it associated with developing the APG-68. But its problems continued to impose substantial costs on the Air Force and other contractors that the incentive contract did not even address. The Air Force could use Westinghouse's failure to perform as leverage for concessions elsewhere. However, the form such leverage would take could not be predicted or even addressed in terms of the share line and ceilings so often emphasized in discussions of contracting. Other terms of the contract, many of them implicit, were more important.

More generally, MSIP has offered a context in which the work statement is continually being revised. Although specific price terms apply to each new task negotiated, the continuing flexibility of MSIP offers ample opportunity to override or renegotiate those terms. That more general environment is more important to understanding MSIP than the specific terms of any one task. We found no evidence that the parties to MSIP have abused the flexibility allowed by the program. But future users of the approach should be aware of the potential for abuse.

Good managers made MSIP's flexible environment work. MSIP provides its managers with considerable freedom to act; it can do so only because the MSIP planners had confidence that MSIP managers would act properly and effectively. MSIP provides a flexible environment in which developers can react to surprises as they arise. Given the nature of risks in the F-16 development, the contracting literature would generally support such an approach. That literature gives little attention to the question of how developers will exploit that flexible environment.

In MSIP, management experience does not necessarily lie in the SPO leadership. Although the F-16 SPO was well established and organized well before MSIP began, MSIP has been run primarily by military personnel with limited tenures at the SPO. That limits their accumulation of experience working in the MSIP environment. Greater stability has existed in the predominantly civilian functional offices of the SPO and at General Dynamics.

A program like MSIP, which constantly presents opportunities to reopen the relationship between the Air Force and the prime contractor, offers the potential for skilled personnel to exploit those opportunities in specific circumstances, endangering the broader relationship over the long run. That has not happened in MSIP. Finding the reason deserves more attention. Perhaps the staffs of the SPO and contractor are well enough matched in their skills and experience that neither has been able systematically to exploit the other. Perhaps they share a set of values that limit their willingness to pursue opportunities for short-term gain.

Developers considering a program like MSIP in the future must focus particularly on the people who will manage it. Given the freedom that such a program allows, those people will have more effect on its success than they would in a traditional development. As noted above, developers should examine their people's experience, their skills and, to the full extent possible, their commitment to preserving the contracting environment over the long term.

Multiyear production contracts have limited risk in MSIP. For the duration of most of MSIP, one of three multiyear contracts was in place for the F-16. Those contracts were important to MSIP for two reasons. First, they alleviated concern that the survival of the F-16 program itself might be at risk. Their existence, in itself, probably only had a limited effect on risk in MSIP. But the fact that both Congress and the Air Force approved this series of contracts points to a degree of stability in and consensus about the F-16 program that had to ease the minds of developers. In particular, such stability meant that developers would not feel as much pressure to overpromise to maintain support for their development efforts. Not having to overpromise limited their own risks and allowed them to pay greater attention to the management and reduction of those risks over time.

The second reason the multiyear contracts were important to MSIP was that they mitigated the different kind of pressure ongoing production programs put on developers. As aircraft were scheduled for delivery, developers had to ensure that the aircraft being delivered were complete enough to fly safely. The developers effectively did not have the option of simply delaying delivery of new systems in response to a development problem. MSIP was deliberately structured so that if it could not deliver a new subsystem as expected, placeholders were incorporated for that subsystem in new production aircraft. Thus, the aircraft could operate safely, but the new subsystem could replace the placeholder or be retrofitted to achieve the final capability when it became possible. This response to surprises during development occurred repeatedly in MSIP.

Developers considering a future program like MSIP should be aware of the positive effects that the multiyear contracts had on MSIP. Where such contracts are used in the future, programs like MSIP may be more attractive. Where they are not, developers should be aware that a development program like MSIP will face different pressures: Success will be more difficult to achieve, and it will not depend as heavily on the strategy that MSIP has used—incorporating partially capable subsystems early and replacing or retrofitting them later.

U.S. dominance of MSIP simplified risk management. Although MSIP is known explicitly as a *multinational* program to recognize the participation of Belgium, Denmark, The Netherlands, and Norway, the United States has been the dominant partner in this program from the beginning. U.S. dominance has limited risk by allowing MSIP to focus its activities on U.S. priorities first and then to turn to the priorities of the other participants. That focus has limited risks associated with the development of specifications for new configurations developed under MSIP. It has also simplified considerably the integration of options offered to foreign air forces. U.S. dominance has also reassured other foreign buyers of F-16C/Ds of the United States' continuing interest in and commitment to the F-16C/D program. This effect is best exemplified by the concern that grew among potential foreign buyers of the F-16A/B until the U.S. undertook efforts to upgrade it to preserve its utility to U.S. forces.

Future developers will probably work in an environment in which multinational sales become increasingly important. To promote multinational participation in a future program like MSIP, those developers might be tempted to seek a larger foreign role in the development process. What that role might be will obviously depend primarily on the nature of the discussion among the countries involved. But U.S. participants in such talks should keep in mind that a dominant U.S. role in this so-called multinational F-16 program has contributed significantly to the success of MSIP, from U.S. and foreign perspectives. That said, the roles that foreign governments have played in the F-16 MSIP deserve more attention than we could give them in this study.

In sum, a program like MSIP offers great promise for future system developers who seek to react as quickly and flexibly to changes in the threat as a derivative development can. MSIP is a subtle program. It has many unique characteristics that will not be present in future efforts. And it has had its own problems that future developers would not want to repeat. But it offers a good example of positive lessons about how to structure future development efforts.

Appendix

INSIGHTS FROM SIX SUBSYSTEMS INTEGRATED DURING MSIP: AN/APG-68 FIRE-CONTROL RADAR, AMRAAM, LANTIRN, HUD, GPS, AND AFEs

The discussion in the text examines MSIP from above, treating it as a single development program with unified goals, management, and schedule. Even viewed from above, MSIP reveals itself as an effort that coordinates many parallel efforts with focused, individual goals. When we think of risk as a situation in which a developer might be surprised, we should expect such surprises to be easiest to observe in the individual development and integration efforts comprised in MSIP. This Appendix seeks a better understanding of surprises by looking at MSIP from the bottom up.

In this Appendix, we follow the integration of six subsystems, listed in Table 1.2, through MSIP: APG-68 fire-control radar, AMRAAM and its launcher, LANTIRN pods, head-up display (HUD), Global Positioning System (GPS), and Alternate Fighter Engines. Ten years of official historical records for the F-16 SPO, from 1979 to 1988, were consulted to examine each integration and identify major surprises, ask why they occurred, and ask how MSIP reacted to those surprises. These questions are answered by addressing each subsystem in turn. Each subsystem is described briefly and a brief history is given, then major surprises are discussed. Table 5.1 should provide a useful temporal context in which to compare timelines for individual subsystem developments, integrations, and production incorporations with the timeline for MSIP. This Appendix closes by looking across the six subsystems and summarizing the major sources of surprise and the principal ways MSIP managers reacted to them.

AN/APG-68 FIRE CONTROL RADAR

Description

This Westinghouse radar was derived from the Westinghouse APG-66 radar used in the F-16A/B. In fact, until early 1983, it was known as the improved APG-66. The key improvements in the radar were the addition of a new programmable signal processor (PSP), a dual-mode transmitter (DMT), and several new radar modes. They enhanced the F-16's ability to deliver air-to-air and air-to-ground munitions in all-weather conditions. By extending range beyond visual range alone, the improvements enabled the F-16 to launch several AMRAAMs at once, and they increased map resolution about eightfold in air-to-ground use and the range of radar modes available. They also improved flexibility by permitting addition of new modes in the future. These improvements were expected to make the APG-68 an effective alternative to the Hughes AN/APG-65 radar.[1] Although the Air Force expected to, and ultimately did, use a version of the improved radar in the B-1B as well as in the F-16, the F-16 SPO oversaw the development of this government-furnished subsystem. When the B-1 program selected the new radar for its use in December 1981, the B-1 and F-16 programs set up a formal memorandum of agreement and began to develop plans to encourage commonality in the F-16 and B-1 versions to be developed.

The APG-66 had been a contractor-furnished item in the F-16A/B. The radar's central role in the F-16 aircraft would appear to favor a contractor-furnished status to promote integration. But the F-16 program changed this status for the APG-66 to government-furnished to reduce its acquisition cost to the Air Force. The APG-68 remained a government-furnished subsystem perhaps because, over the life of MSIP, APG-68 contracts were among the largest that the F-16 SPO signed. The APG-68 had high visibility in the SPO.

The development program for the APG-68 was active throughout MSIP. Although this program was functionally separate from MSIP, F-16 SPO management reduced the distance between the two programs. They were typically managed by the same offices within the SPO. Furthermore, each change in the APG-68 program precipitated related integration problems for MSIP. The presence of both programs in the SPO probably improved its ability to manage these changes and the problems that accompanied them.

History

The development of this radar effectively began in April 1980, when the F-16 program received direction to develop a derivative radar using earlier development efforts on the PSP. The new design had the additional components mentioned above. Its specifications came from the common modular multimode radar program.

Unlike most of the testing associated with MSIP, much of the initial flight testing for the APG-68 occurred *outside* Air Force facilities. The F-16 SPO and Air Force Flight Test Center reached agreement in late 1980 to use the Westinghouse flight test facility in Baltimore. Westinghouse would use a corporate-owned Sabreliner, modified to carry F-16 avionics, as the test platform for much of the early work. This approach was expected to cost less than giving Westinghouse extended access to an F-16 test aircraft and, incidentally, would help relieve excess demand for F-16 aircraft test assets.

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[1]Blake, 1987, p. 867.

