3-10-2005

F-111 Systems Engineering Case Study

Air Force Center for Systems Engineering

G. Keith Richey

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By G. Keith Richey, PhD
SES (Ret.)

10 March 2005

Center for Systems Engineering
at the Air Force Institute of Technology (AFIT/SY)
2950 Hobson Way, Wright-Patterson AFB OH 45433-7765

PREFACE

In response to Air Force Secretary James G. Roche's charge to reinvigorate the systems engineering profession, the Air Force Institute of Technology (AFIT) undertook a broad spectrum of initiatives that included creating new and innovative instructional material. The Institute envisioned case studies on past programs as one of these new tools for teaching the principles of systems engineering.

Four case studies, the first set in a planned series, were developed with the oversight of the Subcommittee on Systems Engineering to the Air University Board of Visitors. The Subcommittee includes the following distinguished individuals:

Chairman

Dr. Alex Levis, AF/ST

Members

Brigadier General Tom Sheridan, AFSPC/DR

Dr. Daniel Stewart, AFMC/CD

Dr. George Friedman, University of Southern California

Dr. Andrew Sage, George Mason University

Dr. Elliot Axelband, University of Southern California

Dr. Dennis Buede, Innovative Decisions Inc.

Dr. Dave Evans, Aerospace Institute

Dr. Levis and the Subcommittee on Systems Engineering crafted the idea of publishing these case studies, reviewed several proposals, selected four systems as the initial cases for study, and continued to provide guidance throughout their development. The Subcommittee's leading minds in systems engineering have been a guiding force to charter, review, and approve the work of the authors. The four case studies produced in this series are the C-5 Galaxy, the F-111, the Hubble Space Telescope, and the Theater Battle Management Core System.

FOREWORD

At the direction of the Secretary of the Air Force, Dr. James G. Roche, the Air Force Institute of Technology (AFIT) established a Center for Systems Engineering (CSE) at its Wright-Patterson AFB, OH, campus in 2002. With academic oversight by a Subcommittee on Systems Engineering, chaired by Air Force Chief Scientist Dr. Alex Levis, the CSE was tasked to develop case studies focusing on the application of systems engineering principles within various aerospace programs. At a May 2003 meeting, the Subcommittee reviewed several proposals and selected the Hubble Telescope (space system), Theater Battle Management Core System (complex software development), F-111 fighter (joint program with significant involvement by the Office of the Secretary of Defense), and C-5 cargo airlifter (very large, complex aircraft). The committee drafted an initial case outline and learning objectives, and suggested the use of the Friedman-Sage Framework to guide overall analysis.

The CSE contracted for management support with Universal Technology Corporation (UTC) in July 2003. Principal investigators for the four cases included Mr. John Griffin for the C-5A, Dr. G. Keith Richey for the F-111, Mr. James Mattice for the Hubble Space Telescope, and Mr. Josh Collens from The MITRE Corporation for the Theater Battle Management Core System effort.

The Department of Defense continues to develop and acquire joint complex systems that deliver needed capabilities demanded by our warfighters. Systems engineering is the technical and technical management process that focuses explicitly on delivering and sustaining robust, high-quality, affordable products. The Air Force leadership, from the Secretary of the Air Force, to our Service Acquisition Executive, through the Commander of Air Force Materiel Command, has collectively stated the need to mature a sound systems engineering process throughout the Air Force.

These cases will support academic instruction on systems engineering within military service academies and at both civilian and military graduate schools. Plans exist for future case studies focusing on other areas. Suggestions have included various munitions programs, Joint service programs, logistics-led programs, science and technology/laboratory efforts, additional aircraft programs such as the B-2 bomber, and successful commercial systems.

As we uncovered historical facts and conducted key interviews with program managers and chief engineers, both within the government and those working for the various prime and subcontractors, we concluded that systems programs face similar challenges today. Applicable systems engineering principles and the effects of communication and the environment continue to challenge our ability to provide a balanced technical solution. We look forward to your comments on this case study and the others that follow.

MARK K. WILSON, SES

Director, Center for Systems Engineering
Air Force Institute of Technology
http://cse.afit.edu/

ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions of: Mr. James M. Phillips, Lockheed-Martin Aeronautics Company, for his assistance in the research; Mr. Robert H. Widmer, retired Vice President of Engineering at General Dynamics for his insights into F-111 development; and Mr. Frederick T. Rall, Jr., for his insights into F-111 Systems Engineering from the standpoint of the F-111 System Program Office at Wright-Patterson AFB. The author is indebted to the candor and recall of other General Dynamics engineers/managers and F-111 System Program Office Directors interviewed for this case study. Finally, credit is due to Ms. Lauren Proffit of Universal Technology Corporation for final formatting and manuscript preparation.

A special thank you and note of appreciation to our AFIT Project Leader, Lt Col John Colombi, who provided guidance to the authors, along with continuous motivation. And the time spent reviewing and discussing the cases with the UTC authors, Jim Mattice (Hubble Space Telescope) and John Griffin (C-5 Galaxy), was the true foundation for building our studies.

G. Keith Richey

EXECUTIVE SUMMARY

The application of key Systems Engineering principles to the F-111 provides a wealth of lessons learned to be used as heuristics for future development and production programs and to compare to the modern systems engineering theory and practices taught in the leading universities today. The systems engineering lessons from the F-111 program will facilitate learning by emphasizing practical applications and resulting outcomes to the current processes and tools used on today's programs. The student will understand the long-term consequences of systems engineering as implemented on the F-111 and its effect on cost, schedule, and operational effectiveness. The reader can then postulate outcomes of alternate decisions at the program/system level.

The General Dynamics (GD) F-111 is unarguably the most controversial fighter-attack aircraft ever developed. It suffered from a nearly impossible multi-role/multi-service requirement specification, and a protracted development cycle in which numerous serious technical problems had to be identified and corrected. Of the 1,726 total aircraft buy that had originally been planned in 1962, only 562 production models of seven different variants were completed when production ended in 1976.

The systems engineering process and its application to the F-111 program from 1958 to 1976 will be examined through discussion of five fundamental systems engineering learning principles that were derived from research on the F-111 program and from interviews with key F-111 government and contractor managers. Through examination of these systems engineering learning principles, the reader will gain an appreciation of the circumstances in the F-111 program that had the most influence on the outcome of the program and the government and contractor personnel who managed the F-111 systems development. For the F-111, these systems engineering learning principles are:

LP 1, Requirements Definition and Management. Ill-conceived, difficult-to-achieve requirements and attendant specifications made the F-111 system development extremely costly, risky and difficult to manage.

LP 2, Systems Architecture and Design Trade-Offs. F-111 Systems Engineering managers (both government and contractor) were not allowed to make the important tradeoffs that needed to be made in order to achieve an F-111 design that was balanced for performance, cost and mission effectiveness (including survivability) and the attendant risk and schedule impacts.

LP 3, Communications and Systems Management. The F-111 suffered from poor communications between the Air Force and Navy technical staffs, and from over-management by the Secretary of Defense and the Director, Defense Research and Engineering, and it came under intense congressional scrutiny, which restricted the System Program Office (SPO) Director from applying sound systems engineering principles.

LP 4, Validation and Verification. The F-111, like any complex weapon system development program which provides new war-fighting capability, had areas of risk or deficiency that came to light during RDT&E even though there was perceived low risk in the design. The F-111 development program introduced concurrency (overlap) between design validation/verification and production to accelerate program

schedules because there was an urgent need for the capability. However, technical problems uncovered in verification and validation led to costly retrofits and redesign of the production versions. The most notable technical problems during the F-111 development were inlet-engine compatibility, structural failures in the wing carry-through structure, and the introduction of the technically immature digital avionics system (called the Mark II) to replace the baseline analog avionics system.

LP 5, Program Management. Cancellation of the Navy F-111B in 1968, after the bi-service design was frozen in 1964 and production of the Air Force F-111A was well underway, had a lasting impact on the United States Air Force (USAF) F-111 performance and cost.

Despite the many problems, the F-111 turned out to be one of the most effective all-weather interdiction aircraft in the world (see Appendix 5). Since the interdiction mission was primary, the F-111 was deficient as a close-in air-to-air combat aircraft, although it had capability as a stand-off missile launch platform. The F-111 series of combat aircraft established the best safety record of any of the aircraft in the Century Series of fighters (F-100 to F-110) --- only 77 aircraft being lost in a million flying hours.

There was no other fighter-bomber in service with the USAF at the time which could carry out the F-111's mission of precise air strikes over long ranges. During *Desert Storm* in 1991, 67 F-111Fs of the 48th TFW operated from air bases in Saudi Arabia. Because of their ability to deliver precision-guided ordinance in all-weather conditions, they played a key role in the destruction of the Iraqi command and control structure and in the elimination of key targets in the Kuwait theatre of operations. These aircraft flew 2500 sorties, destroyed 2203 targets, including direct hits on 920 tanks, 252 artillery pieces, 245 hardened aircraft shelters, 13 runways, 113 bunkers, and 12 bridges. A total of 5500 bombs were dropped. The last USAF F-111s were retired from service in 1996. Thirty-six aircraft are still in service with the Royal Australian AF Air Combat Group stationed at RAAF Amberley.

F-111

Table of Contents

List of Figures

List of Figure (Cont'd)

List of Tables

1.0 SYSTEMS ENGINEERING PRINCIPLES

1.1 General Systems Engineering Process

1.1.1 Introduction

The Department of Defense continues to develop and acquire joint systems and to deliver needed capabilities to the warfighter. With a constant objective to improve and mature the acquisition process, it continues to pursue new and creative methodologies to purchase these technically complex systems. A sound systems engineering process, focused explicitly on delivering and sustaining robust, high-quality, affordable products that meet the needs of customers and stake holders must continue to evolve and mature. Systems engineering is the technical and technical management process that results in delivered products and systems that exhibit the best balance of cost and performance. The process must operate effectively with desired mission-level capabilities, establish system-level requirements, allocate these down to the lowest level of the design, and ensure validation and verification of performance, meeting cost and schedule constraints. The systems engineering process changes as the program progresses from one phase to the next, as do the tools and procedures. The process also changes over the decades, maturing, expanding, growing, and evolving from the base established during the conduct of past programs. Systems engineering has a long history. Examples can be found demonstrating a systemic application of effective engineering and engineering management, as well as poorly applied, but well defined processes. Throughout the many decades during which systems engineering has emerged as a discipline, many practices, processes, heuristics, and tools have been developed, documented, and applied.

Several core lifecycle stages have surfaced as consistently and continually challenging during any system program development. First, system development must proceed from a well-developed set of requirements. Regardless of overall waterfall or evolutionary acquisition approach, the system requirements must flow down to all subsystems and lower level components. System requirements need to be stable, balanced and must properly reflect all activities in all intended environments.

Next, the system planning and analysis occur with important tradeoffs and a baseline architecture developed. These architectural artifacts can depict any legacy system modifications, introduction of new technologies and overall system-level behavior and performance. Modeling and simulation are generally employed to organize and assess alternatives at this introductory stage. System and subsystem design follows the functional architecture. Either newer object-oriented analysis and design or classic structured analysis using functional decomposition and information flows/data modeling occurs. Design proceeds logically using key design reviews, tradeoff analysis, and prototyping to reduce any high-risk technology areas.

Important to the efficient decomposition and creation of the functional and physical architectural designs are the management of interfaces and integration of subsystems. This is applied to subsystems within a system, or across large, complex systems of systems. Once a solution is planned, analyzed, designed and constructed, validation and verification take place to ensure satisfaction of requirements. Definition of test criteria, measures of effectiveness (MOEs) and measures of performance (MOPs), established as part of the requirements process well before any component/ subsystem assembly, takes place.

There are several excellent representations of the systems engineering process presented in the literature. These depictions present the current state of the art in the maturity and evolution of the systems engineering process. One can find systems engineering process definitions, guides and handbooks from the International Council on Systems Engineering (INCOSE), European Industrial Association (EIA), Institute of Electrical and Electronics Engineers (IEEE), and various Department of Defense (DoD) agencies and organizations. They show the process as it should be applied by today's experienced practitioner. One of these processes, long used by the Defense Acquisition University (DAU), is depicted by Figure 1-1. It should be noted that this model is not accomplished in a single pass. Alternatively, it is an iterative and nested process that gets repeated at low and lower levels of definition and design.

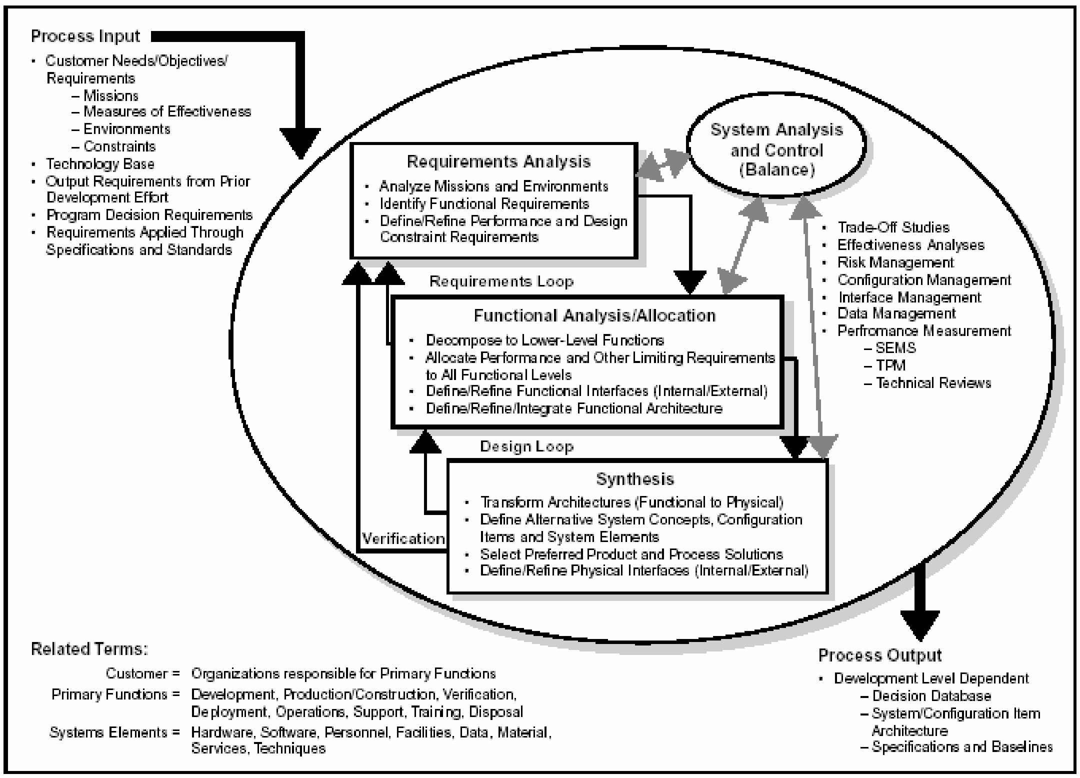

Figure 1-1. The Systems Engineering Process as Presented by the Defense Acquisition University

1.1.2 Evolving Systems Engineering Process

The DAU model, like all others, has been documented in the last two decades, and has expanded and developed to reflect a changing environment. Systems are becoming increasingly complex internally and more interconnected externally. The process used to develop the aircraft and systems of the past was a process effective at the time. It served the needs of the practitioners and resulted in many successful systems in our inventory. Notwithstanding, the cost and schedule performance of the past programs are fraught with examples of some well-managed programs and ones with less stellar execution. As the nation entered the 1980s and 1990s, large DoD and commercial acquisitions were overrunning costs and behind schedule. The aerospace industry and its organizations were becoming larger and were more geographically and culturally distributed. The systems engineering process, as applied within the confines of a single system and a single company, is no longer the norm.