Despite the unorthodox test site and test vehicle, the F-16 SPO coordinated this development effort with MSIP early in its life. Flight tests began on the Sabreliner in early 1982, focusing especially on high-risk modes to assess their feasibility. The design reviews that followed these flights raised serious concerns about some of the modes tested; developers expected additional tests to alleviate those concerns. Sabreliner tests continued.

By early 1983, development was sufficiently advanced for Westinghouse to sign a production contract. The contract included a reliability incentive program in which the Air Force would use subjective criteria to award Westinghouse a fee every six months based on the reliability level achieved in the new radars. Although development was running a few months late, production schedules were expected to be achieved. By this time Westinghouse also began development work on a version suitable for foreign military sales.

In June 1983, Westinghouse was able to send General Dynamics an improved APG-66, modified to interact with a full-scale-development AMRAAM system. General Dynamics used this system to begin tests in its Systems Integration Laboratory (SIL). Conflicts in access to the SIL between the APG-68 and LANTIRN were resolved in the LANTIRN's favor, to support efforts to meet its schedule.

As radars were produced and delivered, flight testing on MSIP F-16s began. Unfortunately, problems delayed the APG-68 program; two restructurings occurred in 1983 alone. Delays in software upgrades delayed flight tests at Edwards and Westinghouse. By late 1983, a growing shortage was expected to affect the development of other systems associated with the APG-68. To aggravate the shortage, the radars delivered did not meet their performance specifications. They were not even as capable as the APG-66 from which they were derived. Westinghouse had exceeded the ceiling on its fixed-price incentive full-development contract, effectively shifting the risk of additional cost increases solely to Westinghouse. But the shortages and performance shortfall continued to impose costs on MSIP.

The F-16 SPO responded to these problems in a variety of ways. It developed an incentive program to encourage more rapid production of radars. As the situation deteriorated, it withheld progress payments and then contract profit on production deliveries. The Air Force paid award fees of zero on the reliability incentive program. General officers imposed intense pressure on their Westinghouse counterparts. The F-16 SPO negotiated no-cost contract-change proposals with Westinghouse to get additional work in compensation for the delays. Westinghouse replaced its general manager and developed a recovery program. Westinghouse and the Air Force restructured the schedule and agreed to split the costs of retrofitting capabilities not delivered when expected, to reflect who had caused the delay.

In the end, Westinghouse succeeded in delivering production APG-68s as agreed for installation in the first MSIP Stage II aircraft in April 1984. But design of the DMT remained incomplete and software in the radar could not meet key specifications. These problems persisted. APG-88 performance did not reach the level of APG-66 performance until February 1985. Recovery schedules could not be met. Software upgrades continued, finally achieving the performance specification expected in October 1987. By that time, Westinghouse had agreed to pay for retrofits to bring previously delivered units up to par. Meanwhile, manufacturing problems with the key new components, the PSP and DMT, caused further problems and delayed design stability for the radar. Westinghouse brought these problems under control by late 1987.

Although these aspects of the APG-68 development had the largest negative effects on MSIP, several other events were also important. First, in late 1985, Westinghouse began development work to add VHSIC capability to the PSP, using funding from OSD and the F-16 SPO. Developers expected to introduce that capability into MSIP in 1991, suggesting a very aggressive, success-oriented program.

Second, initial tests of the airborne self-protection jammer (ASPJ) raised the possibility of serious interference with radio frequencies important to the coordination of the APG-68 and AMRAAM systems. MSIP began to address this possibility in 1984. As tests accumulated, it appeared that the problem was not as serious as expected. Nonetheless, by early 1986, unavailability of ASPJ assets slowed the integration of the APG-68 into future MSIP blocks. The ASPJ problem persisted into 1987. In the meantime, MSIP initiated efforts to develop an advanced interference blanking unit (AIBU) and a radio-frequency (RF)-switchable notch filter to alleviate the problem. Efforts to achieve RF compatibility continued into 1988 and included coordination with the Navy at the Electromagnetic Compatibility Analysis Center at Annapolis, Maryland; antenna testing at the Rome Air Development Center at Rome, New York; and anechoic chamber testing of AMRAAM and other munitions. In the end, such compatibility problems appear to have been resolved.

Third, in early 1986, OSD recommended that APG-66C radars be used in place of APG-68s in over half of the new F-16C/Ds included in the FYDP. Westinghouse countered with a proposal that the APG-68 be modified to reduce its cost. The most prominent change would remove flight-line programmability in the PSP. The package, which became known as APG-68M, reduced initial acquisition cost and increased reliability to reduce overall ownership cost for the system. In August 1986, the F-16 SPO received direction to use this somewhat less capable, but substantially less costly, version of the radar in Block 40 aircraft to be introduced in December 1988.

Finally, the Air Force sought further improvements in reliability: an increase in mean flight time between maintenance actions (MFTBMA) from about 60 hr for the existing system to over 100 hr and ultimately over 150 hr. It also wanted to cut the initial acquisition cost of the radar by about 25 percent. The new radar would be known as the "three-digit" APG-68(V), for breaching the three-digit MFTBMA threshold. Beginning in early 1987, Westinghouse undertook an Air Force funded development effort to achieve these goals in anticipation of providing a no-cost warranty agreement that rewarded Westinghouse for performances above 100 hr. The new radar entered the F-16 on schedule in December 1988. It achieved its goal during the following year, saving the Air Force $60 million and restoring the mission-capable rate for F-16C/Ds to over 90 percent.[2]

Discussion

This very brief history reveals eight surprises, or problems. Speaking broadly, three involve surprises caused by technical risk, two concern surprises associated with the availability of test assets, and three involve surprises associated with changes in system specifications.

1. **Early Indications of Design Risk.** Development managers essentially maintained their optimism in the face of disturbing evidence. Without a more detailed examination, we cannot know whether they could have avoided later problems by taking these early indications more seriously.

2. **Difficulty Maintaining Production Schedules.** A serious problem resisted repeated efforts to resolve it. This problem resulted primarily from an immature design that was, in part, related to a series of producibility issues. Later, the F-16 SPO would also attribute part of the problem to an inexperienced manufacturing facility. As the problem persisted, the SPO brought all the means at its disposal to bear on resolving the problem. It is worth noting that special provisions of the contract provided few such means. Withholding progress payments and profits, bringing high-level pressure, and intervening directly in Westinghouse's operations would have been possible in almost any contract. Only the reliability incentive and fixed-price-incentive arrangements in the contract provided customized instruments for specific response. It is also worth noting that, in the end, the problem precipitated targeted management interventions that required the Air Force to have detailed knowledge of Westinghouse's activities.

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[2]Wolf, 1987, p. 162; Wolf, 1989, p. 17.

This problem had significant effects on MSIP activities that had not been contemplated in any detail or planned for in any contractual device to which MSIP was a party. The fact that the F-16 SPO oversaw both MSIP and the APG-68 development probably limited the damage to MSIP. But a creative response from MSIP managers also played an important role.

3. Difficulty Achieving Performance Specifications. It is difficult to separate the origin of this problem or the Air Force response to it from those of the one above. But one additional issue comes up here. Even if production had not been a problem, the quality problem would remain. And MSIP's response to this problem is illustrative of a common response throughout MSIP. MSIP accepted the substandard radars to maintain its production-incorporation schedules and planned retrofits to correct problems in these substandard systems as solutions could be developed. In a sense, the substandard radars served as placeholders for the final radar configuration.

This approach incurred retrofit costs, complicated efforts to integrate the radar with other subsystems while final corrections were pending, and reduced the capabilities of the aircraft produced with substandard radars. Viewed from this perspective, this approach spread the effects of a technical surprise over the cost, schedule, and performance of the F-16C/D. It is also worth noting that, in the end, these effects were transitional. Later versions of the F-16C/D received a highly capable fire control radar, fully integrated into the aircraft.

4. Conflict at the SIL. General Dynamics' SIL served as a powerful development, test, and integration asset during MSIP. It could not accommodate all demands placed on it by the various subsystems associated with MSIP. This is not to say that the SIL should have been designed with greater capacity; without a detailed analysis, we cannot say whether excess demand for the SIL was too high or too low during this development. When conflict occurred, however, MSIP managers set priorities by examining the relative situations of the subsystems involved in MSIP and then gave them access to the SIL on the basis of those priorities. No formal system appears to have been instituted to set priorities; MSIP managers simply set priorities as required to promote the best use of the SIL.

5. Nonavailability of ASPJ Assets. The persistent nonavailability of ASPJ assets during MSIP was clearly not anticipated and was caused by irresolvable problems in the ASPJ development program. The Air Force finally placed the ASPJ program on hold in December 1989, pending an assessment of its likely future success. During MSIP, the Air Force and Navy participants in the joint program (the Navy was the lead) had very different views of how to manage the program. We cannot determine to what extent the Navy role in this program complicated MSIP dependence on this subsystem.

Given that dependence, however, and the continuing problems that it created for MSIP, the developers had little specific protection prepared in advance. As managers facing a new problem, they reacted in several ways. They began new development efforts to reduce the difficulty of integrating the APG-68 and ASPJ system, when that became possible. As we shall learn in the LANTIRN history below, they also considered changes in the operation of the aircraft and alternatives to the ASPJ system itself.

6. Introduction of VHSIC Capability. Although a "surprise," this was less a problem than a simple change in MSIP plans. MSIP was structured explicitly to allow such changes, even if this specific change could not be anticipated. The procedures in place handled it without difficulty.

7. Introduction of the Less Capable APG-66C. This is an unusual example of direct OSD intervention in MSIP. Rather than accept the initial proposal, Westinghouse offered an alternative way to cut cost, one that required far less sacrifice in performance. Once this alternative was accepted, the change in configuration inevitably required new integration tasks. MSIP managers, working within the standard MSIP process, were able to accommodate it without difficulty.

8. Introduction of the More Reliable APG-68(V). This intervention appears to have originated in the Tactical Air Command, where low radar reliability was retarding the readiness of the F-16C/D fleet. Like the introductions above, it seemed to proceed without serious difficulty in MSIP. The incentive structure used to implement it was unusual. Although implemented outside MSIP, it presumably affected Westinghouse's performance within MSIP in a positive and ultimately successful way.

ADVANCED MEDIUM RANGE AIR-TO-AIR MISSILE (AMRAAM)

Description

The AIM-120A AMRAAM provides an air-to-air attack capability beyond visual range. The Air Force and Navy developed it jointly (the Air Force had lead responsibility) to replace the AIM-7M Sparrow, a less capable, significantly heavier air-to-air missile. When used with the APG-68 fire control radar, the AMRAAM can launch up to eight all-weather, all-aspect radar-guided missiles beyond visual range; the missiles then become autonomous. That is, the aircraft radar acquires potential targets, tracks them, and highlights them for the pilot. If the pilot decides to launch a missile at a target, the system feeds initial reference data on the target and the launch vehicle into a computer on the missile. Following launch, the computer guides the missile to a midpoint where a target seeker on the missile becomes active and continues to guide the missile to the target. Several missiles launched by the aircraft can do this simultaneously. In the meantime, the pilot is free to maneuver. The criticality of the integration of missile and aircraft radar, navigation, control and display, and other systems should be apparent.[3]

History

The AMRAAM completed its initial 33-month concept phase just as planning for MSIP began. In February 1979, the Air Force chose Hughes and Raytheon from five competitors to conduct parallel proof-of-concept efforts, leading to a competition between them for the full-scale-development contract. In December 1981, Hughes won the contract to conduct full-scale development through 1986. Raytheon later reentered the program as a second production source for the Hughes design. This development could not realize the highly optimistic goals set for it. As a result, the AMRAAM full-scale development was unusually turbulent. A series of schedule revisions beginning in 1984 moved back the in-service date for production missiles from 1986 to 1988. In 1985, the development program conducted an extensive cost reduction exercise.[4] In its efforts to integrate AMRAAM, MSIP was forced to react to the turbulence. Difficulty mating the missile's modular rail launcher to the F-16 further complicated MSIP.

The F-16 SPO became involved in the AMRAAM development during its proof-of-concept stage. With the AMRAAM JSPO, the F-16 SPO developed a "minimum proof of concept" definition designed to ensure that no high technical risks related to the integration of aircraft and missile would remain to be resolved in full-scale development. This definition provided a basis for ground simulation, wind tunnel tests, and flight tests. Wind-tunnel tests completed in late 1979 revealed no integration problems. Related work continued into the next year, and led to the need for General Dynamics to develop new software for an advanced control interface unit (ACIU) to integrate the aircraft and missile. Development work began on that software, for use with a brassboard ACIU in 1981 proof-of-concept tests on both AMRAAM systems; funding limitations ultimately restricted those tests. This work also led to extensive exchange of technical data and hardware, under contract, between General Dynamics and Westinghouse (the radar contractor) on the one hand and the missile contractors on the other. And it led to a management plan for integrating the F-16 and AMRAAM during the AMRAAM full-scale development.

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[3]Pretty, 1986, pp. 198–199.

[4]Pretty, 1986, p. 199. For more detail on this development program, see Mayer, forthcoming.

By the time AMRAAM full-scale development began in December 1981, F-16 support for the program was firmly integrated with MSIP through a contract-change proposal, CCP 9140, under the MSIP contract. Associate contractor arrangements and an interface-control working group were quickly established among Hughes, General Dynamics, and Westinghouse as part of the new development effort. The F-16 program agreed to provide eight test F-16s modified to support AMRAAM capability; Westinghouse agreed to modify APG-66 Block 15 radars to support AMRAAM capability during full-scale development. Development of the ACIU continued, but, by June 1983, the AMRAAM JSPO concluded, in concurrence with the F-16 SPO and General Dynamics that it would not be available in time for full-scale-development tests. The JSPO used the existing central interface unit instead.

General Dynamics began to plan for production incorporation of AMRAAM in early 1983 and for its integrated system performance responsibility for AMRAAM later in the year. To reduce retrofit costs, General Dynamics planned to install Group A wiring provisions on new aircraft beginning at Block 25A (December 1984), although full AMRAAM capability was not expected to be available until Block 25D (October 1985). The final AMRAAM incorporation was then expected to be primarily a low-cost software insertion. By the time it was approved, the European Participating Governments had expressed an interest in a similar enhancement for their aircraft. The F-16 SPO arranged for a limited release of the common flight-control computer required to achieve that enhancement for the governments.

By early 1984, it was clear that AMRAAM would not be available when expected, leading MSIP to move production incorporation back to Block 30B (February 1987). This block became part of a larger F-16C/D reconfiguration designed to better coordinate hardware and software production incorporations. The AMRAAM full-scale development was restructured again in early 1985, delaying the end of full-scale development until April 1988, and again in early 1986, delaying the end of full-scale development to late 1988. MSIP held to its production incorporation schedule at Block 30B, incorporating the interfaces required to accept the missile whenever it became available.

With this incorporation schedule in mind, planning for the Hughes modular rail launcher, required for the AMRAAM system, continued during this period. A critical design review was held successfully in November 1984 and a production contract was issued in June 1985, with delivery of 263 launchers expected during March to October 1987. That contract proceeded smoothly, and planning was initiated for a follow-on buy. Then, in early 1987, developers concluded that weight growth in the modular rail launcher and in its center of gravity was not compatible with the F-16. To ensure compatibility, the F-16 SPO took responsibility for the necessary redesign, which was expected to delay launcher availability for 18 months. Redesign continued in late 1987. By then, a 20-month lead time, following establishment of a stable design, would be required to start production and an additional 14 months would be necessary to acquire the 900 launchers required in the fleet. By early 1988, prototypes were expected in October 1988 and initial production by May 1989. Difficulties continued as the proposed LAU-129 launcher failed several key qualification tests late in 1988. Problems appeared to be resolved by the end of the year, with initial production then expected in July 1989.

Other parts of the development went more smoothly. The first full-scale-development missile launch, in December 1984, was successful in the sense that the missile passed close enough to the target to destroy it. The first guided launch, in May 1985, was similarly successful, as was the first shot from an F-16 using a data link, in September 1985. This pattern of success continued, with each launch becoming more difficult. As tests on the F-16/AMRAAM integration neared completion in late 1987, the first dual launch from an F-16C was successful. Despite this pattern of success, problems arose in late 1988 when the system was first tested in a real, multiple-target environment.

Two more technical aspects of the development are worth noting. One concerns radio-frequency (RF) compatibility. As noted above, tests of the *airborne self-protection jammer* (ASPJ) raised the possibility of serious interference with radio frequencies important to the coordination of the APG-68 and AMRAAM systems. Efforts to achieve RF compatibility continued into 1988.

The second aspect concerns software development and the integration of software with test assets as development improved capabilities. Because software was advancing simultaneously on several fronts relevant to AMRAAM, achieving compatible software for adequate testing was a continuing problem. Especially relevant systems included the APG-68 radar—which itself experienced significant instability and growth through MSIP—the central interface unit, controls and displays, and the ASPJ and advanced interference blocker unit developed to reduce interference from ASPJ. A great deal of imagination was required to combine various generations of software for different systems and infer performance for a complete set of software. The Systems Integration Laboratory played a central role in this part of the AMRAAM integration effort.

Discussion

Eight surprises emerge from the above discussion. The first two relate to the development process used in MSIP. The other six result from technical risk.

1. Coordination of Software Development. The testing of software and, in particular, the integration of software from different subsystems presented a challenge throughout MSIP. MSIP anticipated the challenge by maintaining support for the SIL and the F-16C/D simulator. It also used a system of software blocks and block upgrades that appeared to be managed in a coherent and fairly predictable way. But the official history files are full of instances when the software-integration process did not work as well as expected, and delays and conflicts occurred because mature software from one system was not available to test another, generally causing MSIP managers to intervene to improvise a creative solution to a software-development problem. Such problems may be especially prominent for AMRAAM because its software interfaces with other systems are so important to MSIP and because, with delayed delivery of the missiles themselves, AMRAAM software integration may have received more attention than expected early in MSIP.

A related issue is the willingness to retrofit upgraded software to replace earlier versions inserted in the F-16C/D as placeholders. The direct cost of retrofitting software is apparently low enough to encourage such a solution when software matures more slowly than expected. However, measured in terms of degraded aircraft capability and the effects of development problems during the period when upgraded software is not available, the cost of this solution is much higher.

2. Limited Funding for Early ACIU Testing. MSIP managers proceeded with the ACIU development and continued to rely on it to support integration efforts, even though funding was not available to support the early tests planned for it. Much more careful analysis would be required to determine whether such tests might have identified any of the problems experienced later.

3. Slow Development of the ACIU. MSIP's quick and effective substitution of the central interface unit for the ACIU is a good illustration of a principle applied many times in MSIP: If a system fails to work as expected during a development, an effective substitute should be available to replace it. The substitute should not unduly degrade performance or complicate testing. Unlike immature software blocks substituted in a similar way for unavailable final software, this substitution does not appear to have caused serious problems in MSIP.