Today, many factors overshadow new acquisition, including system-of-systems (SoS) context, network centric warfare and operations, and the rapid growth in information technology. These factors have driven a new form of emergent systems engineering, which focuses on certain aspects of our current process. One of these increased areas of focus resides in the architectural definitions used during system analysis. This process will be differentiated by greater reliance on reusable, architectural views describing the system context and concept of operations, interoperability, information and data flows and network service-oriented characteristics. The DoD has recently made these architectural products, described in the DoD Architectural Framework (DoDAF), mandatory to enforce this new architecture-driven systems engineering process throughout the acquisition lifecycle.

1.1.3 Case Studies

The systems engineering process to be used in today's complex system-of-systems projects is a process matured and founded on the principles of systems developed in the past. The examples of systems engineering used on other programs, both past and present, provide a wealth of lessons to be used in applying and understanding today's process. It was this thinking that led to the construction of the four case studies released in this series.

The purpose of developing detailed case studies is to support the teaching of systems engineering principles. They will facilitate learning by emphasizing to the student the long-term consequences of the systems engineering and programmatic decisions on program success. The systems engineering case studies will assist in discussion of both successful and unsuccessful methodologies, processes, principles, tools, and decision material to assess the outcome of alternatives at the program/system level. In addition, the importance of using skills from multiple professions and engineering disciplines and collecting, assessing, and integrating varied functional data will be emphasized. When they are taken together, the student is provided real-world, detailed examples of how the process attempts to balance cost, schedule and performance.

The utilization and mis-utilization of systems engineering learning principles will be highlighted, with special emphasis on the conditions that foster and impede good systems engineering practice. Case studies should be used to illustrate both good and bad examples of acquisition management and learning principles, to include whether:

- Every system provides a balanced and optimized product to a customer
- Effective Requirements analysis was applied
- Consistent and rigorous application of systems engineering Management standards was applied
- Effective Test planning was accomplished
- There were effective major Technical program reviews
- Continuous Risk assessments and management was implemented
- There were reliable Cost estimates and policies
- They used disciplined application of Configuration Management
- A well defined System boundary was defined
- They used disciplined methodologies for complex systems
- Problem solving incorporated understanding of the System within bigger environment (customer's customer)

The systems engineering process transforms an operational need into a set of system elements. These system elements are allocated and translated by the systems engineering process into detailed requirements. The systems engineering process, from the identification of the need to the development and utilization of the product, must continuously integrate and balance the requirements, cost, and schedule to provide an operationally effective system throughout its life cycle. Case studies should also highlight the various interfaces and communications to achieve this optimization, which include:

- The program manager/systems engineering interface essential between the operational user and developer (acquirer) to translate the needs into the performance requirements for the system and subsystems.
- The government/contractor interface essential for the practice of systems engineering to translate and allocate the performance requirements into detailed requirements.
- The developer (acquirer)/User interface within the project, essential for the systems engineering practice of integration and balance.

The systems engineering process must manage risk, both known and unknown, as well as both internal and external. This objective will specifically capture those external factors and the impact of these uncontrollable influences, such as actions of Congress, changes in funding, new instructions/policies, changing stakeholders or user requirements or contractor and government staffing levels.

Lastly, the systems engineering process must respond to “Mega-Trends” in the systems engineering discipline itself, as the nature of systems engineering and related practices do vary with time.

1.1.4 Framework for Analysis

The case studies will be presented in a format that follows the learning principles specifically derived for the program, but will utilize the Friedman-Sage framework to organize the assessment of the application of the systems engineering process. The framework and the derived matrix can play an important role in developing case studies in systems engineering and systems management, especially case studies that involve systems acquisition. The framework presents a nine row by three column matrix shown in Table 1-1.

Table 1-1. A Framework of Key Systems Engineering Concepts and Responsibilities

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management			
B. Systems Architecting and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			

Six of the nine concept domain areas in Table 1-1 represent phases in the systems engineering lifecycle:

A. Requirements Definition and Management

B. Systems Architecting and Conceptual Design

C. Detailed System and Subsystem Design and Implementation

D. Systems and Interface Integration

E. Validation and Verification

F. System Deployment and Post Deployment

Three of the nine concept areas represent necessary process and systems management support:

G. Life Cycle Support

H. Risk management

I. System and Program Management

While other concepts could be have been identified, the Framework suggests these nine are the most relevant to systems engineering in that they cover the essential life cycle processes in systems acquisition and the systems management support in the conduct of the process. Most other concept areas that were identified during the development of the matrix appear to be subsets of one of these. The three columns of this two-dimensional framework represent the responsibilities and perspectives of government and contractor, and the shared responsibilities between the government and the contractor.

The important feature of the Friedman-Sage framework is the matrix. The systems engineering case studies published by AFIT employ the Friedman-Sage construct and matrix as the baseline assessment tools to evaluate the conduct of the systems engineering process for the topic program. The Friedman Sage matrix is not a unique systems engineering applications tool per se, but rather a disciplined approach to evaluate the systems engineering process, tools, and procedures as applied to a program.

The Friedman-Sage matrix is based on two major premises as the founding objectives:

- In teaching systems engineering, case studies can be instructive in that they relate aspects of the real world to the student to provide valuable program experience and professional practice to academic theory.

In teaching systems engineering in DoD, there has previously been a little distinction between duties and responsibilities of the government and industry activities. More often than not, the government role in systems engineering is the role as the requirements developer.

1.2 F-111 Major Learning Principles

The systems engineering process and its application to the F-111 program from 1958 to 1976 is highlighted in five fundamental systems engineering learning principles that were derived from research on the F-111 program and from interviews with key F-111 government and contractor managers. For this case study, a learning principle is a discussion of the key points relevant to the appropriate concept domain in Table 1-1. In this sense, a learning principle is really a systems engineering "lesson learned", for the F-111. Through examination of these systems engineering learning principles, the reader will gain an appreciation of the circumstances in the F-111 program that had the most influence on the outcome of the program and the government and contractor personnel who managed the F-111 systems development.

The F-111 learning principles are:

LP 1, Requirements Definition and Management. Ill-conceived, difficult-to-achieve requirements and attendant specifications made the F-111 system development extremely costly, risky and difficult to manage.

LP 2, Systems Architecture and Design Trade-Offs. F-111 Systems Engineering managers (both government and contractor) were not allowed to make the important tradeoffs that needed to be made in order to achieve an F-111 design that was balanced for performance, cost and mission effectiveness (including survivability) and the attendant risk and schedule impacts.

LP 3, Communications and Systems Management. The F-111 suffered from poor communications between the Air Force and Navy technical staffs, and from over-management by the Secretary of Defense and the Director, Defense Research and Engineering, and it came under intense congressional scrutiny, which restricted the System Program Office (SPO) Director from applying sound systems engineering principles.

LP 4, Validation and Verification. The F-111, like any complex weapon system development program which provides new war-fighting capability, had areas of risk or deficiency that came to light during RDT&E even though there was perceived low risk in the design. The F-111 development program introduced concurrency (overlap) between design validation/verification and production to accelerate program schedules because there was an urgent need for the capability. However, technical problems uncovered in verification and validation led to costly retrofits and redesign of the production versions. The most notable technical problems during the F-111 development were inlet-engine compatibility, structural failures in the wing carry-through structure, and the introduction of the technically immature digital avionics system (called the Mark II) to replace the baseline analog avionics system.

LP 5, Program Management. Cancellation of the Navy F-111B in 1968, after the bi-service design was frozen in 1964 and production of the Air Force F-111A was well underway, had a lasting impact on the United States Air Force (USAF) F-111 performance and cost.

1.2.1 Friedman- Sage Matrix

The major systems engineering principles for the F-111 are shown in Table 1-2, which is shown in the format of the Friedman- Sage Matrix [1] for Systems Engineering. The Friedman-Sage matrix is a highly effective tool to determine how the application of the systems engineering process is progressing. Use of the Friedman-Sage matrix in a system development program forces the systems engineering practitioners to critically assess their processes and determine weaknesses, risks, and strengths and take appropriate action.

Table 1-2. Friedman-Sage Matrix: Major Systems Engineering Principles from F-111 Case Study

Concept Domain	Responsibility Domain		
	1. SE Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management			LP 1 Requirements definition and management
B. Systems Architecting and Conceptual Design		LP 2 Systems architecture and design tradeoffs	
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification	LP 4 Technical problems uncovered in verification and validation		
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			LP3 Poor communications and excessive management by SECDEF and DDRE. LP5 F-111B cancellation

As noted, the three columns of this two dimensional concept framework represent the responsibility domain and perspectives of the government, contractor, and shared responsibilities. The complete systems engineering process for the F-111 program is shown in matrix form in Appendix 1 to illustrate the application of the framework and matrix for this case study. The five learning principles and the highlighted boxes of the matrix will organize the data and discussion of the body of this case study.

2.0 F-111 SYSTEM DESCRIPTION

The F-111 aircraft, the first U.S. production swing-wing flight vehicle, is a supersonic all-weather multipurpose tactical fighter bomber developed as a result of the Department of Defense plan for a single aircraft to fulfill both a Navy fleet-defense inceptor requirement and an Air Force supersonic strike aircraft requirement. The F-111 has variable-sweep wings that allow the pilot to fly from slow approach speeds to supersonic velocity at sea level and more than twice the speed of sound at higher altitudes. Wings sweep from 16 degrees (full forward- Figure 2-1) to 72.5 degrees (full aft - Figure 2-2). With wings fully extended, the F-111 can take off and land in as little as 2,000 feet, although the brakes get very hot on short landings. With wings fully swept back, it can reach supersonic speeds at high or low altitudes. The F-111 can operate from tree-top level to altitudes above 50,000 feet. Full-forward wings give the most surface area and maximum lift for short takeoff and landing. The F-111 needs no drag chute or reverse thrust to slow down after landing.

Figure 2-1. Wings Forward

Figure 2-2. Wings Swept Back

The F-111 provided many firsts among weapons systems. It was the first production aircraft with variable sweep wings that could be swept back or brought forward to increase efficiency. It also had the first terrain-following radar, allowing it to fly at night at high speeds and low altitudes, as well as the first crew escape module.

The two crew members sit side-by-side in an air-conditioned, pressurized cockpit module (Figure 2-3) that serves as an emergency escape vehicle and as a survival shelter on land or water. In emergencies, both crew members remain in the cockpit to avoid limb-flailing injuries associated with high speed ejection using a conventional ejection seat. An explosive cutting cord separates the cockpit module from the aircraft, which then descends by parachute. The ejected module includes a small portion of the wing fairing to stabilize it during aircraft separation. Airbags cushion impact and help keep the module afloat in water. The module can be released at any speed or altitude, even under water. For underwater escape, the airbags raise the module to the surface after it has been severed from the plane. Over the life of the F-111, many ejections were safely performed across the entire speed/altitude envelope of the F-111.

Figure 2-3. Escape Capsule and Test

The aircraft's wings and much of the fuselage behind the crew module contain fuel tanks. Using internal fuel only, the plane has a subsonic (Mach 0.7) ferry range –no payload - of more than 2,500 nautical miles. External fuel tanks can be carried on the pylons under the wings and jettisoned if necessary.

The F-111 can carry conventional as well as nuclear weapons. It can carry up to two bombs or additional fuel in the internal weapons bay. External ordnance includes combinations of bombs, missiles and fuel tanks on eight wing pylons (Figure 2-4). The loads nearest the fuselage on each side pivot as the wings sweep back, keeping ordnance parallel to the fuselage. The two outer pylons on each wing do not move, but can be jettisoned for high-speed flight.

Figure 2-4. Eight Wing Pylons Loaded

The avionics systems include communications, navigation, terrain following, target acquisition and attack, and suppression of enemy air defense systems. A radar bombing system is used for precise delivery of weapons on targets during night or bad weather. The PAVE TACK forward-looking infra-red seeker was introduced into F-111Fs in 1984, and greatly enhanced the ability of the F-111 to acquire, recognize, and laser-designate a target with precision (Figure 2-5). This capability was used in the night-time Libyan raid in 1986.

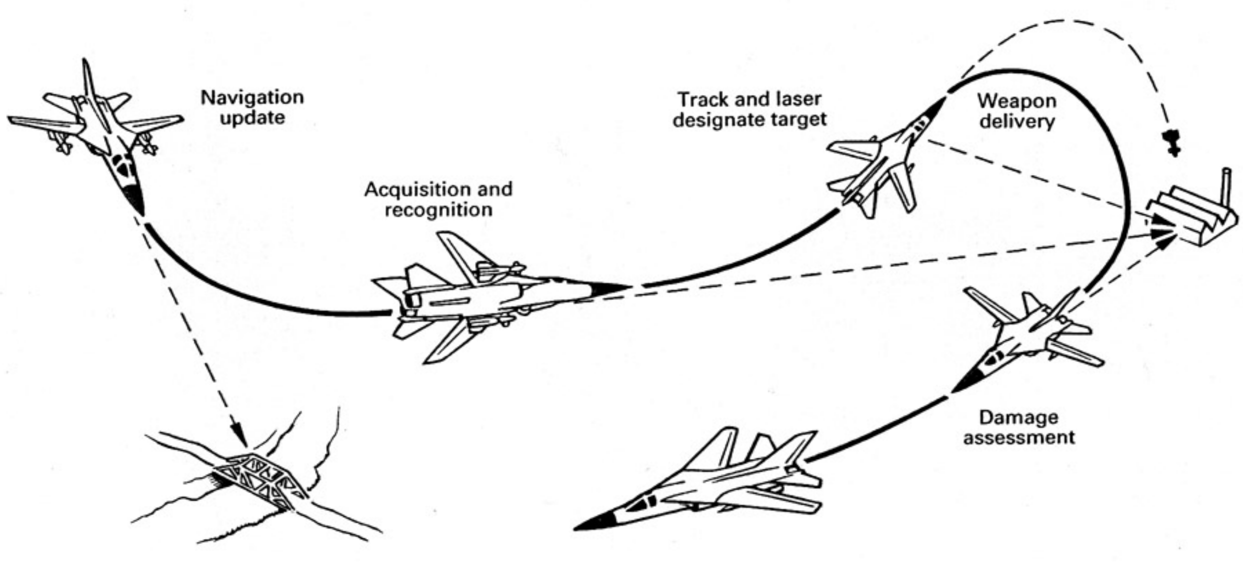

Figure 2-5. **PAVE Tack Bomb-Toss Maneuver**

The F-111's automatic terrain-following radar (TFR) system flies the craft at a constant distance above ground level, following the Earth's contours. It allows the aircraft to fly in valleys and over mountains, day or night, regardless of weather conditions. Should any of the system's circuits fail, the aircraft automatically initiates a climb. The system meets the original proposal specification and works reliably.

2.1 F-111 Characteristics

Primary Function: Multipurpose tactical fighter bomber.

Contractor: General Dynamics Corporation.

Variants: F-111A (159), EF-111A converted from F-111A (42), F-111B (7), RAAF F-111C (24), F-111D (96), F-111E (94), F-111F (106), FB-111A (76), RAAF F-111G converted from FB-111A (60). See Appendix 3 for details on variants.

Thrust: F-111A/E, Pratt &Whitney TF30 P-103 engines with 18,500 pounds thrust each with afterburners; F-111D, TF30 P-109 engines with 20,840 pounds thrust each, with afterburners; F-111F, TF30 P-100 engines with 25,000 pounds thrust each, with afterburners.

Length: 73 feet, 6 inches.

Height: 17 feet, 1 1/2 inches.

Wingspan: 63 feet full forward; 31 feet, 11 1/2 inches full aft.

Speed: F-111F -- Mach 1.2 at sea level; Mach 2.5 at 60,000 feet.

Ceiling: 50,000-plus feet.

Range: 3,565 miles (3,100 nautical miles) with external fuel tanks.

Weight: F-111F, empty 47,481 pounds.

Maximum Takeoff Weight: F-111F, 102,000 pounds

Armament: Up to six nuclear bombs on four pivoting wing pylons, and two in internal weapons bay. Wing pylons carry total external load of 25,000 pounds of bombs, rockets, missiles, or fuel tanks.