4. Late Delivery of AMRAAM. The first delay in the AMRAAM came at a time when information about MSIP as a whole was accumulating rapidly. That information suggested that MSIP had been somewhat overoptimistic about how quickly it could integrate subsystems into a new F-16C/D. Given this general pattern, MSIP responded reasonably by readjusting its schedule in response to the first AMRAAM delay.

5. Still Later Delivery of AMRAAM. Once MSIP decided to introduce Group A provisions for AMRAAM early and retrofit final provisions when AMRAAM was available for incorporation, the actual availability of AMRAAM assets did not impose much constraint on MSIP. The integration of other systems did not appear to suffer much from nonavailability of AMRAAM assets. Therefore, MSIP had less need to respond to much of the continuing turbulence experienced within the AMRAAM program.

6. Poorly Mated Modular Rail Launcher. Given the apparently smooth development of the AMRAAM launcher, the late discovery of inadequacies in it is a puzzle. Presumably the developers responsible for this item experienced genuine technical surprise. Continuing design instability is even more puzzling. The F-16 SPO's decision to take responsibility for the continuing design effort presumably promoted integration. Perhaps this redesign effort did not receive higher priority because later delivery of the AMRAAM missiles meant that a delay in incorporating launchers would have little effect on operational capability.

7. Operational Problems in a Complex Target Environment. The official historical files register one successful test firing after another through MSIP. They provide no basis for anticipating any trouble later in the program. Some observers have suggested that early tests were so carefully controlled that they did not provide realistic data on the likely performance of AMRAAM when it was fielded. This point deserves more detailed examination.

8. RF Incompatibility with ASPJ. AMRAAM experienced problems with ASPJ similar to those discussed in the history of the AN/APG-68 fire-control radar. The emphasis for AMRAAM is more on incompatibility and less on a shortage of ASPJ assets available for testing, but all issues are the same.

LOW-ALTITUDE NAVIGATION TARGETING INFRARED FOR NIGHT (LANTIRN)

Description

This system consists of two pods attached to the exterior of the F-16 and a head-up display (HUD); we cover the HUD below and focus on the pods here. The navigation pod uses a wide-field-of-view forward-looking infrared (FLIR) sensor to create a "night window" on the terrain below that the pilot can view through the HUD. It also includes terrain-following radar that supports low-level flight. The target pod includes a stabilized wide- and narrow-field-of-view targeting FLIR that, again, provides a display that the pilot can view on his HUD, a laser/designator for "painting" targets so that laser-guided munitions can attack them, and an electronic hand-off unit for coordination with Maverick missiles. The pods can be used together or separately. Used together, they enable an attack aircraft to use a safe, survivable, low-level penetration route to approach and exit a target area and acquire, track, and destroy ground targets in that area with guided or nonguided munitions, day or night. The prime contractor is Martin Marietta.[5]

History

The Air Force began studying tactical applications of FLIR-based systems like LANTIRN in restricted "black" programs in the 1970s. Those efforts yielded a formal "white" LANTIRN program in December 1979, just as the F-16 MSIP was beginning. The new LANTIRN program, overseen by the LANTIRN SPO, was designed to support single-seat combat aircraft, the A-10 and the F-16. LANTIRN was expected to increase a single pilot's ability to perform complex flying, targeting, and weapon-delivery tasks simultaneously in a hostile environment. Early on, the F-16 was chosen as the test platform for the LANTIRN, allowing integration efforts to begin early as the pods were fitted to test F-16 aircraft and integrated with pre-MSIP generations of avionics and software in that aircraft. Technical difficulties in the LANTIRN program led to substantial reductions in the capability of the targeting pod and to delays in the delivery of both pods to MSIP. First production of the navigation and targeting pods finally occurred in March 1987 and July 1988, respectively.[6]

The initial Air Force view of a FLIR-based system on an F-16, from December 1979, placed a single 500-pound pod on the right side of the F-16 engine inlet and interfaced this unit with a wide-angle raster HUD and an IIR Maverick air-to-ground missile system. The pod would provide automatic target recognition, correlation, and launch capability. Both General Dynamics and the F-16 SPO played important roles in defining this concept and, in particular, in defining how the system would integrate with an F-16. The request for proposal for LANTIRN full-scale development grew out of this work. Martin Marietta ultimately won the full-scale-development contract in September 1980.

MSIP's serious interest in integrating LANTIRN was expressed in the first official contract change proposal of MSIP, CCP 9101, in February 1981, which put General Dynamics on contract to integrate LANTIRN. General Dynamics became chairman of the LANTIRN interface-control working group, which also included Martin Marietta, Hughes, and Fairchild Republic and met regularly with the LANTIRN, A-10, and F-16 SPOs. Interface-control documents for the F-16/LANTIRN pods and HUD were completed by July

[5]Blake, 1987, p. 974; General Dynamics, 1990, pp. 53–58.
[6]For more details on this program, see Bodilly, 1993b.

1981. In late 1983, General Dynamics assumed integrated-system performance responsibility for LANTIRN.

During the LANTIRN full-scale development, MSIP provided a dedicated F-16A for testing. Flight tests also provided data for the F-16 flight manual. General Dynamics provided access, under contract, to its Systems Integration Laboratory (SIL), where LANTIRN pods were tested and prepared for flight test. Conflicts among the LANTIRN, APG-68, and General Dynamics core avionics over access to the SIL during this period were resolved in favor of the LANTIRN program, to keep it on schedule for its flight tests. Immature aircraft software hampered these activities.

LANTIRN would play an integral role in giving the F-16 terrain-avoidance and terrain-following capabilities. Planning for an advanced terrain-avoidance (ATA) system in May 1983 led to full-scale development that was closely coordinated with LANTIRN development. Similar coordination with the development of the digital flight control system (DFLCS) and combined altitude radar altimeter (CARA) was similarly important to this effort. The F-16 SPO reorganization in 1983, which divided MSIP activities between two SPO directorates, YPD and YPR, placed these activities in different offices until ATA and DFLCS were considered mature enough, in April 1984, to join LANTIRN activities in YPD. Efforts to integrate these capabilities continued through 1988. Difficulties in any one of these subsystems could slow the integration of all. MSIP developers repeatedly developed work-arounds to keep integration efforts on schedule. General Dynamics' simulation of the F-16C/D also played an important role in promoting integration among these systems.

The close relationship of the LANTIRN and MSIP developments was exemplified by the decision in September 1985 to combine the LANTIRN and F-16 combined test forces (CTFs) at Edwards Air Force Base. It was also evident in early 1986, less positively, when a lack of ASPJ hardware in F-16 test aircraft and poor representation of it in the SIL slowed F-16 integration testing relevant to LANTIRN.

More generally, the integration of ASPJ and LANTIRN caused continuing difficulties; spurious radiation from ASPJ interfered with LANTIRN. As noted above, in the history of the AN/APG-68 fire-control radar, MSIP began development of an advanced interference blanking unit (AIBU) to overcome this problem. Developers also separated the LANTIRN and ASPJ antennas on the F-16 to reduce the problem. In the meantime, using only one of the LANTIRN and ASPJ systems at a time in operations provided another solution, but one that degraded performance considerably. By late 1986, the AIBU and an RF-switchable notch filter appeared capable of overcoming these problems. As development difficulties grew for the ASPJ, however, MSIP's problem became less one of eliminating RF incompatibility between ASPJ and systems like LANTIRN and more one of identifying an alternative to ASPJ and asking how compatible LANTIRN would be with it. For example, by mid-1986, the LANTIRN and F-16 SPOs had begun compatibility tests between LANTIRN and ALQ-131 electronic countermeasure pods, which the F-16 program was considering for use until ASPJ development was complete.

Problems within the LANTIRN pod developments themselves significantly delayed their delivery to General Dynamics. Because LANTIRN is so central to the operation of the Block 40 aircraft, other subsystems to be integrated with that aircraft experienced difficulties in testing when LANTIRN deliveries were delayed. MSIP implemented close management of the few LANTIRN assets available to limit the negative effects of such shortages on continuing development.

By the end of 1988, when MSIP had expected the LANTIRN pods to be ready for production incorporation, dedicated MSIP aircraft had provided extensive flight testing of the two pods. The tests verified that the navigation pod had achieved complete integration capability with Block 40 aircraft. Flight test of a production navigation pod was expected in 1989. Flight tests of the targeting pod continued, with tests of a production targeting pod expected in 1989. Contracts for full-rate production of the navigation and targeting pods were signed in November 1988 and January 1989.

Discussion

The history above raises three problems associated with shortages of test assets, two problems associated with the development process, and three associated with technical risk. We have already discussed a number of them above.

1. Conflict over Access to SIL. As noted above, excess demand existed for the SIL. MSIP managers set priorities for different users and provided access on the basis of those priorities. The importance of LANTIRN to Block 40 presumably contributed to the high priority it received for access to the SIL.

2. Nonavailability of ASPJ Assets. The nonavailability noted above affected integration of the LANTIRN system. LANTIRN integration also suffered from a poor representation of ASPJ in the SIL. Neither problem could have been anticipated without anticipating the difficulties in the ASPJ development itself. MSIP managers developed work-arounds. As it became increasingly apparent that ASPJ might not become available, MSIP began to consider LANTIRN's RF compatibility with other electronic warfare systems.

3. Nonavailability of LANTIRN Test Assets. Late production of LANTIRN pods complicated the integration of other assets. MSIP developers managed this problem by imposing close controls on access to the few LANTIRN pods available and developing work-arounds when pods were not available. Because such nonavailability had not been anticipated, no special processes were available to facilitate those management efforts.

4. Interdependencies of Terrain-Related Subsystems. The subsystems associated with terrain following and terrain avoidance, including LANTIRN, required especially close integration. It is not surprising that their integration efforts had to be closely coordinated. MSIP managers repeatedly improvised solutions to keep those efforts synchronized.

5. Immature Test Software. Interim blocks of software had effects on the integration of LANTIRN similar to those noted above for other systems. MSIP managers dealt with them in a similar manner.

6. RF Incompatibility with ASPJ. LANTIRN suffered from problems similar to those discussed above; MSIP managers dealt with them in a similar manner.

7. Late Production Delivery of LANTIRN Pods. LANTIRN pods were not actually available for production incorporation in the first Block 40 aircraft. MSIP prepared for this lack by incorporating all provisions required to accept the pods at Block 40. As pods became available, they could then be retrofitted. This approach had effects similar to those of other retrofits discussed above.

8. Limited Capability of Targeting Pod. The LANTIRN targeting pod never achieved the full capability anticipated for it. Because that problem was faced and resolved within the LANTIRN program, we have not discussed it here. Nonetheless, it is true that MSIP did not receive all the benefits that it expected in the beginning from incorporating the targeting pods into the F-16C/D. When the LANTIRN withdrew from its early performance goals and accepted a more realistic design, MSIP continued to support its incorporation. The new targeting pod would still add value to the F-16C/D design. Perhaps predictably, the LANTIRN designers left room for a module that might provide the unrealized capabilities at some future date. Incorporation of such an attenuated system, with room to allow future enhancement through a retrofit, is entirely consistent with MSIP's approach to the F-16C/D development.

HEAD-UP DISPLAY (HUD)

Description

A head-up display had become a standard part of the cockpit environment before MSIP began. MSIP envisioned an improved version of the HUD used in the F-16A/B. A HUD is essentially a window placed in front of the pilot so that, while looking through it at the scene outside the aircraft, the pilot can also read information on the status of the aircraft and potential targets, projected on the window so that he or she need not take his or her eyes off things outside the aircraft. The HUD also allows the pilot to view a FLIR-generated picture of terrain on the window to support flying at night. The prime contractor for this system, which the F-16 used in several variations, was initially Marconi Avionics, Ltd., a British company. It is now known as General Electric Company Avionics, Ltd., still a British company.[7]

History

The initial version of MSIP included provisions for a wide-angle raster (WAR) HUD in its Stage I. It would display a FLIR-generated image to the pilot to support manual low-level flight at night. This WAR HUD became known as the LANTIRN HUD as the Air Force's plans for a FLIR system coalesced into the LANTIRN program. Because the designer and manufacturer of this HUD was a foreign firm, one of the first tasks of the LANTIRN HUD interface-control working group, which included Marconi and General Dynamics, was to arrange for export licenses so that the associate contractors could exchange technical data.

By early 1981, pilot evaluations of a simulated cockpit including the LANTIRN HUD raised concerns about the "tunnel effect" of the displays, including the HUD, and about the HUD's protrusion into the pilot's ejection envelope. Follow-up tests on the Flight Dynamics Laboratory Advanced Fighter Technology Integration (AFTI) testbed confirmed those problems. MSIP maintained its support for this HUD, however, and continued its test program. By late 1982, that program was revealing significant optical design problems with the LANTIRN HUD. Both Systems Command and Tactical Air Command and pilots rated the HUD as unsuitable for production incorporation; it was not even as good as the HUD used in the F-16A/B. Because the problems were severe enough to threaten the planned July 1984 production incorporation date for the HUD, MSIP developers began looking for an alternative. They chose the wide-angle conventional (WAC) HUD used in the AFTI aircraft, a HUD with a wider angle view than the HUD used in the F-16A/B, but a narrower angle view than the LANTIRN HUD. They continued development of the LANTIRN HUD, intending to replace the WAC HUDs when the LANTIRN HUD completed development. MSIP managers expected that the development of the LANTIRN HUD would be complete in time to match the production incorporation of LANTIRN pods, then expected in 1987.

Efforts to integrate the WAC HUD, which became known as the C/D HUD, began in early 1983. This late start put the C/D HUD at a disadvantage relative to other subsystems

[7]Pretty, 1986, pp. 917–918.

scheduled for incorporation in MSIP Stage II. But the integration went smoothly. In March 1984, the C/D HUD performed well on the first flight of a test F-16 incorporating major MSIP avionics. In late 1984, however, it failed the full-scale-development reliability qualification test. To overcome this problem, General Dynamics and Marconi agreed to continue toward the production reliability qualification test rather than start the full-scale-development test over.

In the meantime, redesign and development of the LANTIRN HUD had proceeded. The F-16 and LANTIRN combined test forces at the Air Force Flight Test Center held a fly-off in August and September 1984 between the C/D and LANTIRN HUDs. On the basis of 16 flights, the pilots preferred the C/D to the LANTIRN HUD. As a result, MSIP decided to equip only LANTIRN-equipped F-16s with the LANTIRN HUDs; all other F-16s would receive C/D HUDs. Specifications that promoted commonality between the two HUDs early in their development simplified the problems of maintaining both in the inventory. Production management of the LANTIRN HUD was transferred from the LANTIRN to the F-16 SPO in June 1985 to continue promoting such commonality.

Unfortunately, the production reliability qualification test for the C/D HUD, begun in January 1985, revealed problems similar to those discovered in the earlier qualification test. MSIP managers considered incorporating the HUD as-is to maintain the schedule and retrofitting corrections. The HUD ultimately completed its qualification test in December 1985. But problems remained, prompting the managers to incorporate an incomplete system at Block 30B (February 1987) as planned and retrofit necessary corrections later. In January 1988, engineering-change proposals were accepted to correct the reliability problems in the C/D HUD and to retrofit an important missing capability.

Development of the LANTIRN HUD continued with few difficulties. In late 1986, problems developed in efforts to integrate the enhanced envelope gun sight (E^2GS) with the LANTIRN HUD. Developers prepared to drop this integration effort if necessary to maintain their schedule. MSIP tested E^2GS software in the Systems Integration Laboratory to isolate the source of these difficulties. Adjustments corrected the problem, allowing flight tests of E^2GS at Edwards. Additional problems with the glare shield for the HUD developed, but the development as a whole remained on schedule for incorporation at Block 40 in December 1988.

All these efforts aimed at placing a single HUD in each aircraft. In 1986, the Tactical Air Command and Air Force Systems Command headquarters concluded that an additional HUD should be added to F-16Ds to promote LANTIRN training. This aft-seat HUD monitor would repeat the video image seen on the primary HUD in front. In late 1987, it was added to the principal contractual vehicle for Block 40, CCP 9226, and scheduled for production incorporation at Block 40C and retrofit into Blocks 40A and 40B. Its development proceeded without difficulty. A similar requirement was added to what would become Block 50.

Discussion

The history above identifies four surprises associated with technical risk and one associated with system specification.

1. **First Rejection of the LANTIRN HUD.** Very early in MSIP, test pilots raised objections to the LANTIRN HUD. MSIP took them under advisement but continued development. Later, a different set of problems arose. MSIP would not have avoided these later problems even if it had reacted more aggressively to the earlier concerns. Its reaction to the new concerns reflected well the general MSIP approach to surprises. Given the potential that additional development work on the HUD would threaten the MSIP schedule, MSIP managers sought an interim placeholder for the HUD. They took advantage of the derivative nature of the HUD by turning to a close variation produced by the same firm. Having found a satisfactory substitute, they then set up an effective competition between the two HUDs. Because a single company designed and produced both, the competition was limited in economic terms. But this aggressive approach effectively took advantage of the flexible MSIP environment to reopen the specifications for the F-16C/D. MSIP used even more aggressive competitions elsewhere to address similar problems.

2. **A Reliability Test Failure.** When the C/D HUD failed its reliability test, MSIP again responded flexibly. It resolved to eliminate the reliability problem, but was prepared to introduce a less-than-final HUD to maintain its schedule. Such an introduction was ultimately required; future retrofits would implement full capability.

3. **Second Rejection of the LANTIRN HUD.** The competition confirmed that the LANTIRN HUD had not met the specification expected early in the program. MSIP responded with a creative change in the system specification: The F-16C/D program would now support two HUDs. MSIP undertook measures to limit the cost of that support, and it would accept HUDs less capable than those initially expected. But the program would maintain its basic schedule for Block 40.

4. **Difficulty Integrating the E²GS.** When difficulties arose, MSIP undertook aggressive development activity to resolve them. But managers were fully prepared to drop this capability if it threatened their basic schedule.

5. **Adding an Aft Seat HUD Monitor.** As with other changes in system specifications, this one proceeded smoothly. It came late, presumably because designers and

users could not fully appreciate its usefulness until they had some experience with the LANTIRN system. MSIP was well structured to allow an effective response to such learning.

GLOBAL POSITIONING SYSTEM (GPS)

Description

GPS is a space-based radio positioning, navigation, and time-transfer system composed of three basic segments. The space segment includes many satellites that continuously broadcast information that can be used to provide instantaneous and precise location. The control segment includes numerous monitor stations and ground antennas located around the world to coordinate the satellites. The user segment includes user equipment sets that derive navigation and time information from satellite-transmitted data for use on a host vehicle.[8] A Joint Program Office that included many defense and nondefense agencies managed the development; the Air Force has played the role of first among many equals in that office. The F-16 was only one of many planned host vehicles in the user segment. The F-16 program coordinated the integration of GPS user equipment into the F-16C/D. MSIP concerned itself primarily with the user-segment portion of the GPS program. Availability of satellites during MSIP, however, also affected MSIP's ability to integrate GPS fully into the F-16C/D.