Unit cost: $18 million.

Crew: Two; pilot and weapon systems officer.

Date Deployed to USAF: October 1967.

Date retired from USAF: 1996.

3.0 F-111 SYSTEMS ENGINEERING PRINCIPLES

There were five primary systems engineering principles which adversely affected the F-111 System Development; these will be discussed in the following sections. Other systems engineering principles shown in the complete Friedman-Sage matrix (Appendix 1) were also in play to various degrees, but they had less impact on the F-111.

The chronological context of these key systems engineering learning principles is shown in Table 3-1. Some of the SE learning principles were (mostly) in play for specific time periods in the F-111 development; others were influential throughout the development program.

Table 3-1. F-111 General Chronology

Calendar Year 1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Events																	
6/58-USAF GOR 169/SDR 17						4/64 - CDR											
		6/60 -USAF SOR 183				3/64 - SWIP Design Start		5/66 - SWIP F-111A First Flight									
			2/61- SECDEF Directive for Bi-service TFX			12/64 - F-111A First Flight											
							5/65- F-111B First Flight			7/68 - F-111B Cancelled							
			11/61 - TFX RFP to Industry														
				12/62 - Contract Award to GD/Grumman				6/66 - MK II Avionics Award							F-111 D with MK -II Avionics becomes operational		
												4/70 -Four Life Fatigue Test compl					
								12/66 - F-111A Full Scale Static Struct Test start		5/68 - Full Scale Fatigue Test start		9/70 -FS Static Test compl					
											12/69- F-111A crashes due to wing pivot structural failure. (F-111A fleet grounded and no new del accepted by AF)						
												7/70 Grounding Lifted					
	F-111 Case Study Sec 3.2 - Tradeoffs																
								F-111 Case Study Sec 3.2 (MK II Avionics Tradeoffs and Development)									
			F-111 Case Study Sec 3.1- Requirements Definition														
						F-111 Case Study Sec 3.3, 3.5 Management - System and Program											
								F-111 Case Study Sec 3.4 Inlet-Engine Compatiblity Issues									
												F-111 Case Study Sec 3.4 Wing Carry- through box and pivot structures issues					
1958	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**

3.1 Learning Principle 1 - Requirements Definition and Management

Synopsis

Ill-conceived, difficult-to-achieve requirements and attendant specifications made the F-111 system development extremely costly, risky and difficult to manage.

In a sound Systems Engineering approach to a major weapon system development, the system requirements and specifications are thoroughly evaluated from effectiveness, cost, and technical risk aspects before beginning the program, and they are held constant as much as possible throughout the development program.

In the case of the F-111[1], the development of a set of specifications based on service requirements was seriously flawed. The fundamental issue was the disparate requirements for speed, altitude, range, and weight between the Air Force's requirement for a low-altitude penetrator (at Mach 1.2 Sea Level) and high altitude supersonic (Mach 2.5) fighter/interceptor, and the Navy requirement for a subsonic fleet defense missile launcher which could operate at long distances from the fleet for extended periods of time to detect and destroy enemy aircraft outside the range at which they could launch anti-ship missiles.

Background

The evolution of the F-111 systems requirements began in the late 1950s. At that time, the Tactical Air Command (TAC) of the USAF expressed a future need for a replacement for the F-100, F-101, and F-105 fighter-bombers which were currently in service. With this goal in mind, on March 27, 1958, the Air Force issued General Operational Requirement (GOR) Number 169, calling for Weapon System 649C, which was a Mach 2+, 60,000 foot altitude, all-weather fighter capable of vertical and short takeoff and landing (V/STOL). The Air Force wanted this aircraft to be ready for operational deployment by 1964.

This GOR lasted only a year. GOR 169 was cancelled on March 29, 1959, with the Air Force recognizing that a V/STOL fighter capable of such performance was simply not feasible with the technology available at that time. The Systems Engineering process of evaluating designs and technologies to satisfy potential mission requirements was used successfully by the Air Force. On February 5, 1960, the Air Force rewrote its requirements and issued System Development Requirement (SDR) No. 17, incorporating most of the provisions of GOR-169 but eliminating the VTOL requirement. It allowed the subsequent development of specific requirements for a new weapon system--WS-324A.

The general requirements of SDR-17 were brought together into Specific Operational Requirement number 183 (SOR-183[2]), issued on June 14, 1960. It called for an attack aircraft

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[1] The F-111 was known in the beginning as the Tactical Fighter Experimental or TFX; for a more complete discussion of F-111 history, see Appendix 3

[2] Air Force Specific Operational Requirement (SOR) 183, was issued by Tactical Air Command on June 14, 1960. SOR 183 called for an attack aircraft capable of achieving a Mach 2.5 performance at high altitude and a low-level dash capability of Mach 1.2. It was to have short and rough airfield performance, and was to be capable of operating out of airfields as short as 3000 feet in length. The low-level radius was to be 800 miles, including 400 miles on the deck at Mach 1.2 speeds. In addition, it was to have an un-refueled ferry range capable of crossing the Atlantic Ocean. It was to have a 1000-pound internal payload plus a lifting payload between 15,000 and 30,000 pounds.

capable of achieving a Mach 2.5 performance at high altitude and a low-level dash capability of Mach 1.2. It was to have a short and rough airfield performance, and was to be capable of operating out of airfields as short as 3000 feet in length. The low-level radius was to be 800 miles, including 400 miles "on the deck" (sea level or 200 ft above terrain) at Mach 1.2 speeds. In addition, it was to have an un-refueled ferry range capable of crossing the Atlantic Ocean. It was to have a 1000-pound internal payload plus a lifting payload between 15,000 and 30,000 pounds. Air Force analysts at ASD Development Planning Office, and independent prime contractor design studies showed that a variable sweep wing based on technology developed at the NASA Langley Research Center, and an afterburning turbofan engine, would be needed to satisfy these diverse Air Force mission requirements.

At the same time, the Navy had a requirement for a two-seat carrier-based fleet air defense (FAD) fighter that would replace the McDonnell F-4 Phantom and the Vought F-8 Crusader. This aircraft was to have the ability to loiter on patrol for much longer times with substantially larger and more capable air-to-air missiles, and was to be able to meet and counter threats to the carrier group at much larger ranges.

Originally, the Navy had planned to meet this FAD requirement with the Douglas F6D-1 Missileer design (Figure 3-1). The F6D-1 was to be a subsonic aircraft that looked a lot like a scaled-up F3D Skyknight. It was to be powered by two 10,000 lb.thrust non-afterburning Pratt & Whitney TF30-P-2 turbofans, and was to carry a three-man crew (pilot, co-pilot, and weapons system operator). The Missileer was to be capable of remaining on patrol for up to six hours, tracking targets at long range using its powerful Hughes pulse-doppler track-while-scan radar and attacking threats with its six long-range Bendix XAAM-10 Eagle air-to-air missiles. The Eagle was a long-range air-to-air missile with a maximum speed of Mach 4. It was equipped with an advanced pulse-doppler active radar homer. The warhead of the Eagle could be either conventional or nuclear.

Figure 3-1. Douglas F6D-1

The F6D aircraft was considered by DOD analysts [6] to be too costly and too specialized, and was thought to be too slow to be capable of defending itself once its missiles had been launched. Consequently, the F6D and its Eagle missiles were both cancelled in December of 1960 in the waning days of the Eisenhower administration. This still left the FAD requirement unfulfilled.

The Air Force and Navy requirements for their respective fighter-attack aircraft were obviously completely different. However, on February 16, 1961 the new Secretary of Defense, Robert McNamara, directed that the Services study the development of a single aircraft that would satisfy both the requirements of the Air Force's SOR 183 mission (the low-level dash distance at Mach 1.2 was reduced from 400 NMi to 200 NMi – Figure 3-2), and the Navy requirements for the carrier-based FAD mission. In addition, McNamara wanted the aircraft to be capable of being used by the Army and the Marine Corps as a close-support aircraft. It was hoped that this strategy would reduce procurement costs substantially. The project came to be known as the Tactical Fighter Experimental or TFX for short.

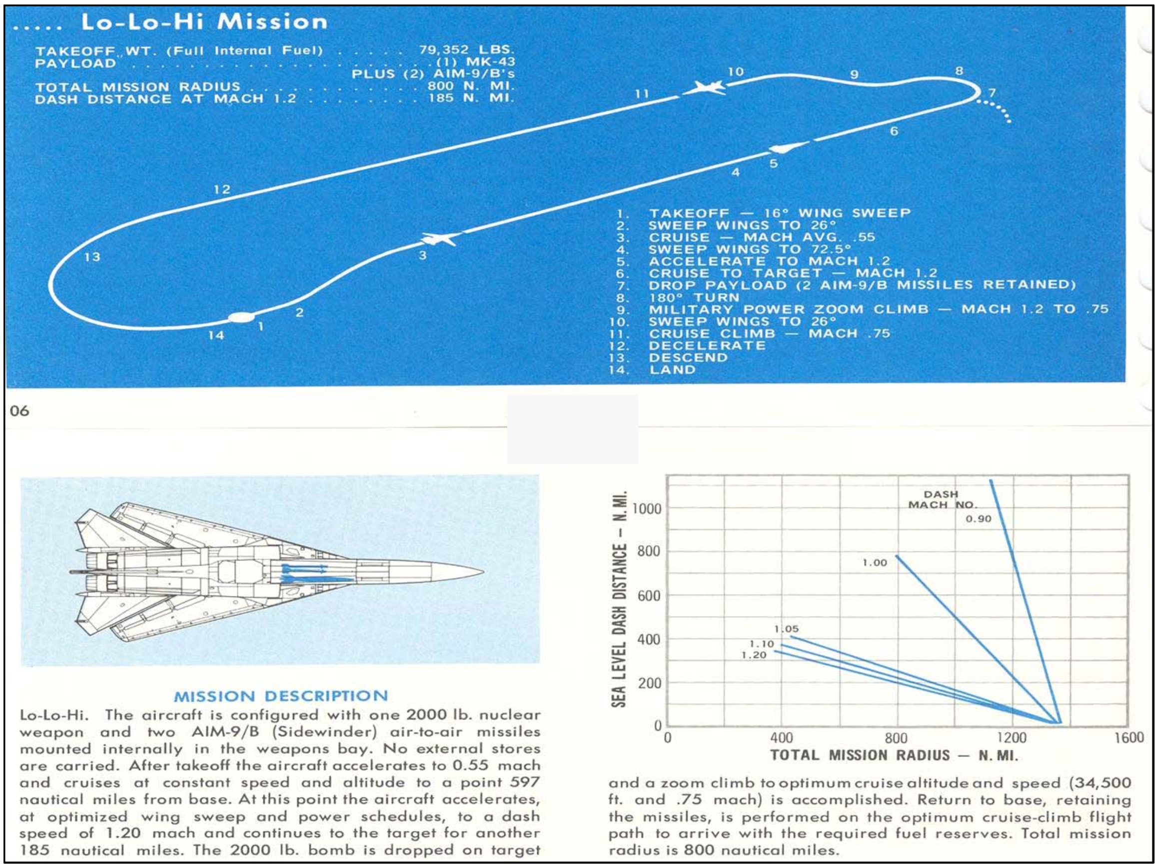

Figure 3-2. Lo-Lo-High Penetration Mission [21]

It did not take long for the services to convince Secretary McNamara that the close air support mission requirement could not be satisfied by the TFX, and the Marine Corps and the Army were dropped from the program at an early stage. However, Secretary McNamara stuck to his idea of maximum commonality between USAF and Navy versions of the TFX, and in June 1961, he instructed the Air Force and the Navy to work closely together to combine their requirements before issuing a joint RFP, although both the USAF and the Navy thought that this idea was completely unrealistic [2, 4, 6, 19].

McNamara and Director of Defense Research and Engineering Harold Brown also directed that the TFX Air Force and Navy variants (F-111A and F-111B) would be over 80% common in the airframe, engines, subsystems and avionics in order to save what DOD estimated to be a billion dollars in development cost for a joint service aircraft compared to two service-specific development programs. The commonality was to be both in terms of structural weight and parts count. However, conflicting requirements between AF and Navy missions made a "common" TFX or F-111 a nearly impossible task for the contractor and government to accomplish. The mission analysts at the Air Force and Navy were very aware of this, as was the contractor, but DDRE, SECDEF and the civilian leadership at the Service Secretary level believed that a common system would save development cost.

Both the USAF and the Navy agreed that the use of variable-geometry wings would be a good idea. However, on just almost everything else, they differed substantially. The Navy favored side-by-side seating for its FAD fighter, whereas the Air Force preferred tandem seating. The Navy wanted an aircraft equipped with a long-range search and intercept radar having a dish 48 inches in diameter, whereas the Air Force needed an aircraft equipped with a terrain-following radar optimized for low-altitude operations. The Navy wanted an aircraft that was optimized for long loiter times at medium to high altitudes at subsonic speeds, whereas the Air Force insisted on an aircraft capable of low-altitude operations and supersonic dash performance.

By August of 1961, the Secretary of the Navy reported to Defense Secretary McNamara that the compromise TFX design could not meet the Navy requirements. The Air Force mission requirements resulted in an aircraft weighing 75,000 pounds gross, while the Navy desired that the gross weight be kept below 50,000 pounds for operation on a wide variety of aircraft carriers. In addition, carrier operational requirements necessitated that the overall length be kept below 56 feet so that it could fit aboard existing carrier elevators. McNamara ordered the Navy to accept a design sized to accommodate a 36 inch radar rather than the 48 inch radar it really wanted and to accept a gross takeoff weight of 55,000 pounds [6, 19].

The design of a weapon system to meet the common performance requirements and over 80% empty weight commonality while maintaining cost, weight and schedule, was clearly shown to be exceedingly difficult in the four rounds of proposals received from industry in late 1961 through late 1962. Most of the industry, including one of the finalists, Boeing, conceded that it simply could not be done and proposed a design (see Figure 3-3) which was about 40% common based on structural (empty) weight. General Dynamics and sub-contractor Grumman proposed what they believed to be an innovative design (see Figure 3-4) that, although close to weight limits for the Navy version, could exceed the 80% commonality requirement. The Air Force and Navy military operators favored Boeing because two structurally different planes would not be compromised as much as a common design to meet disparate service performance requirements – in effect, two different airplanes, as originally desired by AF and Navy. But to SECDEF McNamara, commonality in the GD/Grumman design validated his fundamental premise that a joint-service fighter was feasible, and would be most likely to realize the cost savings inherent in the TFX joint development approach, so he unilaterally over-turned the source selection board recommendation for Boeing, and awarded the F-111 contract (RDT&E to be followed by production of Air Force F-111A and Navy F-111B) to General Dynamics and Grumman in December 1962 [2, 6, 19].

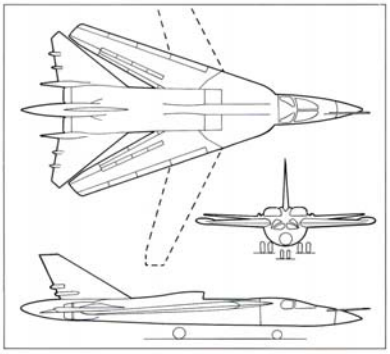

Figure 3-3. Boeing
TFX Proposal 1962

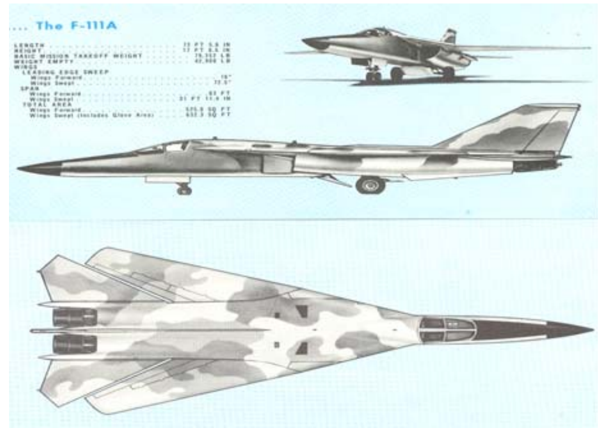

Figure 3-4. General Dynamics
TFX Proposal 1962

It is clear from the interviews [25, Rall, Widmer, Zoeckler] and reference documentation [2, 6, 19, 23] that the Air Force and Navy analysts and planners knew that the bi-service requirements would be very difficult to achieve in a "common" design, but their advice and analysis was rejected by DOD leadership, which sought to reduce development, production and operating cost through a bi-service solution.