By improving location data and providing it in real time, GPS was expected to support the efforts of the F-16C/D associated with LANTIRN, which allowed low-altitude flying and high-precision attack of ground targets. Testing revealed that it reduces an F-16 pilot's workload associated with night terrain following by 50 to 75 percent in a benign environment and by 90 percent in a high-threat environment.[9]

History

The relationship between the GPS and F-16 programs appeared to begin smoothly. OSD approved a development program for GPS in 1973; full-scale development began in 1979, and development testing of user equipment began in 1983. Integration with the F-16 was well under way before General Dynamics and the F-16 SPO even began to talk about MSIP. The F-16 SPO used contract-change proposals[10] outside the normal MSIP series to set up its GPS integration work. But the office in the SPO responsible for MSIP at that time, YPR, also oversaw this contract change proposal. The GPS JPO awarded Magnavox and

[8]Navstar GPS JPO, 1982; for more information on the space segment, see Webb, unpublished.
[9]Clark, n.d.
[10]CCP 5321 for the initial phase of integration, 5430 for F-16 installation design, 5535 and 5536 for integration and flight test on the F-16. CCPs added later also lie outside the normal MSIP series.

Rockwell Collins full-scale-development contracts for user equipment in late 1979; the two contractors coordinated with the F-16 SPO immediately, and TAC quickly provided F-16 aircraft for test purposes. Development testing and evaluation would end in April 1985 with a demonstration of competing user systems, which Rockwell won, clearing the way to integrate this equipment for production incorporation in Block 40 aircraft starting in December 1988.

Integration problems began in 1981. GPS funding problems led to delays in integration testing. And problems with the Kalman filter that integrated alternative sources of location data arose and persisted. The F-16 SPO continued work on integration, using insights from the work it had done to integrate the precision location strike system (PLSS). In the meantime, in early 1982, the F-16 program management directive dropped GPS from the MSIP configuration as too risky to include at that time.[11] The Air Force reinstated it later in the year, but moved its production-incorporation date back 15 months to December 1988. This change disrupted the GPS JPO's planning.

Among the many integration issues that arose, three stand out. First, in early 1982, integration agreements were revised to add software modifications that would provide bombing algorithms, moving way-point steering, self-contained airborne instrumented landing approach, and GPS backup steering. That is, the location and time data provided by GPS could support each of these functions. Those modifications effectively automated such support. Later modifications would make similar changes, effectively making applications of data from GPS part of the the GPS introduction to the F-16. Such integration appears to have proceeded without serious difficulty.

Second, in early 1984, developers found that insufficient space remained in the avionics suite to accommodate and integrate GPS, PLSS, and the Enhanced JTIDS (EJS) communications system. The Air Force set up an independent review team to assess and resolve the problem. The use of such teams was unusual during MSIP, suggesting that this issue presented especially difficult problems. The team generated two alternatives later that year. The one chosen altered the PLSS vehicle navigation system (VNS) to create an adaptive targeting data link (ATDL) that could provide data transfer capability for PLSS or JSTARS and could be integrated with the navigation capabilities of GPS. It left EJS as a stand-alone system, initiating a new effort to develop the ATDL in the PLSS SPO, under F-16 SPO oversight, and resolving the integration problem within the F-16 itself.

[11]U.S. Air Force, Headquarters, 1984, Revision 18.

This was the highest visibility problem to arise in integrating GPS with other subsystems. Other subsystem integrations explicitly highlighted in official historical documents include those between GPS and the AMRAAM, APG-68, HAVE QUICK radio, inertial navigation system, antennas, and systems associated with terrain following and avoidance.

Third, in early 1986, the F-16 SPO discovered that the GPS JPO had not been pursuing design and production of mounting racks for the GPS as they had agreed. The F-16 SPO had great difficulty getting the GPS JPO to specify mounting-rack requirements to Rockwell Collins. A critical design review was finally held in June 1987, raising a few final questions about this problem and resolving it.

GPS was ultimately successfully integrated, incorporated into Block 40, and will be retrofitted into Blocks 25, 30, and 50 aircraft. But integration testing continued beyond the December 1988 deadline for Block 40. The tests took longer than expected because the full constellation of satellites for the GPS had not been launched. Because the location accuracy that can be achieved with GPS depends on how many satellites are within line of sight of the user equipment, enough satellites were rarely available at the test site to test GPS fully. Test schedules had to be carefully arranged to take advantage of the limited constellation of satellites available for testing.

Discussion

Six surprises come up in the course of this history. The first is more a decision milestone than a problem. The next three concern problems of coordinating the F-16 and GPS programs. The last two surprises concern technical risk.

1. Rockwell Collins Wins. As the date for choosing between Rockwell Collins and Magnavox approached, the F-16 program negotiated complete contract-change proposals on the MSIP contract tailored to each of the contractors. Hence, as soon as the choice was made, the F-16 program was prepared to proceed immediately.

2. Early Instability in GPS Program. As uncertainty arose in the F-16 program about the stability of GPS, it was predictable that the F-16 program would back away. To limit the already substantial risk associated with multiple, parallel integrations, the MSIP sought to include lower risk subsystem developments in the F-16C/D configuration. As constraints on space, weight, or other dimensions forced MSIP to choose among subsystems to include in a particular configuration, the relative levels of risk associated with individual systems figured prominently in the deliberations. As MSIP approached production incorporation at Stage II, the SPO even divided its activities into those mature enough to be managed as production-oriented programs and those that should still be considered development programs. Hence, the F-16 program's reaction to instability in the GPS program is consistent with its broader attitude toward risk. What exactly tipped the balance to first exclude the GPS program and then fairly quickly readmit it is less clear. Perhaps because MSIP did not have to find a placeholder for GPS if it was not included, MSIP could handle GPS more flexibly than other risky programs.

3. Problems with Mounting Racks. Technologically, mounting racks may be the least challenging part of the GPS system; therefore, it might not be surprising if they were overlooked. Without them, however, the F-16 could not incorporate the GPS system—a fact that was probably clearer to the F-16 program than to the GPS program. Although proper integration of the racks and GPS hardware would most likely succeed if the GPS program took responsibility for these racks, the F-16 program may have been better suited to address what was essentially a system-integration issue. In any case, the problem was not resolved until the F-16 SPO acted. It apparently had to act with some conviction to resolve a problem that its managers believed had already been adequately planned for in an earlier agreement.

4. A Shortage of Satellites. The number of satellites to be included in the final constellation of the GPS program and the schedule for launching them varied over the program life. This instability resulted mainly from factors beyond the control of the GPS and F-16 programs. Therefore, these programs could not avoid uncertainty about this factor. Given the uncertainty, all the F-16 managers could do is what they did. This kind of problem again emphasizes the importance of good managers in an uncertain development environment.

5. Problems with the Kalman Filter. Such technical problems could easily be expected in an integration. They persisted for some time but do not appear to have presented any serious problems. The opportunity to draw lessons from a program, PLSS, that used a Kalman filter in a similar way illustrates a (probably unexpected) advantage of dealing with many parallel integrations.

6. Conflict in the Avionics Suite. Although we should not have expected the MSIP to predict this precise conflict, it is the type of problem one would expect in an integration program. Independent review teams were a standard part of the F-16 SPO repertoire for managing such problems. The team used in this conflict appears to have resolved the problem quickly and effectively. Standard procedures handled this surprise without difficulty. Also worth noting is MSIP's willingness to initiate a new development program as part of the solution to the problem, a program that would, if successful, change the specifications for the F-16C/D under development. Such flexibility allowed an independent team to consider a broad range of potential solutions.

ALTERNATE FIGHTER ENGINES: F100-PW-220 AND F110-GE-100

Description

Alternate Fighter Engines (AFEs) are high-performance fighter engines that became interchangeable in the F-16C/D, which is not to say that they have equivalent performance. The F110-GE-100, designed and built by General Electric, has slightly higher thrust than Pratt and Whitney's F100-PW-220, especially when paired with a modular common inlet duct (MCID) and large forward input module (FIM), both developed as part of MSIP. These modifications increase the airflow available to the F110-GE-100, thereby increasing the thrust that it can generate. But relative to the engine used in the F-16A/B, the F100-PW-200, the AFEs display significantly improved operability, safety, and supportability; significantly longer lives; and less performance loss over those lifetimes. And the two are interchangeable in the configured engine bay (CEB) developed during MSIP to accommodate them in the single-engine F-16C/D.[12]

The Propulsion SPO oversaw the development of these government-furnished systems and continued to supervise their production. It also oversaw the annual production competition that determined the splitting of the Air Force's annual buy of engines for the F-15 and F-16 between the two engines. The first annual competition was held in 1984, generating the result that all engines purchased that year for the F-16 would come from General Electric. Pratt and Whitney was more successful in later competitions, leading the F-16 SPO to integrate both designs in the F-16C/D aircraft that it was developing in MSIP.

History

Development efforts for these new engines began at just about the same time that General Dynamics and the F-16 SPO began to discuss MSIP. Both engines began as efforts to develop new derivative engines based on other engines already in the inventory. Although General Electric had been working on the engine that evolved into the F100-GE-100 for some time, the Air Force only began to fund that effort in February 1979. The effort attempted to use the F101 engine developed by General Electric for the B-1 as the basis for deriving a longer lived, more operable fighter engine that could compete with or conceivably replace the F100. In July 1979, the Air Force began to fund the development work that led to the

[12]For additional details on the development of these subsystems, see Camm, 1993.

F100-PW-220, work that sought modifications to the F100 engines used in the F-15 and F-16 to improve their operability and lifetimes.