3.2 Learning Principle 2 - Systems Architecture and Design Trade-Offs

Synopsis

Systems Engineering did not identify the important tradeoffs that needed to be made in order to achieve a design that was balanced for performance, and mission effectiveness, including survivability, and cost, risk and schedule impacts.

Systems Architecture and Conceptual Design has to identify the important design choices very early in the design process that need to be made in order to achieve a design that is balanced for performance, mission effectiveness, including survivability, and cost, risk and schedule impacts. In the case of the F-111, the "customer", Tactical Air Command, and DOD senior leadership, did not allow or accept any trade-off analysis that would result in a change to the system requirements [2, 6].

Low Altitude Dash Speed/Survivability Tradeoff

An example of a trade-off which was not permitted by the DOD leadership was the analysis of the impact of dash speed at sea level versus sea level dash distance (Figure 3-5) and the resultant impact on survivability against enemy defenses. The political climate often tied the hands of the Program Director [25].

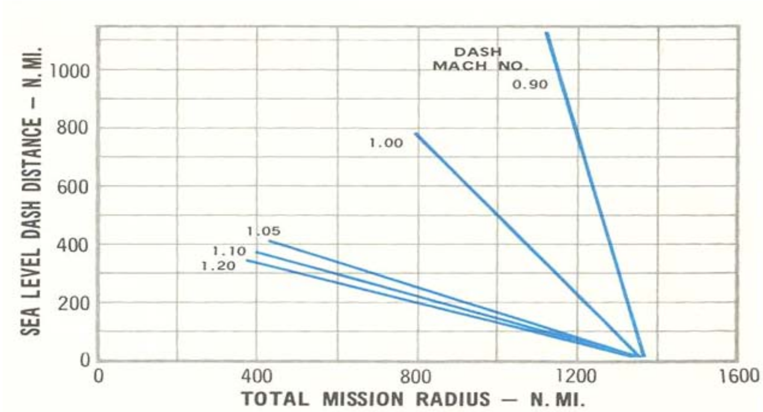

Figure 3-5. Predicted Sea Level (SL) Dash Distance at Various SL Penetration Speeds

From the F-111 systems architecting and conceptual design standpoint, the question should have been – very early in the conceptual design process- "what is the survivability benefit of Mach 1.2 versus Mach 0.7 or 0.8, or whatever Mach number is just below the 'drag rise' for the F-111 aerodynamic configuration?" The drag rise is discussed in more detail in Appendix 6. The 200 NMi dash could have been met easily if the dash Mach number was reduced to subsonic, rather than Mach 1.2 (see Figure 3-5 taken from GD TFX proposal, [21]).

This dash-range/mission-range trade off analysis was shown in the original TFX proposal by GD in 1962, but was never pursued further because the SPO believed that the Tactical Air Command absolutely required Mach 1.2 [6]. GD did not do a survivability analysis because in 1962, the threat models were not accurate enough to perform a credible analysis. Operations research analysts at Wright-Patterson [23] questioned whether the increase in survivability from enemy defenses would be significantly increased by a Mach 1.2 dash compared to Mach 0.8. The analysts concluded that the survivability increase was marginal, but the impact on aircraft weight to penetrate for 200 NMi at sea level flying at Mach 1.2 was substantial.

It was well known (in the 1950's) from aerodynamic theory and test that Mach 1.2 could be within the "transonic drag rise" which occurs when an aerodynamic body accelerates from about Mach 0.7 to about Mach 1.4. This Mach range (dependent on body cross-sectional area distribution and ratio of body length to diameter) is where the shock waves are nearly perpendicular to the surface and the resultant pressure distribution on the body creates the most drag (see Appendix 6). The cross-sectional area distribution of the F-111 was poor for transonic drag because the Navy required that the two crew members would sit side-by-side rather than in tandem. In order to maintain "at least 80% commonality between AF and Navy variants" – as required by the TFX Request for Proposal, General Dynamics designed the F-111 with the Navy cockpit arrangement. General Dynamics knew the drag at Mach 1.2 would be high but their analysis, based on data from a small scale model in the Cornell Aeronautical Lab transonic wind tunnel, indicated that the 200 NMi dash requirement could be met [19]. NASA Langley had tested an F-111 model in their larger transonic wind tunnel and the drag was indicated to be considerably higher. Using the NASA data, the 200 NMi dash would be less than 100 NMi. Eventually the NASA data was shown to be more nearly correct, and when all the flight test data was in, the predicted dash distance was only 39 NMi. In 1970, this was pointed out by the US Senate Permanent Subcommittee on Investigations of the Committee on Government Operations, (chaired by Senator John L McClellan (D) of Arkansas), as a serious deficiency [20].

In 1978, at the 67th Wright Memorial Lecture, David S Lewis, Chairman and CEO of General Dynamics said:

> *"The F-111 is truly a remarkable aircraft but unfortunately is very heavy, expensive and has poor reliability. Had more thorough tradeoffs been made at the outset, it is almost certain that a decision would have been made that a sea level dash speed of Mach 0.8 or 0.9 would have had an acceptably high probability of survival. The airplane would have been smaller, simpler and much cheaper. The USAF could have afforded many more and the effectiveness of the overall inventory would have been much higher for the dollars expended".*

High Altitude Maximum Mach Number

A system architecture and design trade-off analysis that should have been done was to determine the impact on mission effectiveness of the high altitude maximum Mach number being reduced from Mach 2.5 to about 2.0. Mach 2.5 is near the upper limit of an efficient external compression inlet design (Figure 3-6 "critical") which has simplified controls relative to a mixed compression inlet where the terminal shock is allowed to go downstream of the inlet throat (Figure 3-6 "supercritical"). External compression inlet designs ideally have the terminal shock placed just upstream of the cowl lip (Figure 3-7).

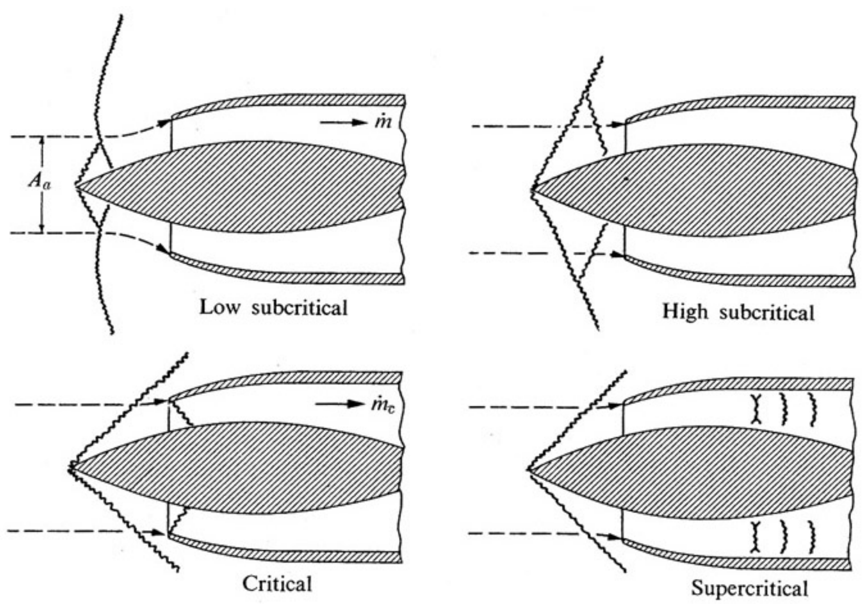

Figure 3-6. Supersonic Inlet Shock Structure

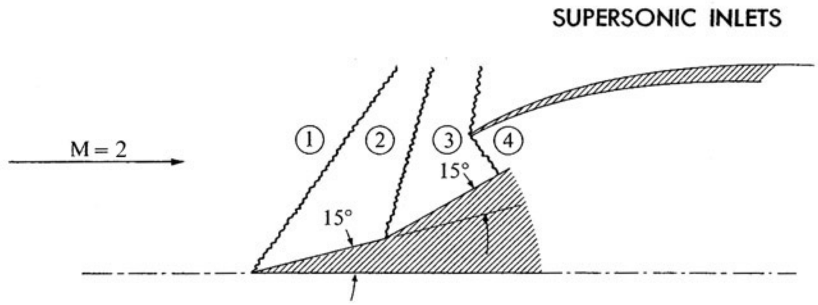

Figure 3-7. External Compression Inlet

The final shock (3/4 in Figure 3-7) is stronger for an external compression design so the inlet total pressure recovery (and therefore net engine thrust) is lower than a mixed compression design. At about Mach 2.5, these shock losses are so high that a mixed compression inlet becomes the design of choice (for example, the inlet system in the B-70). So if the conceptual design of the F-111 had been based on Mach 2.0, the external compression design chosen for the F-111 would not have been operating so close to the limit.

Several million dollars and expensive retrofits were needed to develop and install a modified inlet that had satisfactory flow distortion at Mach 2.2 with maneuvers and to Mach 2.5 without hard maneuvers, in order to avoid engine stalls (see Appendix 7).

If a tradeoff analysis had been run, which likely would have shown a small impact on mission performance by accepting Mach 2.0 instead of striving for Mach 2.5, considerable time and money would have been saved.

Mark II Avionics Systems Development and Trade-off of Mission Performance vs Reliability, Cost and Program Risk

Description

The Mark II digital avionics system for the F-111 was designed to replace the analog avionics system in the F-111As[3] and provide increased inertial navigation accuracy and

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[3] Notes on F-111 Avionics:

a) The Navigation Computer Unit (NCU) of the analog "Mark I" system was an electro-mechanical analog computer, with synchros, gears, dials, and electro-mechanical capacitor-tachometer (cap-tach) integrators. The gears and indicator dials were susceptible to mis-alignment, jamming due to dirt, etc.

b) The Stable Platform Unit (SPU) of the "Mark I" system was a traditional gimbaled inertial reference unit, and was quite large and heavy.

c) The Ballistics Computer Unit (BCU) of the "Mark I" system was, like the NCU, a box with potentiometers, gears, etc. which gave information to the NCU to allow more accurate ballistics computations for various air-to-surface "dumb" bombs.

d) The Mark-II inertial navigation system utilized a stable platform unit generally similar to that of the analog systems, but the inertial navigation computations were performed by a digital Navigation Computer Unit, not to be confused with the Mark-1 NCU, which not only performed inertial navigation but also solved weapon delivery calculations.

e) For both the Mark-II and Mark-IIB digital systems, the weapon delivery and navigational calculations were performed by a pair of IBM "4-Pi" first generation airborne digital computers with serial core memory arrays. Although two identical computers were used, they ran different software loads. One was called the General Navigation Computer (GNC) and the other was called the Weapon Delivery Computer (WDC).

f) For both the Mark-II and Mark-IIB digital systems, the communications translator or analog-to-digital converter between the GNC/WDC and the rest of the aircraft's mostly analog instruments and systems was performed by a unit called the "Converter Set". The reliability of the Converter Set was never as good as desired, and when it failed, the GNC and/or the WDC couldn't communicate with the rest of the aircraft's analog systems.

capability, increased bombing accuracy, all-weather air-to-air capability when integrated with the Sparrow air-to-air missile, and all-weather air-to-surface capability, including the ability to strike moving targets.

The major innovation in the Mark II avionics was a new radar that could eliminate ground clutter and only show the crew the "hard targets", such as buildings, bridges, roads and railways. The pilot or weapon systems officer in the right-hand seat could then "fix" the radar on the hard target, and the aircraft would automatically drop the bomb at the point selected. In the full-up Mark II avionics with an advanced Autonetics doppler radar processor, a moving target, such as a tank or train, could be detected, fixed, and targeted, all in blind flight, regardless of weather or darkness [22].

The Mark II was to incorporate two new digital computers –one for navigation and the other for weapons delivery; however if one of the computers failed, the other could take over its functions, so the system was to be fully redundant. The navigation computer got its information from the cockpit or a magnetic tape for automatic mission accomplishment from takeoff to landing. Clearly, the Mark II avionics was years ahead of its time in terms of capability.

Mark II Avionics Systems Engineering

The Mark II avionics system did not originate from the Air Force in response to a stated deficiency by the user. It came from advocacy by the DOD DDRE based on assessments and analyses conducted in 1963 and 1964 by the President's Scientific Advisory Board, the Air Force Scientific Advisory Board, and DDRE assessments.

The Air Force System Program Office strongly opposed the program. It considered the analog avionics (commonly known as Mark I), specified as part of the original F-111 Work Statement, to be a reliable, highly accurate, fully sufficient system. In the view of the SPO, the proposed Mark II program threatened to increase F-111 costs and development risk, all to achieve an additional capability that the Air Force primary user, Tactical Air Command, considered unnecessary. In the B-58 program of the 1950s, General Dynamics (the F-111 prime contractor) had experienced severe difficulties with that plane's complicated avionics. During this same period, the TAC Commander at the time, General Frank F Everest, was close to some of the major Air Force system developments and was keenly aware of the avionics problems that those programs encountered. Reportedly [6], he paid great attention to the F-111's avionics specifications and was ruthless in resisting any proposals that would push the Mark I system beyond technical frontiers. Regardless, DDR&E pushed hard for the new avionics program [6]; DDR&E described the "Mark I" analog avionics system as being primarily useful for the nuclear mission and not capable of giving the F-111 the true multi-purpose capability McNamara sought in the plane. McNamara was thus easily sold on the program. DDR&E performed the Mark II source selection in June 1966

The Mark II program schedules slipped by two years, and the system itself proved to be only 15 percent as reliable as stated in the proposal. The F-111D's Mark-II radar and its displays were the big development and cost problem. The F-111D Mark-II APQ-130 fire control radar by Autonetics (and its required display panels by Norden) was a first generation digital fire control radar. The APN-189 Doppler radar was also new. The Mark II had first-generation Heads-Up Displays (HUDs) which had development problems. The trouble-plagued, Mark II equipped F-111Ds were not operational until 1973. Ultimately, the Mark II program cost four times original estimates, or approximately one billion dollars, with a unit cost installed in the F-111D of about

2.2 million dollars. Because of the expense and the delay on the Mark II avionics, a stripped-down Mark II system (called the Mark IIB), suffering only marginal performance reductions, was developed and used, starting in 1972, for the F-111Fs (and, with further modifications, for the FB-111As). The analog MARK I APQ-113 (F-111A/C/E), and analog/digital Mark IIB APQ-114 (FB-111A) and APQ-144 (F-111F) fire control radars were much simpler, and were made by a different vendor (General Electric). The Mark-IIB displays were the much simpler and less expensive Lead Computing Optical Sight (LCOS) and Optical Display Sight Set (ODSS). The Mark IIB system lacked the Mark II's ability to track moving targets on the ground, had nine percent less accuracy for weapons delivery, less air-to-air radar capability, and less sophisticated cockpit display systems compared to the Mark II; however the Mark IIB unit cost was about 1.1 million dollars. In the end, the Mark II-IIB acquisition program equipped 278 planes (the F-111Ds, F-111Fs, and FB-111s) with improved avionics.

3.3 Learning Principle 3 - Communications and Systems Management

Synopsis

The F-111 suffered from poor communications between the Air Force and Navy technical staffs, and from over-management by the Secretary of Defense and intense congressional scrutiny, which restricted the SPO Director from applying sound management principles.

Air Force and Navy Program Management Issues

The System Program Office (SPO) was led by an Air Force General Officer with a Navy Captain Deputy Director. The AF SPO director was supported by engineering staff of the Aeronautical Systems Division at Wright-Patterson AFB, Ohio, while the Navy Deputy Director was supported by engineers from the Navy Bureau of Weapons (BUWEPS) in Washington DC. It appears from interviews with AF SPO Directors and from George Spangenberg's memoirs [24] that the F-111 SPO did not operate as a joint program office where Air Force and Navy needs were balanced. The Air Force was the lead service and the Navy played a subordinate role. There was little communication between the two engineering staffs [24] and there was often open disagreement between AF and Navy engineers on key technical issues such as the aircraft empty weight [26, Widmer, Curtis, Dietz]. The main design issue with the F-111B (and to a lesser extent the F-111A) was the empty weight. The Navy projected much higher weights from the beginning than the Air Force or the contractor. The first Naval Preliminary Evaluation was held at NATC Patuxent River in October of 1965. The F-111B was seriously overweight. Takeoff weight for a fully-equipped aircraft was estimated by the Navy at nearly 78,000 pounds, well over the upper limit of 55,000 pounds required by the Navy.

The contractor had limited technical ability to take weight out of the F-111A/F-111B if commonality was to be maintained as desired by DOD. To address Navy concerns about weight, which in turn affected aircraft carrier operations (elevator weight limits, takeoff and landing speeds, wind-over-deck requirements, etc.), the contractor introduced a Super Weight Improvement Program (SWIP) in 1964, but empty weight was only reduced by about 4%.Most of the SWIP changes were incorporated into the twelfth and 545 later USAF/RAAF F-111s/FB-111s.

The Air Force monitored the weight empty but believed it would cost too much to re-design the F-111 just to reduce the empty weight; introducing new materials, such as composites or titanium, would have increased risk [20].

Over-Management by SECDEF and Congressional Scrutiny

Since McNamara unilaterally made the F-111 contract decision over the recommendation of the joint-service source selection board, he took a larger than normal personal interest in the program. He wanted to vindicate his controversial decision by having a successful program [2, 6, 7]. He also came under severe criticism from Congress [19, 20], specifically the Permanent Subcommittee on Investigations of the Committee on Government Operations, United States Senate (chaired by Senator John L McClellan (D) of Arkansas). The Air Force, Navy and contractor came under intense scrutiny in McClellan committee hearings in 1963 and again in 1970 [19, 20].

SECDEF McNamara became the ultimate "program manager" for the F-111. Although the AF was the lead service, he saw it as his responsibility to maintain jointness and hold the program to its original cost and performance objectives. McNamara sensed that the Navy was a reluctant partner. By force of his office and personality, he kept the Navy in as long as possible [6]. McNamara oversaw program details by personally meeting on Saturday morning every two weeks from August 1966 to January 1968 with DDRE, Service Secretaries and contractors. These meetings were called Project ICARUS. This political pressure had an impact on day-to-day operations of the F-111 SPO, the AF Systems Command, the Air Staff F-111 Program Manager and ASD at Wright-Patterson [25]. The mandate by McNamara to maintain a common AF/Navy system with specified cost and performance restricted the SPO from applying systems engineering trade-offs and re-directions to manage cost and schedule.

3.4 Learning Principle 4 - Validation and Verification

Synopsis

The F-111 introduced concurrency (overlap) between design validation/verification and production to accelerate program schedules because there was an urgent need for the weapon system capability; however, technical problems uncovered after the design was "frozen", and production was underway, led to costly retrofits and schedule delays.

The F-111, like any complex weapon system development program which provides new war-fighting capability, had areas of risk or deficiency that came to light during RDT&E even though there was perceived low risk in the design. Verification and validation testing of the design is meant to both verify performance and uncover unanticipated design shortfalls. Ideally, the verification and validation leads production so that if changes are necessary, there is no impact on production, and a minimal impact on program cost. However, technical problems uncovered during F-111 validation and verification led to costly retrofits and redesign of the production versions (see F-111 program schedules, Appendix 4). Unlike the transonic drag risk area, which was known before F-111 RDT&E began, there were other risk areas which came to light during RDT&E – in the case of the F-111 – after Critical Design Review and first flight. Two areas are high-lighted: inlet-engine compatibility (Appendix 7) and structural failures in the wing carry-through box (Appendix 8). A catastrophic failure in the wing pivot structure as late as 1969 caused the entire F-111 fleet to be grounded for several months, and required cold-proof testing of all models which had been built to that time and subsequent production units. Both of these risk areas required excessive resources by the contractor and the F-111 System Program Office to solve, with significant retrofits of over 200 previously-built aircraft, and a schedule impact on F-111 production and operation date.

F-111 Inlet-Engine Compatibility

During development of the F-111, there was a problem with flow incompatibility between the inlet and engine compressor of the TF-30. F-111 SPO and contractor propulsion engineers knew at the beginning of the F-111 program [25, 26] that a high level of inlet flow distortion at the inlet exit/compressor face plane could cause compressor stall. Compressor stall occurs when the compressor blades, which are like small airfoils, encounter local regions of low pressure air, which increases the lift coefficient required to maintain pressure ratio to increase to an unacceptable (compressor blade stall) level. A partial compressor stall (also called a rotating stall) can then propagate to other blades and cause the entire compressor to stall. The fuel control system senses this loss of pressure and shuts down the engine. A re-start procedure is necessary when the inlet flow distortion is reduced, usually by lowering the aircraft angle of attack or air speed.

The risk area that was not known prior to F-111 RDT&E was that high performance engines, such as the TF-30 afterburning turbofan, are sensitive to time-dependent inlet flow distortion where the inherently unsteady flow in the inlet duct can produce regions of distortion that are much higher than the time-averaged distortion that is measured by slow-acting pressure rake surveys in the duct [14]. If the higher unsteady distortion region lasts long enough for all the fan/compressor blades to pass through it once, the compressor will stall just as if the distortion were steady state. This is known as time-dependent distortion/engine incompatibility. The F-111 inlet turbulence factor T_u, which is the average unsteady pressure fluctuation at the compressor face as a fraction of the overall pressure, has a sharp increase above Mach 1.6. This is where the time-dependent distortion is becoming much higher than the time-averaged (steady-state) distortion. For additional details on time-dependent inlet distortion, see Appendix 7.

Appendix 7 traces the development of a modified F-111 inlet system from the original RDT&E prototype design (1962-1964) to a modified Triple Plow I inlet in 1967, installed on all F-111A and RAAF F-111C aircraft, and a further, more radical modification known as Triple Plow II, developed in 1968, and installed on all USAF F-111D, E, F and G models and on all but the first production FB-111 aircraft. The Triple Plow I and Triple Plow II inlets provided the F-111 with a full capability flight Mach/maneuvering envelope free of compressor stalls. Fifteen F-111Gs (modified from FB-111As) with Triple Plow II inlets and TF-30 P-7 engines were sold to Australia and delivered in 1993/1994 to keep the RAAF F-111 fleet operational to 2010. The transonic (Mach 1.2) drag was somewhat higher with Triple Plow II, but by 1967, the transonic sea level dash distance was so far reduced from the original 200 NMi specification that the SPO made the management judgment [25, Rall] that having a stall-free aircraft was desirable, even if it meant losing a few more miles of dash distance.

Wing-Box Carry Through Structure Failure

Another risk area that developed late in RDT&E, and thus had a significant impact on cost and schedule, was unexpected structural failures of the wing- box carry through structure, which carries all the loads from the variable-sweep wing. See Appendix 8 for more details on the F-111 structural issues. Figure 3-8 shows the major structural elements of the F-111A. Note the wing carry-through box (WCTB).

A full-scale F-111 static load test was begun in December 1966 and a structural fatigue test program was initiated in May 1968, with the entire structural test program lasting about six years. It should be noted that when the structural fatigue test program began, over 40 F-111As had been delivered to the Air Force, and in fact the initial deployment of F-111s to Southeast Asia had occurred in March 1968. The goal of the fatigue test was to demonstrate a 4,000 flight hour safe-life design of the full F-111 airframe and various representative components to a safety factor of 4x, or 16,000 test hours, as required by the aircraft structural integrity program specification, using a relatively severe block-type spectrum loading to duplicate flight loads including high-g maneuvering.

After less than 600 cyclic test hours, failure occurred unexpectedly in the wing carry through structure box (WCTB) (Figure 3-9) at approximately 80% simulated flight maximum load.

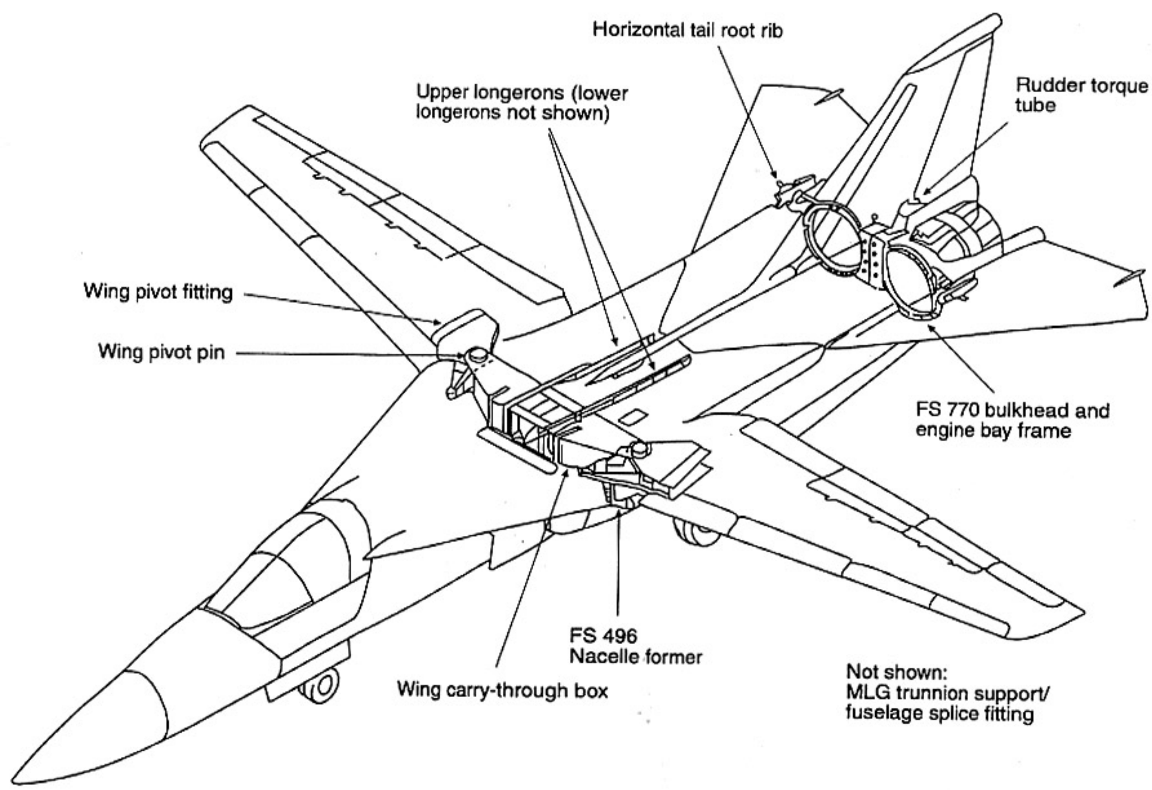

Figure 3-8. F-111A Structural Arrangement

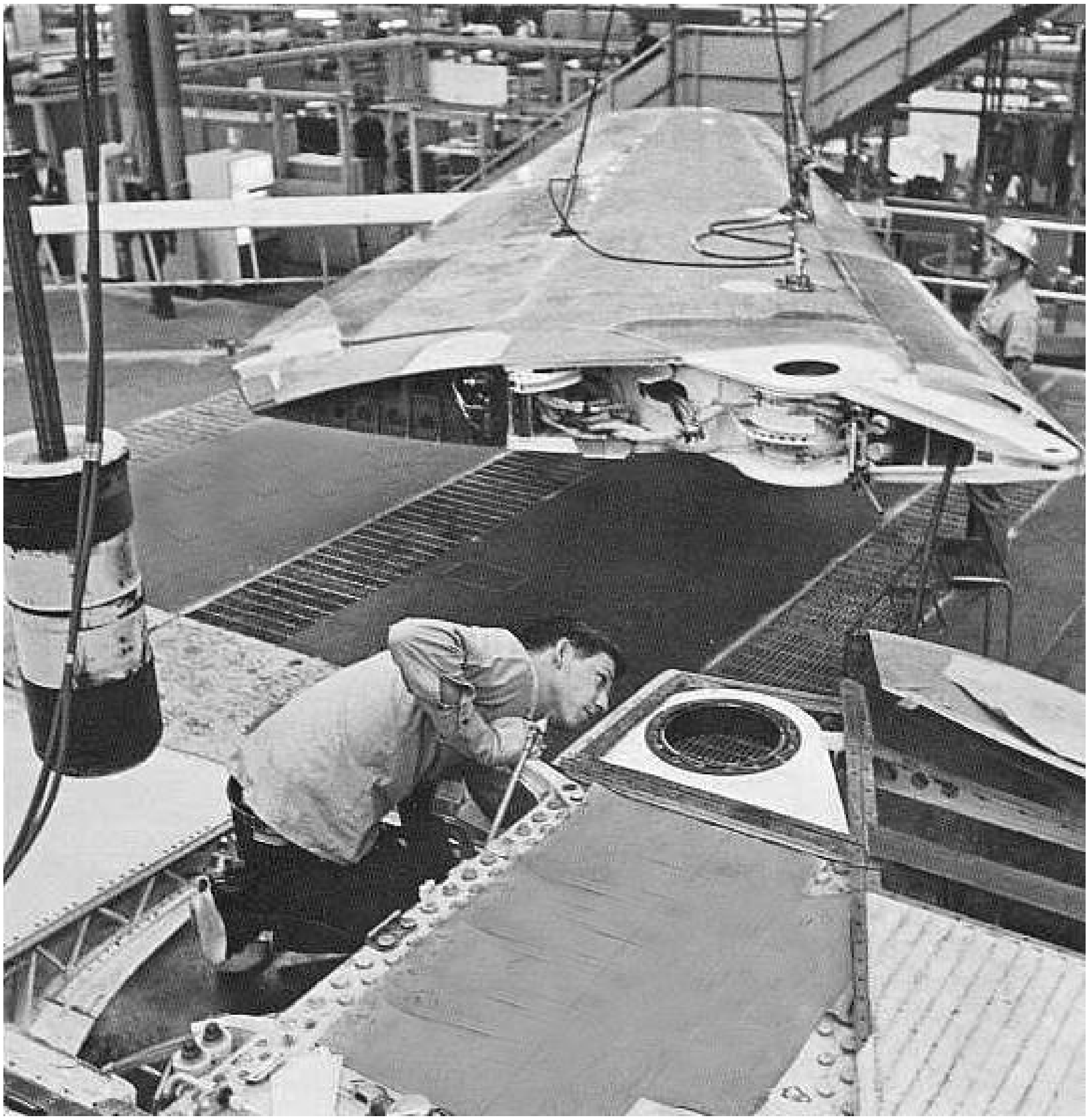

Figure 3-9. F-111A Wing Pivot and Wing Carry-Through Structure Box

This failure, which occurred in August 1968, was the initial event in a series of subsequent F-111 structural problems. A fatigue crack initiated in a "taper lok" bolt hole, and progressed rapidly through the lower rear spar and lower box cover plate – causing complete failure of the WCTB. A re-inspection of all of the approximately 200 WCTBs manufactured by that time found no bolt hole cracks; however, the quality of some holes required rework and improvement.

A second failure of the test article WCTB, which occurred in February 1969 after 2,800 test hours, originated in a 3/16 inch diameter straight -through hole in the lower plate of the box which had been used to secure a mounting bracket for hydraulic lines. Cracking was initiated by local bending effects not accounted for in the original fatigue analysis.