By the end of 1980, the General Electric prototype had already executed extensive test flights on an F-16, with positive results. Early test flights for modified versions of the Pratt and Whitney F100 were more likely to take place on the two-engine F-15. Its two-engine design facilitated safe engine testing, because it could always use a standard engine in tandem with an engine to be tested. Only because the F-15 could not accommodate early versions of the General Electric engine was it tested on an F-16 as early as it was.

The F-16 SPO's serious involvement with these engines began as it became involved in preparations for the Alternate Fighter Engine competition in 1984. Its directorate of development programs, YPR, played an active role in planning the integration of both engines in the F-16 airframe at that time. The idea of designing a common engine bay to enable any F-16C/D to use either engine grew out of this integration effort. Design work that would lead to the configured engine bay (CEB) began in YPR in late 1983. The CEB was approved for incorporation of the F110-GE-100, selected for the F-16 in the February 1984 competition, shortly after the selection.[13] In June, that engine flew in an MSIP aircraft for the first time.

By the end of 1984, the F-16 SPO's test F-16XL-2 aircraft was testing the F110-GE-100 with an enlarged inlet to take advantage of its full thrust. Planning began for a modular inlet that would allow such a capability on the F-16C/D. By early 1985, the CEB had been scheduled for production incorporation at Block 30 (June 1986); an enlarged inlet had been scheduled for production incorporation in Block 30B (February 1987). By the end of the year, inlet design had evolved to a modular common inlet duct (MCID) that could optimize air flow for the engine installed at production. It was to be incorporated at Block 30D (October 1987) with a large forward inlet module (FIM) for the F100-GE-100. Work on a small FIM for the F100-PW-220 continued.

In the meantime, a preproduction F100-PW-220 flew in an F-16 for the first time in May 1985. These Pratt and Whitney engines would be incorporated for the first time at Block 30C (June 1987). The portion of the block receiving this engine then became 32C to distinguish these aircraft from those with General Electric engines.

By 1986, production of Alternate Fighter Engines was well under way. Production proceeded more slowly than expected and many quality and manufacturing problems were uncovered, attracting high-level concern at the F-16 SPO and Aeronautical Systems Division.

[13]Pratt and Whitney also won a share of the competition, but all its engines would be used in F-15s. Later buys of Pratt and Whitney engines would be used in the F-16, as well.

The F-16 SPO worked daily with the Propulsion SPO to overcome such problems. General Dynamics was forced to use extensive overtime to make the first F110-GE-100s delivered acceptable for Block 30 aircraft. By the end of 1986, however, both engine suppliers had achieved their contractually agreed-upon delivery schedules. Although problems severely complicated production of new F-16s, their effects on MSIP were limited. Late engines do not appear to have hampered other development efforts under way in MSIP.

One problem that emerged at this stage can be linked directly to an integration problem. In late 1985, test pilots began to notice a "thump" during flight, which they associated with the F110-GE-100 engine. Extensive tests, conducted jointly by the F-16 and Propulsion SPOs and their contractors, could not identify the problem; in the meantime, the flight of F-16s was carefully circumscribed to avoid thump. A process of elimination finally determined that the problem did not come from the engine per se but from the way in which the engine, inlet, and airframe were integrated. Under certain flight conditions, a shock wave formed in the inlet and manifested itself by creating a distinct thump. When this phenomenon was finally understood, developers concluded that, although disconcerting, it was not dangerous. They would continue to search for solutions, but the search no longer had the urgency assumed when pilots first reported thumps. The F100-PW-220 experienced no similar integration-related problems.

Development work continued on the MCID. Flight testing, which began in late 1987, discovered severe vibrations during high-speed maneuvers, particularly in a high angle of attack. Flight tests continued into 1988 without resolving the problem. During that period, most development interest shifted to the next generation of derivative engines, the improved performance engines, that would be incorporated at Block 50. The F-16 SPO was actively involved in planning for the design, integration, and production incorporation of these engines from the beginning of their development. That is, it became involved much earlier than it had with the Alternate Fighter Engines.

Discussion

This history reveals five surprises associated with the integration of the Alternate Fighter Engines. These surprises take on a somewhat different cast from those for other systems, perhaps because the engine-development programs entered MSIP later than those for the five subsystems described above and presented a different kind of integration problem. The first three concern new information on what subsystems would be integrated. The last two stem from technical risks.

1. The Alternate Fighter Engine Competition. The announcement of this competition presented MSIP with the prospect of having to accept either or both of two new engines that were designed with only limited MSIP input. MSIP participated actively in the preparations for the competition, but by then, the designs for both engines were fairly well defined. The nature of the competition presented MSIP with the prospect of continuing uncertainty: Each year, it might be required to integrate a different kind of engine chosen by someone else. For the competition to be effective, the F-16 SPO could exercise only limited control over source selection. MSIP's response to this persistent uncertainty was to develop the CEB, a device that would minimize the effects of uncertainty. It represented the first of a series of large steps that MSIP would take to integrate these engines as it learned more about them. The standard processes within MSIP readily provided the flexibility required to initiate and execute the CEB development effort.

2. Selection of General Electric. Once General Electric was chosen as the sole source of new engines in the first year of the competition, MSIP could begin to focus on engine integration. MSIP sought to exploit the principal advantage of the General Electric engine over its rival, its thrust, by initiating developments to increase the inlet size for those F-16C/Ds that would use the General Electric engine. To maintain commonality between the engines that might be used in the future, it used an approach that focused on a module to accommodate the General Electric engine first. Again, MSIP was well structured to admit the specification changes and execute the development efforts required to realize them. It is worth noting that, as development and learning about the integration issues associated with the new engine proceeded, MSIP was able to adjust its design and schedule without much difficulty.

3. Selection of Dual Sources. Perhaps inevitably, the time came when MSIP had to accept two separate engine designs. The CEB changes anticipated that date. When it became real, MSIP could begin to focus on introducing an inlet for the Pratt and Whitney as well. It also modified its block structure to identify separate miniblocks with General Electric and Pratt and Whitney engines. Although this last change was made primarily at the request of logistics planners concerned about the growing variety of F-16C/Ds that they would have to support, it also helped MSIP manage its affairs in the presence of separate engine designs.

4. Thump. When test pilots first noticed thump, they did not associate it with the airframe. As a result, early attempts to deal with it occurred in the engine program. Only when efforts there failed to resolve it did the possibility of an integration problem become apparent. Even then, MSIP's role in resolving the problem was limited. The Propulsion SPO ultimately reached the determination that it was not dangerous.

5. Vibration in the MCID. MSIP was much more engaged in resolving this problem, which was detected in early flight tests of an MSIP-developed subsystem. Our period of analysis, however, ends before the problem was resolved, not even allowing us to determine whether its magnitude was comparable to that of the others discussed her

SOURCES OF SURPRISES AND REACTIONS TO SURPRISES: SOME GENERAL PATTERNS

Integration of each of the six subsystems obviously has a distinct story to tell. When we look across them, however, certain patterns emerge. In particular, consider the set of 40 surprises or problems identified in this Appendix. (A *surprise* is a discrete event; it .s a specific manifestation of risk, which is the defining characteristic of a state in which bad things—surprises—can happen, but need not. Risk persists without surprises.) They reveal useful insights into the sources of risk or surprise during MSIP and the ways in which MSIP developers have reacted to surprise. Table A.1 summarizes these insights. As we examine Table A.1, keep in mind that the subsystems discussed here are representative of

Table A.1

Sources of and Reactions to Surprises in Six Integrations

Source of Surprise	Number	Developer's/Integrator's Reaction to Surprise
Technical risk	20	Add resources and time to overcome problem Incorporate partial system and retrofit upgrades Accept lower capability in subsystem Seek alternative subsystem Delay schedule Change development/integration responsibilities Add pressure and sanctions
Development program	5	Manage difficulties as they arise Use analytic aids to support development
Shortage of test assets	5	Manage shortage Attempt to relieve shortage
Specification change	4	Develop and integrate new subsystem
Milestone	4	Anticipate and develop flexibility to react Use outcome to update program

those associated with MSIP; they are not close to being a comprehensive list of those included and they do not represent a random sample.[14] Furthermore, there are many ways to identify surprises in these integrations; the method used here is unavoidably subjective. As a result, we should be cautious about making specific inferences about MSIP as a whole on the basis of this sample. With these caveats in mind, we can still garner useful insights from the instances of surprise identified above.

Technical Risk

The predominant source of risk among the six subsystems was clearly technical risk—the risk that a technical development or integration effort will not proceed exactly as expected because of problems verifying the design developed for integration. Also predominant were the number of responses to surprises associated with this risk. The primary response to a surprise appears to be a decision to continue work, but to add resources and time to the effort. Such a response need not affect expected cost or schedule for the full integration effort. MSIP development and integration planning expected such surprises, even if it could not predict where they would occur, and provided resources and time to accommodate many of those associated with technical risk.

When a schedule must slip, integrations often attempt to maintain part of the schedule by getting a partially completed integration into place in a new configuration, even if it does not allow the full capability anticipated. This partial integration measure can then be completed with a retrofit or, less likely, treated strictly as a temporary fix and replaced entirely when a fully capable subsystem becomes available. This approach is consistent with the broader MSIP view of integration and retrofit as a way to balance integration and production-incorporation costs with risk. It appears to be especially attractive when software can be upgraded and retrofitted, perhaps because software retrofit is not generally considered costly.