A new WCTB test specimen was fitted with all of the changes considered appropriate from the earlier test failures and underwent testing based on an improved fatigue analysis and a load spectrum more accurately reflecting programmed fleet usage. A failure occurred in June 1969 after 8,000 test hours of operation at the spectrum loads representing the projected TAC usage. This failure was located in the outboard closure bulkhead of the WCTB, in the return flange of the bulkhead at the rear spar. An investigation, which included a strain survey in the failure location, revealed a very high strain gradient at the front and rear spar joints with the more flexible lugs.

At 12,400 test hours in the full-scale fatigue test article, a failure occurred in the F-111 wing pivot fitting. This failure resulted in the development of a boron-epoxy-reinforced composite doubler patch modification, which was the first use of advanced composites to reduce the stress levels in metallic aircraft structures (see Appendix 8). The wing then completed the 24,000 test hours without any further significant events. This patch became a fleet fix for all F-111s.

A fourth WCTB was modified incorporating all of the changes from the previous tests and tested to a representative load spectrum. This structural configuration completed almost 20,000 test hours, equivalent to 5,000 flying hours with predicted TAC usage. This became the baseline WCTB design which was retrofit to over 200 previously-built F-111s and applied to all newly manufactured F-111s after early 1970.

Then, in December 1969, an F-111A crashed at Nellis AFB during a low level weapon delivery maneuver. Two crew members were killed. The cause of the crash was determined to be a failure in the wing pivot structure (Figure 3-10).

Figure 3-10. F-111A Wing Failure Dec 1969

This aircraft was a low-time aircraft so it was not a classical fatigue problem as was being addressed in the above-mentioned fatigue test. Since the failure was unknown at the time, the entire F-111 fleet (223 aircraft) was grounded and no new airplane deliveries were made until the problem was identified and the grounding lifted in July 1970. The problem turned out to be a manufacturing flaw buried in a forging which was not detected by the inspection techniques used.

After considerable research by experts, including the Air Force Scientific Advisory Board, the SPO implemented a cold proof load stress test in which every F-111, previously built and new, was subjected to a +7.33g and -2.4g load in specially-designed structural ground test facilities in which the entire F-111 structure was cold-soaked to -40 degrees Fahrenheit before the load was applied. See Figure 3-11.

Figure 3-11. F-111 Cold Proof Load Test

The cold proof test facilities are unique to the F-111. This type of test had never been used on any other aircraft. The theory is that any undetected flaw in the structure, including the wing pivot, would cause a failure when loaded at this cold-soak condition. If the structure passes the cold proof load test, it is cleared for the next several hundred flight hours. The Air Force tested all aircraft that had been built before December 1969 (about 200) and continued to cold-test each new F-111 (grand total of 562). Twenty-three Australian F-111Cs were produced from August 1969 to November 1969 before the wing-pivot failure and crash in December 1969, but delivery was delayed until spring 1974 until they could all be proof-tested. Virtually all the active F-111s were proof-tested at least three times, since cold proof- load testing was repeated at intervals as low as 1500 flight hours. Through this proof - load testing, numerous failures (11major) were detected and fixed; failures which could have resulted in loss of aircraft and air crews, had the failures occurred in flight. The cost of the testing was estimated at about 100 million dollars.

3.5 Learning Principle 5 - Program Management

Synopsis

Major changes in program direction made after the design is frozen at Critical Design Review (CDR) will impact system performance and cost.

The pace of the F-111 RDT&E program (two years from contract award to first flight of a production version) meant that a lot of technical issues would come out during RDT&E testing, which was concurrent with full rate production. Some re-design features were incorporated in later models of the F-111, but other changes, such as a modified wing carry-through box structure, had to be retrofit into previously-produced F-111As.

The F-111 was developed before Systems Engineering Management Plans (SEMPs) were required. However, various senior retired contractor personnel related that they were performing engineering functions which would be spelled out in a SEMP [25].

Both contractor and government engineers [25, Rall, Zoeckler] stated that they were continually doing "systems engineering" even though it was not a separately documented or funded process. The contractor was responsible for day-to-day "hands-on" engineering, which they stated was the essence of systems engineering. The government engineers had technical oversight of engineering processes and in some cases performed independent analysis and tests.

GD-retired personnel who managed the F-111 [Widmer, Curtis, Dietz- 26] said they "engineered the system" by staying on top of the issues, communicating with design engineers in the company and Air Force SPO; by paying close attention to ground and flight test results, and making cost-effective design changes and retrofits.

Cancellation of the Navy F-111B in 1968, after the bi-service design was frozen at CDR in 1964 and production of the Air Force F-111A was well underway, had a lasting impact on the USAF F-111 performance and cost.

The F-111B was the naval version of the TFX fighter project, which was to be designed in common with the Air Force version, even though the requirements were completely different. The first F-111B (Bu No 151970), Figure 3-12, was assembled at Bethpage NY from components produced by both General Dynamics and Grumman. It was powered by the same Pratt & Whitney TF30-P-1 afterburning turbofans that powered the F-111A. It was rolled out at Bethpage NY on May 11, 1965 and transported to Calverton NY. It made its first flight at Calverton on May 18 1965 (Figure 3-12). Note the shortened nose of the F-111B compared to the F-111A. This was specified by the Navy to accommodate the aircraft on a wide variety of Navy aircraft carriers. Aside from a problem with compressor stall (as already experienced by the F-111A), the first flight was trouble-free.

The F-111B was seriously overweight. Takeoff weight for a fully-equipped aircraft was estimated by the Navy at nearly 78,000 pounds, well over the upper limit of 55,000 pounds required by the Navy. The problems with the overweight F-111B were so severe that in 1964 General Dynamics and Grumman began a Super Weight Improvement Program (SWIP), but empty weight was only reduced by about 4% (about 2000 lbs). The fourth F-111B (BuNo 151973) was fitted with the F-111 escape capsule in place of the individual ejection seats that were fitted to the first three F-111Bs. However, the fitting of this capsule more than offset the modest weight reductions achieved by the SWIP, and the F-111B remained grossly overweight and therefore underpowered. Range was also below specifications and could only be increased by adding more fuel, making the aircraft even heavier.

Figure 3-12. F-111B First Flight May 1965

The Navy suggested more extensive weight reduction programs with more extensive re-design (and lower commonality between AF and Navy aircraft), but these changes were resisted by the Air Force and were not implemented by the contractor.

By October 1967, the Navy Bureau of Weapons (BUWEPS) management [24] was convinced that the F-111B would never be developed into a useful carrier aircraft and recommended that the project be terminated

The extreme difficulty of meeting all the Air Force and Navy requirements in a single design affected the F-111 throughout the RDT&E phase from 1962 to 1968. From the beginning, the F-111B aircraft was close to maximum weight and minimum thrust that the Navy could accommodate for carrier operations, and after the inevitable weight growth that an aircraft incurs as it goes from paper design to hardware, in 1968 the Navy recommended, and Congress approved, cancellation of the Navy F-111B . On July 19, 1968, a stop-work order was issued to General Dynamics, after $377 million had been spent on the program. By this time (McNamara had left office in 1968), the F-111 was in full production; the design was frozen at Critical Design Review (CDR) in 1964, and the bi-service influence on the F-111 weapon system design (e.g., side-by-side seating, escape capsule, overall length, radar dish size) could not be “backed out” without a significant cost and schedule impact which would have risked program cancellation.

4.0 SUMMARY

The General Dynamics F-111 suffered from a nearly impossible multi-role/multi-service requirement specification, and a protracted development cycle in which numerous serious technical problems had to be identified and corrected.

The "forced commonality" of the Air Force and Navy versions of the TFX, which later became the F-111A/B, drove the design in terms of shape, weight and key avionics equipment such as the size of the radar dish [2, 6, 19].

The pressurized political environment from Secretary of Defense Robert McNamara, DDRE Director Harold Brown and the McClellan congressional oversight committee prevented the F-111 System Program Office and the contractor from conducting trade-off analyses which could have relieved mission performance, cost and schedule issues.

The Navy was a reluctant partner with the Air Force from the beginning of the F-111 program. The F-111 System Program Office was led by the Air Force with the Navy in a subordinate role. Detached from the Navy Bureau of Weapons in Washington DC, the SPO tended to emphasize Air Force needs [2, 6, 19, 24]. Several of the senior F-111 managers [25, 26, Widmer, Rall] believed that the Navy and Grumman had an "agenda" to get out of the F-111 program and used the F-111B weight as an excuse to terminate it and begin the F-14 Tomcat Fighter program in the early 1970's, which used the F-111 engine and a modified variable sweep wing design.

As in any complex weapon system development program which provides new war-fighting capability, there were areas of risk or deficiency that come to light during F-111 RDT&E. However, the contractor and the government System Program Office engineers eventually found satisfactory solutions to these problems, albeit at considerable cost and schedule impact.

In the end, the F-111s used by the Tactical Air Command and FB-111 for the Strategic Air Command turned out to be one of the most effective all-weather interdiction aircraft in the world. There was no other fighter-bomber in service with the USAF at the time which could carry out the F-111's mission of long –range/ high payload precise air strikes. The F-111 served the United States Air Force well from 1967 to 1996.

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6.0 LIST OF APPENDICES

Appendix 1 - Completed Friedman Sage Matrix for F-111

Appendix 2 - Author Biography

Appendix 3 - F-111 History and Variants

Appendix 4 - Program Milestone Charts

Appendix 5 - Combat Operations

Appendix 6 - Transonic Drag

Appendix 7 - F-111 Inlet-Engine Compatibility Problem

Appendix 8 - Wing Carry Through Box Failure and Impact on Subsequent Aircraft Development

Appendix 1

Completed Friedman Sage Matrix for F-111

Table A1-1. The Friedman Sage Matrix for the F-111

	Contractor	Shared	Government
A. Requirements Def. and Management	Requirements shall flow down in a coherent and traceable manner from the top level to all lower levels of the system being engineered. **Response:** Contractor attempted to meet disparate AF and Navy requirements in the design. The proposed (paper) design met the requirements but as the system evolved, the capability for SL dash distance, ferry range, Max Mach and carrier suitability in terms of weight and wind-over-deck diminished.	Customer and contractor shall share the state of technical maturity for new, unprecedented procurements. **Response:** The state of technical maturity was not well understood by either contractor or govt in the case of inlet-engine compatibility (dynamic distortion) and structural fracture mechanics of brittle materials. Technical maturity of terrain-following radar was generally understood.	The government shall integrate the needs of its user organizations with the management activities of its developmental organizations. **Response:** It appears that the AF and Navy set their requirements separately and did not work out a set of mutually agreeable joint requirements. There is anecdotal evidence that the Navy did not want to participate in the TFX but wanted a Navy-only fleet defense aircraft. DDRE and SECDEF (Mr. McNamara) imposed arbitrary joint requirements and commonality requirements (over 80%) in order to serve both AF and Navy needs. Objective was to save development and production costs. AF changed sea level dash requirement from subsonic to Mach 1.2 without sufficient analysis as to tradeoffs between survivability and weight/drag/performance. High altitude Max Mach (2.5) was set without sufficient operational utility analysis (insufficient risk/benefit analysis).
B. Systems Architecting and Conceptual Design	The systems architecture of complex programs shall be established early in every program and shall involve all dimensions of technical issues, as well as such enterprise architecture issues as customer needs and satisfaction, political pressures and continuity of funding. A properly executed systems architecture activity provides benefits of effectiveness far in excess of its costs. **Response:** the contractor identified the systems architecture issues for the TFX (F-111) weapon system in the proposal to the best of his ability.	The systems architecture should be established early for the reasons stated above and the best judgment of both government and contractor shall be employed across all the key issues, including the choice of employing newly developed or legacy systems. **Response:** The government provided the systems architecture specifications and the contractor responded, although there were concerns expressed by Navy and AF analysts that the disparate range of system architecture requirements could be met while maintaining the required level of commonality.	A total systems architecture shall be employed by the government for the reasons stated above in order to provide a sound basis of effectiveness across the broadest spectrum of contractors and operations. **Response:** The AF wanted a replacement for the F-105 with more range and payload; the Navy wanted a fleet defense interceptor with long loiter capability at distances from the carrier battle group which exceeded the threat range. AF and Navy knew this was a difficult system architecture, but DOD imposed common system architecture requirements which emphasized commonality between service variants. The services acquiesced, sensing that individual system developments would not be allowed by SECDEF. Throughout the TFX bi-service requirements definition. AF and Navy could not agree on a common systems architecture. DDRE and SECDEF imposed the "common" systems architecture on which the proposals would be based.

Table A1-1. The Freidman Sage Matrix for the F-111 (Cont'd)

	Contractor	Shared	Government
C. System and Subsystem Detailed Design and Implementation	System design shall proceed in a logical and orderly manner through a process of functional decomposition and design traceability that originates with the system functional architecture and ultimately results in design specifications for the system to be engineered. **Response:** GD used a sound WBS which was supported by GD engineering to achieve the design specs. They maintained vigilance on impact of technology or design shortfalls, such as weight growth, on the system architecture requirements.	Government customers and contractors shall have a contractually feasible sharing of systems design responsibility. **Response:** The AF (Aeronautical Systems Division) and Navy (BUWEPS) reviewed critical aspects of the contractor design, and reviewed test data and analysis. The government engineers also conducted independent analysis and shared the results with the contractor. In general the government analysis, particularly weight analysis, was more conservative than the contractor's. The Navy predicted the weight growth early on, but their analysis was not accepted by the contractor. The government was in a technical review role, rather than sharing in system design. The contractor stated that the relationship with the AF engineers was mostly collegial, while the relationship with Navy engineers was more confrontational.	The customer shall share high level measures of effectiveness with the contractor, thereby ensuring that the proposals selected for funding are those which are most responsive to all stakeholders, especially the operational organizations. **Response:** The system measures of effectiveness were defined by the government in general terms but there is little evidence that quantitative effectiveness analysis was done in depth to support trade-off studies. The AF and Navy development engineers believed they were representing the end-item users but in 1960's there was less coordination between developers and users than there was in later systems developments. The Boeing design addressed the differences in AF and Navy requirements but commonality suffered as a consequence. The Boeing proposal was slightly favored by the services although the GD design was rated acceptable. SECDEF chose the GD design on the basis of commonality and more confidence in GD cost estimates and experience with fighter aircraft compared to Boeing.
D. Systems & Interface Integration	The contractor shall assure that systems integration and interfaces at each of the subsystems and components levels supports total system functionality throughout its life cycle. **Response:** GD engineering department demonstrated a good knowledge of sub-systems integration where the technical/physical interfaces were well known. In the case of inlet-engine subsystem integration, the severity of the impact of time-dependent distortion on compressor stall margin was not well known and was not forecast by either GD or the government. In retrospect, an inlet less integrated with wing and fuselage than the quarter-round buried inlet design would have had less distortion, as was shown by F-15, F-14 inlet systems. However the quarter-round inlet was predicted to have less transonic drag.	The contractor and government shall assure that all systems are integrated within themselves as well as interfaced with other existing operational equipment and systems. **Response:** The government and the contractor emphasis and understanding of sub-systems integration was basically the same, although the government was more insistent on the incorporation of the Mark II avionics upgrade. The contractor's assessment of it was that there was high technical and cost risk of integrating Mark II avionics into the aircraft.	The government shall assure that all its operational systems – in development, in operation, or in planning – are compatible and mutually supportive in a broad "system of systems" and "federation of systems" context. **Response:** The original RFP addressed the overall "system of systems" in an operational framework. The specifications did not change drastically during the development program although many of the original requirements were never met. In hind-sight, there should have been more operation/systems trade off studies on the key performance parameters to establish cost/benefit/risk factors. One key example is the specification of Mach 1.2 at SL vs. high subsonic (Mach 0.8 to .85) which is below the transonic drag rise. Transonic drag rise is a well known aerodynamic characteristic which can be estimated by analysis (even more crude analysis used in the 1960's) and measured by wind tunnel test of specific configurations.