In many cases, the development and integration effort simply accepts lower-than-expected capability in a subsystem. As often as not, such acceptance occurs in the development program for the subsystem itself and is then carried into MSIP as the less capable system is integrated into the F-16C/D. That is not to say that MSIP plays no role in such decisions. Users of the F-16C/D and, by implication, the designer/integrators in MSIP,

[14]The surprises are not independent of one another, either. Each surprise associated with ASPJ or the SIL, for example, affects several of the subsystems reviewed here. In the analysis below, we treat each association of a surprise with an individual subsystem as a separate case for analysis, an approach that allows us to distinguish the ways in which the managers of different subsystems reacted to surprises. In other contexts, some alternative treatment might easily be preferred. Two singleton cases do not fit into any general category and are not included in Table A.1.

have been actively involved in decisions on final capability. As described above, that involvement need not be especially visible in the events.

As indicated in the table, a variety of other responses to technical risk also occurred, and, notably, few of them reflect a belief that developers or integrators were failing. The major exceptions are responses to technical difficulties in the APG-68 program, responses that occurred primarily in the subsystem development, not in its program for integration into the F-16C/D. Because the F-16 SPO was intimately involved with that development, the above discussion gave it more attention than the other individual subsystem developments. Perhaps if we looked more closely inside other subsystem developments, the use of severe management pressure and sanctions on the contractor would be more common.

For each of the various surprises, MSIP managers responded to a specific circumstance and developed a solution that served the needs of the program as a whole. For example, when a slip in the AMRAAM schedule occurred in tandem with other events that led MSIP managers to be less optimistic, they responded by slipping their own schedule. By the time that additional AMRAAM schedule slips occurred, however, they had structured MSIP as a whole so that such slips had little effect on other parts of MSIP and hence made no further adjustments in their schedule.

Such adjustments point to the importance of experienced managers. The range of technical surprises experienced in the integration of these six systems and the range of responses developed emphasizes the difficulty of developing detailed contingency plans for such surprises in a development program like MSIP. It also emphasizes the importance of having an experienced staff working in a well-structured setting to deal with such contingencies individually, as they arise.

Development Program

The next two sources of risk originate in the development process and are inherent results of the development and integration approach employed in MSIP.

The first source, "development program," concerns risks associated with concurrent integration of many subsystems. It shows that the concern expressed by MSIP managers, that pursuing many concurrent integrations would raise the level of risk for MSIP as a whole, was reasonable. In the sample presented here, the prototype subsystems used to test one another were rarely equally mature; typically, earlier versions of a set of subsystems would be used to test a new version of a particular subsystem. Such a problem is unavoidable unless the developer waits for each set of improvements in all subsystems to be complete before testing any of them. But waiting is inconsistent with the test-analyze-fix

(TAF) approach to development that emphasizes the need for continuous, iterative empirical testing to identify and resolve technical problems. MSIP chose to use a TAF approach and experienced the risks identified here as a result. Using another approach would presumably have generated its own set of problems.

The primary response to development-program-related surprises was to manage each one as well as possible on its own terms. MSIP managers repeatedly developed work-arounds to overcome inconsistencies among subsystems being tested together. They looked for opportunities to develop valid empirical results based on less mature test assets whenever possible and opportunities to use less mature test assets to make useful inferences that would expedite future empirical testing. The availability of analytic tools, especially General Dynamics' Systems Integration Laboratory and F-16C/D simulator, facilitated the coordination of differing-maturity subsystems.

The general conclusion here is, again, that, although analytic tools and contingency planning can help greatly, a concurrent integration like MSIP necessarily leaves many residual tasks that only experienced managers can handle well. The development approach in MSIP could not have succeeded without such managers.

Shortage of Test Assets

The second category of development-process-related risks, "shortage of test assets," is unavoidable in any endeavor, particularly when the participants do not actually pay for the use of the assets employed. Hence, the existence of shortages per se is not evidence of a problem. But when a scarce resource must be allocated among competing uses, decisions must be made on a continuing basis. In MSIP, shortages of many test assets were not easy to predict, creating surprises that had to be managed like any other source of risk.

Various test assets were important to MSIP, but particularly the SIL and test aircraft used as platforms for individual subsystem developments and the integration of subsystems in MSIP. Because they served many individual development programs, access to them had to be allocated among users. Although the general availability of the two assets could typically be planned with little difficulty, individual demands on them were more problematic. Demands changed as surprises in individual programs affected the programs' readiness to use these common assets and the nature of tests that they wanted to conduct on them. Changes in individual programs affected aggregate demand on the common assets and activities required to customize the common assets for use in specific tests.

Perhaps less obvious as test assets are the subsystem prototypes developed as part of MSIP and its associated subsystem developments. They were required to create the test environment for other subsystems to be integrated with them. Both the availability of such prototypes and the pattern of demand placed on them were uncertain during MSIP. Managers continuously updated specific test schedules to accommodate changes on both sides of such a matchup. They also developed work-arounds to prevent the test program from bogging down when specific test assets were simply not available.

Less obvious still is a test asset like the constellation of GPS satellites, which was required to allow final testing in the GPS development and integration efforts, but was well beyond the control of anyone in MSIP.

In the subsystems studied here, MSIP managers typically responded to these sorts of shortages by managing them, allocating access to common resources and rescheduling the use of other test assets to match the changing circumstances in MSIP. They also fought to expand the availability of test assets, particularly test aircraft on loan from the Tactical Air Command. We cannot assess whether the level of test assets actually made available to MSIP has been the right one. But significantly expanding the availability of assets was usually not an option; management of available assets in the face of uncertainty was the key risk management problem here.

Specification Change

In each case of the next source of risk shown in Table A.1, "specification change," an external agency mandated a change in the specifications for the F-16C/D. In one APG-68 case, the MSIP managers made a counterproposal, which was ultimately accepted. But in all cases, these directives to change specifications initiated an orderly process that created an integration plan, drew up a contractual vehicle, altered organizational relationships as necessary, and implemented the integration as an integral part of MSIP. The standard MSIP structure and procedures were designed to accommodate such changes, and they appear to have proceeded without difficulty.

Milestone

The final source of risk listed in Table A.1, "milestone," is associated with a known date in the future, when MSIP managers know that new information will become available. The risk lies in uncertainty about the content of that information. Our sample does not include many examples of this "source of risk," so perhaps the consistency we observe in MSIP's response to milestones is deceptive. In this sample, MSIP managers reacted to milestones in two ways.

First, they prepared for the date by making arrangements that would facilitate continuing integration, no matter what the outcome at the milestone. In the GPS program, MSIP made contractual arrangements that would accommodate either winner of the user-equipment competition. In the engine program, MSIP began development of an interface, the configured engine bay, that could accommodate either winner of the engine competition.

Second, perhaps where such risk-reducing arrangements are not possible, they delayed their own decisions until a milestone provided new information. Only after the first engine competition revealed General Electric as the sole engine supplier did MSIP focus on tailoring the F-16C/D to the General Electric engine. Only when Pratt and Whitney also became a supplier did the MSIP consider similar arrangements for their engine.

Other Points

Perhaps most obviously missing from this list is risk associated with overall funding for MSIP. MSIP experienced severe budget cuts in 1987, but their effects do not appear in the subsystem histories offered here. Given concerns in the SPO that the budget cut would severely affect its ability to manage the test program for MSIP, that absence is surprising. Perhaps the effects of budget cuts would become more evident if we traced the histories of the subsystems beyond 1988 and, in effect, beyond Block 40. The budget cuts clearly had a major effect on Block 70, which was scaled back to become a significantly less ambitious Block 50. More generally, however, it is clear that MSIP proceeded in a favorable budget environment until 1987. Budget changes could easily provide a more important source of risk in similar analyses of other developments.

Looked at as a whole, this set of surprises emphasizes the pervasive and continuing nature of uncertainty during the MSIP. Without discounting the importance of MSIP's institutional preparations to deal with such uncertainty in its management plan, contracts, test plan, and other arrangements, MSIP could deal with all the surprises it experienced only because it had a well-established and experienced team of managers. Those managers were available to deal with individual contingencies as they arose, flexibly using the management structure that was in place to treat each contingency on its own terms.

SUMMARY

The integrations of these six subsystems illustrate many of the management principles explained in Section 5. The surprises above help document the practical application of the principles advanced in MSIP planning documents. For example, three of the six sample subsystems are derived from earlier systems. Although their derivative character did not avoid problems during integration, it helped limit the effects of problems by providing a ready context in which to seek solutions if a development did not proceed as expected.

Of the subsystems presented here, the three that required the most complex integration with other systems—the APG-68, AMRAAM, and LANTIRN—all present similar problems above: All suffered from the problem that MSIP planners had expected would introduce serious risks into the development of the F-16C/D—the concurrence of many interrelated development and integration programs, which was manifested in shortages of test assets for integrating several subsystems at once and the difficulty of obtaining mature enough subsystem prototypes to test the latest upgrades of other subsystem prototypes.

These subsystem integrations illustrate how heavily MSIP relied on incorporating subsystems with partial capabilities to maintain its schedule. In fact, MSIP had to be coordinated with a set of production contracts that required a steady rate of F-16 production. When MSIP's integration efforts failed to reach their expectations, the program still had to field a producible configuration that could fly safely. Incorporating subsystems with partial capabilities effectively put placeholders in the fleet that could be retrofitted or replaced in the future, when MSIP activities made full capabilities available.

All these subsystem integrations testify to the variety of surprises that arose in the program. MSIP expected such variety and prepared for it in two ways: It established a flexible management structure to accept surprises as they came and work with them, and it maintained an experienced management staff to improvise solutions to the problems presented by those surprises. The success of this approach is evident in the above short histories. Despite substantial turbulence in the developments of many of these systems and continuing surprises during their integrations, MSIP ultimately completed the integrations successfully and achieved its principal goals for the F-16C/D development.

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