Table A1-1. The Freidman Sage Matrix for the F-111 (Cont'd)

	Contractor	Shared	Government
E. Validation and Verification	Every requirement shall have a test and every test shall have a requirement which requires validation and verification. The criteria for determining test success and failure shall be established early in the program, as shall verification and validation measures. **Response:** GD had a sound test and validation plan in key areas such as aircraft performance, avionics performance and other test areas. The test plan was consistent with the WBS. The test plan did not explore test points outside the specified limits, such as structural failure modes or inlet-engine compatibility, but these were unknown to the contractor and government early in the development cycle; GD did address these and other issues as needed in the development of the F-111, albeit with negative impact on cost and schedule.	Government facilities are often the most expensive and their use in the V&V process shall be shared with the contractors. Test criteria shall be shared early. **Response:** Wind tunnel testing on the F-111 was conducted in transonic tunnels at both government (NASA) and contractor facilities (Cornell Aero Lab). NASA Langley believed that the Cornell data was in doubt because of model size. NASA engineers believed that the transonic drag was higher than the contractor -quoted drag from the Cornell data. Structural and avionics subsystem testing was done in GD facilities.	The government shall be the final word on the confidence levels derived from its testing during development, operational test and evaluation, and actual deployment and operational use. These require judgments at the highest levels, because not all operational conditions can be adequately tested and actual operations are frequently far different from what the planners initially imagined and intended. **Response:** The government (AF, Navy and NASA) conducted independent analysis of test data and provided results to the F-111 SPO. In the case of transonic drag level, the wind tunnel data from NASA indicated higher drag than expected which would decrease Mach 1.2 SL dash range. The contractor did not accept the government predictions, believing that actual flight data would show less drag. This turned out to be a false assumption. The SPO kept the drag level at the contractor's estimate because the higher drag had a large impact on sea level dash and other range performance parameters. The SPO attitude seemed to be to require GD to demonstrate the desired performance in flight test, and until that time would not show a decreased performance. Eventually the SPO accepted the decreased Mach 1.2 SL dash range.
F. Deployment and Post Deployment	As systems undergo operational test and evaluation, the contractor shall maintain the appropriate engineering and testing organizational capabilities to support gathering, analyzing and recommending possible changes in the system design or support through reengineering. **Response:** It appears that GD did maintain a capability during DT&E to incorporate design changes. There were numerous large and small design changes in DT&E. As test data indicated problems or issues, GD had the basic capability, as much as the state of the art at the time would allow, to make the necessary changes. Of course there was always a cost impact. For the F-111, there was not a formal OT&E as there is today. However, the F-111 was used in Operation Combat Lancer in Viet Nam in 1968 and the results were fed back to the F-111 design. Combat Lancer was preceded by Harvest Reaper and Combat Bullseye I flight trials in the US in 1967. The F-111 was in full rate production at this time although there was still DT&E testing being performed by GD.	Both government and contractor shall work cooperatively to conduct an effective operational test and evaluation (Opeval) and to be open to feeding information back to the original management organizations to consider design changes or subsequent modifications through reengineering. **Response:** For the F-111, there was not a formal OT&E as there is today. However, the F-111 was used in operational-like trials in 1967 (Combat Bullseye I and Harvest Reaper) and in Operation Combat Lancer in Viet Nam in 1968; the results were fed back to the F-111 design.	The government shall assure that a properly funded Opeval occurs, one which draws upon both contractor and government resources, and that all data gathered in the tests be evaluated for potential recommendation for system modification, redesign, or reengineering. Preplanned product improvement policies shall be encouraged. **Response:** The DT&E program evaluated mission characteristics such as low altitude terrain following, range points, etc. To the extent possible, the results were used to make design changes or system mods. The only OPEVAL-like activity documented is the first actual operations in Viet Nam (March 1968-November 1968).

Table A1-1. The Freidman Sage Matrix for the F-111 (Cont'd)

	Contractor	Shared	Government
G. Life Cycle Support	All design activities shall be performed from the viewpoint of the entire life cycle rather than the early prototype development phase. **Response:** No evidence was found that GD did life-cycle cost estimates or that there was any impact on design. However the proposal and subsequent design activity addressed maintainability, reliability and ease of subsystem upgrades. Total life-cycle cost design did not come into vogue until the 1980's. LCC cost models were at best inaccurate in the 1960's.	A balanced blend of all methods, measurements, technologies and processes shall be employed in support of an effective life cycle. **Response:** The RFP apparently had some emphasis in the airframe and avionics subsystems on reliability, maintainability and other life-cycle support issues.	Funding support, throughout a program's life cycle, shall be maintained in balance, and procurement of early development programs shall recognize the importance of total life cycle cost control through such approaches as earned value management. **Response:** There was no evidence found of earned value management for the F-111.Unit cost (fly-away) and total cost per unit including RDT&E was tracked throughout the F-111 program. Unit fly-away cost increased about 100% due to various factors (a number thought to be reasonable compared to similar programs) and total cost per unit went up about four times, primarily due to much fewer units being produced than planned and added capability in engines and avionics, so RDT&E costs were amortized over fewer units. Final F-111 production was 562 units (all except 8 were AF) compared to 1,726 AF and Navy units planned in the original RFP.
H. Risk Assessment and Management	At every level of detail, risk shall be identified, prioritized and mitigated, since the early management of risk requires orders of magnitude fewer resources and causes orders of magnitude less program disruption than allowing the potential risk become an actual crisis. Risk is associated with all three major programmatic dimensions: technical, schedule and cost. **Response:** GD did not have a formal risk identification/ management/mitigation plan. They applied "hands-on" engineering to monitor performance, cost and schedule, and took remedial action as necessary when problems arose. A good example is the F-111 Super-Weight-Improvement-Program (SWIP). They used work-arounds to minimize the impact on cost and schedule.	It is to the government's benefit as well as the contractor's to identify and mitigate risk early. The government shall insure that risk management is part of the contract SEMP, is properly funded and is represented in every program review. **Response:** The government did not have a risk id, management, mitigation plan. There were concerns, particularly in the Navy, about weight. There were concerns in the AF about drag; but there was no up-front plan endorsed by the SPO to mitigate these concerns or identify alternative courses of action. The SPO took the point of view that the contractor was responsible for delivering the product as specified. The F-111 did not have a SEMP, but the contractor engineering team was addressing issues that would have been in an SEMP had it existed at the time. In the 1960's, SEMPs were not required as formal documents.	Risk management at all program levels shall be an essential and inherent part of all systems management program planning and life cycle activities. **Response:** The government (SPO) used "hands-on" engineering oversight to identify problems as they occurred and to suggest work-arounds to minimize impact on cost and schedule. Examples are the structural wing-box failure at very low flight hours in 1969, and the inlet-engine compatibility problems (1964-1967). The wing box failure grounded the fleet and halted production. The inlet-engine (compressor stalls) limited the flight envelope. Design changes to the inlet were incorporated in later F-111 models such as F-111D.
I. System and Program Management	For each program – even small ones – shall have a Systems Engineering Management Plan (SEMP) which allows the systems engineering process to be tailored to that program. Programs differ by many orders of magnitude in size, complexity, unprecedented technology and difficulty of interface; the SEMP permits the right amount of effort for each circumstance. **Response:** The F-111 was developed before SEMPs were required. However, various contractor senior -retired personnel related that they were performing engineering functions which would be spelled out in a SEMP.	The role of systems engineering in program development and management shall be recognized and supported. **Response:** Both contractor and government engineers stated that they were continually doing "systems engineering" even though it was not a separately documented or funded process. The contractor was responsible for day-to-day "hands-on" engineering, which they stated was the essence of systems engineering. The government engineers had technical oversight of engineering processes and in some cases performed independent analysis and tests.	The government shall establish security levels for programs to protect crucial technologies and special operational capabilities. **Response:** The F-111 had the necessary security procedures to safeguard information crucial to the F-111.

Appendix 2

Author Biography

DR G. KEITH RICHEY

Dr. G. Keith Richey retired in October 1997 as the Director of the Flight Dynamics Directorate, Wright Laboratory, Aeronautical Systems Center, Air Force Materiel Command, Wright-Patterson Air Force Base. He is currently a Senior Management/Technology Consultant for Universal Technology Corp in Beavercreek Ohio, and other clients.

Dr. Richey received a bachelor of science degree in 1961 and a master of science degree in aerospace engineering from Ohio State University, Columbus, Ohio, in 1965, and a doctoral degree in aerospace engineering from the University of Michigan, Ann Arbor, in 1975.

Dr. Richey joined the Flight Dynamics Laboratory in 1961 as an aerospace engineer in the Aeromechanics Division. In 1965 he became technical manager of Internal Aerodynamics in the Flight Dynamics Laboratory's Aeromechanics Division. In this position he was a leader in airframe propulsion integration research.

Dr. Richey served as senior scientist, office of the Director, Flight Dynamics Laboratory, in 1979 and 1980. In November 1980 he became Chief Scientist of the Flight Dynamics Laboratory and was appointed to the Senior Executive Service. In March of 1988, he was appointed as Chief Scientist of Wright Laboratory serving as principal technical advisor to the Commander. From February 1994 to January 1995, Dr. Richey served as the Director of Plans for Wright Laboratory. He was assigned as Flight Dynamics Director in January 1995.

Dr Richey’s awards and decorations include the Society of Automotive Engineers' Charles M. Manly award, 1968; Ohio State University Distinguished Alumnus award; University of Michigan Alumni Society Merit Award 1997; numerous Air Force Systems Command technical achievement awards; and the Air Force Meritorious Civilian Service Award, 1986 and the Air Force Outstanding Civilian Career Service Award, 1997. He was awarded the Presidential Rank of Meritorious Executive by President George Bush in 1989.

Appendix 3

F-111 History and Variants

F-111A

The history of the F-111 begins back in the late 1950s. At that time, the Tactical Air Command (TAC) of the USAF expressed a future need for a replacement for the F-100, F-101, and F-105 fighter-bombers which were currently in service. With this goal in mind, on March 27, 1958, the Air Force issued General Operational Requirement (GOR) Number 169, calling for Weapon System 649C, which was a Mach 2+, 60,000 foot altitude, all-weather fighter capable of vertical and short takeoff and landing. The Air Force wanted this aircraft to be ready for operational deployment by 1964.

This GOR lasted only a year. GOR 169 was cancelled on March 29, 1959, the Air Force recognizing that a V/STOL fighter capable of such performance was simply not feasible with the current technology. On February 5, 1960, the Air Force rewrote its requirements and issued System Development Requirement (SDR) No. 17, incorporating most of the provisions of GOR-169 but eliminating the VTOL requirement. It allowed the subsequent development of specific requirements for a new weapon system--WS-324A.

The general requirements of SDR-17 were brought together into Specific Operational Requirement number 183 (SOR-183), issued on June 14, 1960. It called for an attack aircraft capable of achieving a Mach 2.5 performance at high altitude and a low-level dash capability of Mach 1.2. It was to have a short and rough airfield performance, and was to be capable of operating out of airfields as short as 3000 feet in length. The low-level radius was to be 800 miles, including 400 miles right down on the deck at Mach 1.2 speeds. In addition, it was to have an un-refueled ferry range capable of crossing the Atlantic Ocean. It was to have a 1000-pound internal payload plus a lifting payload between 15,000 and 30,000 pounds. Based on NASA Langley research, the Air Force considered that a variable sweep wing and a turbofan engine would be needed to satisfy these diverse requirements.

At the same time, the Navy had a requirement for a two-seat carrier-based fleet air defense (FAD) fighter that would replace the McDonnell F-4 Phantom and the Vought F-8 Crusader. This aircraft was to have the ability to loiter on patrol for much longer times with substantially larger and more capable air-to-air missiles, and was to be able to meet and counter threats to the carrier group at much larger ranges.

Originally, the Navy had planned to meet this FAD requirement with the Douglas F6D-1 Missileer. The F6D-1 was a subsonic aircraft that looked a lot like a scaled-up F3D Skyknight. It was to be powered by two 10,000 lb.s.t. Pratt & Whitney TF30-P-2 turbofans, and was to carry a three-man crew (pilot, co-pilot, and weapons system operator). The Missileer was to be capable of remaining on patrol for up to six hours, tracking targets at long range using its powerful Hughes pulsed-Doppler track-while-scan radar and attacking threats with its six long-range Bendix XAAM-10 Eagle air-to-air missiles. The Eagle was a massive long-range air-to-air missile with a maximum speed of Mach 4. It was equipped with an advanced pulse-Doppler active radar homer. The warhead of the Eagle could be either conventional or nuclear.

The F6D aircraft was considered by the Navy to be too costly and too specialized, and was thought to be too slow to be capable of defending itself once its missiles had been launched. Consequently, the F6D and its Eagle missiles were both cancelled in December of 1960 in the last waning days of the Eisenhower administration. This still left the FAD requirement unfulfilled.

The Air Force and Navy requirements were at first sight completely different. However, on February 16, 1961 the new Secretary of Defense, Robert McNamara, directed that the Services study the development of a single aircraft that would satisfy both the requirements of the Air Force's SOR 183 mission and the requirements of the Navy's FAD mission. In addition, McNamara wanted the aircraft to be capable of being used by the Army and the Marine Corps as a close-support aircraft. It was hoped that this strategy would reduce procurement costs substantially. The project came to be known as the **Tactical Fighter Experimental, or TFX** for short.

It did not take long for the services to convince Secretary McNamara that the close air support mission requirement could not be satisfied by the TFX, and the Marine Corps and the Army were dropped from the program at an early stage. However, Secretary McNamara stuck doggedly to his idea of maximum commonality between USAF and Navy versions of the TFX, and in June 1961, he **instructed** the Air Force and the Navy to work closely together to combine their requirements before issuing a joint RFP, although both the USAF and the Navy thought that this idea was completely unrealistic

Both the USAF and the Navy agreed that the use of variable-geometry wings would be a good idea. However, on just almost everything else, they differed substantially. The Navy favored side-by-side seating for its FAD fighter, whereas the Air Force preferred tandem seating. The Navy wanted an aircraft equipped with a long-range search and intercept radar having a dish 48 inches in diameter, whereas the Air Force needed an aircraft equipped with a terrain-following radar optimized for low-altitude operations. The Navy wanted an aircraft that was optimized for long loiter times at medium to high altitudes at subsonic speeds, whereas the Air Force insisted on an aircraft capable of low-altitude operations and supersonic dash performance. Undaunted, Secretary McNamara pressed forward with the project and directed that the Air Force would be the lead service for the development of a common TFX aircraft.

By August of 1961, the Secretary of the Navy reported to Secretary McNamara that the compromise TFX design could not meet the Navy requirements. The Air Force wanted an aircraft weighing 75,000 pounds gross, while the Navy wanted the gross weight to be kept below 50,000 pounds. In addition, carrier operational requirements necessitated that the overall length be kept below 56 feet so that it could fit aboard existing carrier elevators. McNamara ordered the Navy to accept a design sized to accommodate a 36 inch radar rather than the 48 inch radar it really wanted and to accept a gross takeoff weight of 55,000 pounds.

On September 29, 1961, a Request For Proposals was issued to Boeing, General Dynamics, Lockheed, Northrop, Grumman, McDonnell, Douglas, North American, and Republic. The Air Force's version of the TFX was to be designated F-111A, with the Navy's version being designated F-111B. In the spirit of commonality, the Air Force and Navy versions did not carry separate designation schemes.

Nine responses were received in early December of 1961. Only Northrop turned down the invitation to submit. In their first evaluation of the proposals on January 19, 1962, the Air Force Selection Board and a Navy representative endorsed the Boeing proposal, but the Air Force Council rejected the Boeing bid as requiring much more work. In late January of 1962, both the Air Force and Navy agreed that none of the proposals were really acceptable, but that two of them --- the Boeing and General Dynamics proposals --- warranted further study. A letter contract was issued to each company requesting more design data.

In the spring of 1962, Boeing and General Dynamics submitted second proposals. In May of 1962, both the Air Force and Navy Secretaries rejected the two contractor's second proposals for lack of sufficient data. A third submission took place in late June. At this time, the Air Force endorsed the Boeing proposal, but the Navy was unhappy with their version and refused to commit themselves. A frustrated Secretary McNamara ordered a final competition for later that year on the basis of a point system for categories based on performance, cost, and commonality.

Boeing and General Dynamics resubmitted their fourth round of proposals in September of 1962. The Air Force Council, the Air Force Logistics Command, and the Bureau of Naval Weapons (the Navy organization which had replaced the Bureau of Aeronautics in 1959) all indicated that they preferred the Boeing design, **but on November 24, 1962 the Defense Department announced that the General Dynamics design had been selected**. The reason given for the selection of the General Dynamics proposal was its promised greater degree of commonality and its more realistic approach to program cost.

A political storm broke out, with Senator Henry Jackson leading the fray in Congress in loudly denouncing the choice in no uncertain terms. A series of congressional investigations led by Senator McClellan from Arkansas was initiated in 1963 (with follow-up hearings in 1970), and the TFX stayed in the headlines for many months. Nevertheless, the decision of the Secretary stood, and the contract remained with General Dynamics. GD received a 479 million dollar letter contract in December 1962 for F-111 RDT&E, including 23 test aircraft (18 Air Force and 5 Navy).

The F-111A and B aircraft shared the same primary structure, the same fuel system, the same pair of Pratt & Whitney TF30-P-1 turbofans, and the same two-seat cockpit in which the two crew members sat side-by-side. The side-by-side seating was a concession to Navy demands. The Navy also insisted that the cockpit be capable of doubling as an escape capsule for the crew which could blown free from the aircraft in the case of an emergency to parachute to the ground, or float on water. The F-111B's nose was 8 feet 6 inches shorter than the F-111A's because of the need of the aircraft to fit on existing carrier elevator decks, and had 3 feet 6 inch extended wingtips in order to increase the wing area so that the on-station endurance time would be improved. The Navy version would carry a Hughes AN/AWG-9 pulse-Doppler radar and an armament of six Hughes Phoenix missiles, which had both evolved from the F6D program. The Air Force version would carry the General Electric AN/APQ-113 attack radar and the Texas Instruments AN/APQ-110 terrain- following radar and an armament of internal and external nuclear and conventional air-to-ground stores.

Since General Dynamics lacked any experience with carrier-based fighters, it teamed with Grumman for the integration of the naval electronics package and Grumman was to assemble and test the entire F-111B production aircraft.

By the spring of 1964, AiResearch, AVCO, Bendix, Collins Radio, Dalmo Victor, General Electric, Hamilton Standard, Litton Systems, McDonnell, Texas Instruments and seven other major subcontractors had become involved with the F-111 project. An associate prime contract for the F-111B's Phoenix missiles had been awarded to Hughes. These major subcontractors were doing business with no less than 6703 suppliers located in 44 states.

The first test F-111A (serial number 63-9766) rolled out of the General Dynamics Fort Worth, Texas plant on October 15, 1964, 37 months after the DOD go-ahead decision, 22 months after the program's actual beginning, and two weeks ahead of schedule. It was powered by YTF30-P-1 turbofans. Pending the availability of the escape capsule, it was fitted with a pair of conventional ejector seats.

63-9766 took off on its maiden flight from Carswell AFB, Texas on December 21, 1964. Dick Johnson and Val Prahl were at the controls. Although the flight was shortened to 22 minutes because of compressor stalls and a flap malfunction, the results were generally satisfactory. On its second flight, on January 6, 1965, the wings were swept form the minimum 16 degrees to the full aft 72.5-degree position.

In 1965, a cost rise from an estimated 4.5 to 6.3 million dollars per aircraft caused the Defense Department to cut the F-111 program sharply. A contract for 431 production aircraft was placed on April 12, 1965. This was more than 50 percent less than the amount originally planned. Eleven production F-111As were added to the extensive test and engineering program.

The escape capsule was first fitted to F-111A number 11 (63-9777).

The Pratt & Whitney TF30-P-1 turbofan was first flown on an F-111A on July 20, 1965. The first 30 F-111As were equipped with this engine, but they experienced numerous engine compressor stalls, particularly at high speeds and at high angles of attack. These necessitated a change to the 18,500 lb.s.t. TF30-P-3 and to new "Triple Plow I" variable-geometry inlet ducts with larger area and a bulged-out splitter plate. This engine was later retrofitted in several of the first 30 F-111As. These changes did not entirely cure the stall problems, but they did help somewhat.

Movable under-wing pylons were introduced from the fourth production aircraft onward, and from the eleventh production aircraft onward a 20mm M61A1 Vulcan cannon was installed in the internal weapons bay in place of two 750 lb. bombs. However, this cannon was rarely carried by actual operational aircraft, the space in the weapons bay being used for bombs, fuel, or electronics.

In the spring of 1967, a series of tests known as *Combat Bullseye I* were carried out with test F-111As. They confirmed the superior bombing accuracy of the aircraft's radar.

A total of 141 production F-111As were delivered by July 17, 1967. The electronics package was known as the Mk I avionics system. It included a Litton AJQ-20 inertial navigation and attack system, a General Electric AN/APQ-113 attack radar, a Texas Instruments AN/APQ-110 terrain-following radar, and Collins ARC-109 UHF and ARC-112 HF radio transceivers.

The underside of the central fuselage of the F-111A is occupied by a giant airbrake which is forced open by a large hydraulic jack. Together with the main landing gear, the presence of this airbrake precludes carrying any bombs or fuel tanks underneath the fuselage. The massive main landing gear has two huge low-pressure tires which, together with the long-stroke legs that are pivoted near the aircraft centerline, enable no-flare landings to be made at high weights. The large airbrake helps cover the retraction bay, and is partially extended when the main gear is down. The nose landing gear has twin wheels and is hydraulically steer-able.

The Triple Plow I air intakes for the TF30 turbofans are mounted underneath the leading edge of the fixed wing glove. A triangular-shaped wedge is fitted to the upper, inner corner of each intake, and a large planar wedge (splitter plate) is mounted ahead of each intake parallel to the sides of the fuselage. The entire intake cowls could be moved forwards or backwards as needed to optimize the air flow into the engines for low speed (takeoff and landing) operation. A set of vortex generators is fitted inside the intake ducts to provide a homogeneous flow of air to the engine. The low-mounted air intakes have a disadvantage in that they tend to suck up a lot of runway debris, dictating that the F-111A use only prepared runway surfaces that are kept thoroughly swept at all times.

The fixed inner wing has a set of pivoted surfaces that normally lie flush to the surface but at high angles of attack or in high-lift situations they can be extended to improve air flow over the glove-wing junction.

The variable-geometry wing outer panels are pivoted to the fixed inner wing gloves and can be driven symmetrically to any sweep angle from 16 degrees to 72.5 degrees. The upper surface of the wing has a set of spoilers which are used for roll control, no ailerons being provided. The main wing has a set of double-slotted flaps which occupy the entire trailing edge of the wing. The flaps are disconnected when the wing is at maximum sweep so that they cannot be operated in such a configuration. A set of slats occupy the entire width of the wing leading edge. These slats can be extended by a rack and pinion system when the aircraft is flying at low speeds or at high angles of attack to increase lift and to prevent the aircraft from stalling.

In an emergency, the cockpit can be used as an escape capsule which separates completely from the aircraft and is blown free from the aircraft by a rocket motor. The pilot and systems officer sit side-by side in a shirt-sleeve environment, e.g., wearing no pressure suits or oxygen masks. If they decide to eject, first a bunch of explosive guillotines sever all the hydraulic lines and cables. Then, a rocket charge separates the entire cockpit from the plane. The ejection capsule takes with it a small portion of the fuselage above and to the rear of the cockpit which acts as a stabilizing airfoil. After the chutes are opened, anti-radar chaff is dispersed, and a cushion/flotation bag is inflated. All of this can be accomplished from zero/zero airspeed/altitude (e.g. from an F-111A parked at rest on a runway). In the case of an over-water ejection, the capsule is supposed to be completely submersible and is capable of floating for a considerable amount of time. While the capsule is floating in the water, the joy stick can double as a bilge pump by moving a pin in its base.

The horizontal tailplane is of the all-flying variety with no separate elevator.

There are six underwing pylons for carrying bombs, rockets, or fuel tanks. The two outboard underwing pylons on each wing are fixed and do not pivot. Consequently, they can only be used between 16 and 26 degrees of wing sweep. However the two inboard pylons do pivot and remain parallel to the aircraft centerline throughout the entire sweep range. There is a small internal weapons bay which can accommodate a pair of nuclear or 750-pound non-nuclear bombs. Alternatively, the bombs in the internal weapons bay can be replaced by a 20-mm M61A1 rotary cannon with 2000 rounds of ammunition.

In an extreme situation, the F-111A could carry as many as 50 750-pound conventional bombs (two of them being carried internally, the rest on the six underwing hardpoints), or 26 1000-pound bombs. However, such loads could only be carried if the wing is swept no more than 26 degrees and would therefore be unlikely to be carried in actual combat. If the wing needs to be swept back at an angle of 54 degrees, the bomb load is limited to 26 750-pound bombs. In standard USAF form, the F-111A's useful payload varies from 8000 pounds to 20,000 pounds, according to range. For example, for a mission range of 1725 miles, the payload is of the order of 16,000 pounds.

The APQ-113 forward-looking attack radar is a large liquid-cooled set that operates in the J-band (16-16.4 GHz). It is used by the navigator sitting in the right hand seat for navigation, air/ground ranging and weapons delivery. It can also be used in the air-to-air mode in conjunction with the 20-mm M61A1 cannon or Sidewinder missiles, although the air-to-air role is not the primary mission of the F-111A.

The F-111A is equipped for midair refueling. A receptacle for a refueling boom is fitted on the top of the fuselage behind the cockpit. The F-111A has no provision for refueling by the probe/drogue method.

The first F-111A deliveries took place on July 18, 1967 to the 428th, 492th and 430th Tactical Fighter Squadrons of the 474th Tactical Fighter Wing based at Cannon AFB in New Mexico.

Based on the results of the *Combat Bullseye I* tests of the spring of 1967, the Air Force decided to send a small detachment of F-111As to Southeast Asia under a program known as *Combat Lancer*. This program was preceded by the *Harvest Reaper* program of June 1967 which was intended to identify known F-111A shortcomings and to prepare the aircraft for combat. It was anticipated that the *Harvest Reaper* modifications would enter the F-111A production lines if they were successfully proven in combat.

Six 428th TFS F-111As were allocated to the *Combat Lancer* program, and departed Nellis AFB for Thailand on March 15, 1968. By the end of that month, 55 night missions had been flown against targets in North Vietnam, but two aircraft had been lost. Replacement aircraft had left Nellis, but the loss of a third F-111A on April 22 halted F-111A Viet Nam combat operations. It turned out that the three F-111A losses were not due to enemy action but were caused by a tail structural defect or other problems. One of the *Combat Lancer* crashes has been traced to a malfunction of the aircraft's tail servo actuator which would cause a sudden and uncontrollable pitch-up.

F-111 testing continued with development of a new inlet design called Triple Plow II, and a fatigue life deficiency on the wing carry-through box was discovered through ground tests. A modified wing box was designed, tested to the requisite four lifetimes (10,000 hours) and retrofit to all previously-produced F-111 As.

The last of 158 F-111As was delivered on August 39, 1969. This total included 17 of the 18 RDT&E F-111As initially ordered in December 1962. The 18th test F-111A was used as a test prototype for the FB-111A bomber program.

The Air Force lost a test F-111A on December 22, 1969, due to failure of the forged wing pivot fitting with less than 200 hours flight time due to a flaw in the wing pivot structure. All F-111As were grounded the next day. The grounding was lifted on July 31, 1970. This accident set in motion a new approach to aircraft structural integrity concerning the growth of small flaws in manufacturing. A cold proof test process was developed to verify structural integrity of all F-111 wings.

The F-111A returned to Southeast Asia in September of 1972. Two F-111A squadrons (the 429th and 430th) left Nellis AFB for Thailand. They participated in the *Linebacker II* aerial offensive against North Vietnam. They flew bombing missions against targets in North Vietnam and Laos in the midst of the monsoon season. They flew without electronic countermeasures escort aircraft or KC-135 tankers. On November 8, 1972, they flew 20 strikes over North Vietnam in weather that grounded other aircraft. Four F-111As could deliver the bomb loads of 20 F-4s. The 429th and 430th TFS flew some 4000 combat missions with excellent success rates in hitting targets even when visibility was near zero. Only six aircraft were lost in action.

In 1982, four F-111As were transferred to the Royal Australian Air Force to cover attrition in their F-111C fleet.

F-111A serial number 67-0067 is currently on display at the USAF Museum at Wright Patterson AFB in Ohio. An escape pod that was successfully used to eject from F-111A 63-9780 is also on display.

RF-111A

The RF-111A was to have been a tactical reconnaissance version of the F-111A with additional avionics and camera installations in the weapons bay. It was authorized on December 3, 1965.

One pre-production F-111A (63-9776) was converted as a prototype for the RF-111A and first flew on December 17, 1967. Imagery testing of the converted F-111A took place between December 1967 and October 1968 achieved fairly good results, indicating that the RF-111A might make a good reconnaissance aircraft. The Defense Department had hoped that the conversion from F-111A to RF-111A configuration could be done in the field in only a few hours, with the reverse conversion being just as simple and straightforward. However, the conversion turned out to be much more cumbersome than expected, taking several days to complete rather than just a few hours. These difficulties caused the Air Force to cancel the RF-111A program.

Grumman EF-111A Raven

In December 1974, the Grumman Aircraft Corporation of Calverton, Long Island was selected as the prime contractor for the conversion of 42 F-111As to EF-111As. On January 30, 1975, Grummann was awarded a contract for the modification of two F-111As (serials 66-0041 and 66-0049) as EF-111A prototypes, the E prefix standing for "Electronic".

The modifications included the installation of an AN/ALQ-99E jamming subsystem. Exciters, antennae, and other items were mounted on a pallet inside the internal weapons bay. Other components were mounted inside a 16-foot ventral "canoe"-shaped radome. A fin-tip pod accommodated the electronic countermeasures receivers. The self-protection subsystem consisted of a jamming system and a countermeasures dispensing set. A terminal threat warning subsystem was installed which consisted of infrared and electronic countermeasures receiver sets. The vertical fin had to be reinforced in order to support the fin-tip pod, new electrical wiring had to be installed, 60 kVA generators were replaced by 90 kVA units, and an improved environmental system for electronic equipment cooling was fitted. The cockpit had to be rearranged to accommodate the new electronic warfare officer position, with the flight controls being removed from the right-hand cockpit, the navigation equipment being relocated so that could be used by the pilot in the left-hand seat, and the controls and displays for the electronics warfare officer being installed in the right-hand cockpit.

These modifications resulted in an increase of empty weight from 46,172 pounds for the F-111A to 55,275 pounds for the EF-111A. However, since the EF-111A carried no weapons, its maximum takeoff weight was only 88,848 pounds as compared with 98,850 pounds for the F-111A. The Pratt & Whitney TF30-P-3 turbofans of the F-111A were retained.

First deliveries of EF-111A Ravens were made to the 390th Electronic Combat Squadron of the 366th Tactical Fighter Wing at Mountain Home AFB in Idaho in November 1981 and to the 42nd ECS of the 20th TFW at RAF Upper Heyford in February 1984. 42 Ravens had been delivered to the 366th TFW and the 20th TFW by December of 1985. Mountain Home AFB received most of them.

The first operational mission for the Raven took place during Operation *Eldorado Canyon*, the retaliatory attack on Libya on the night of April 14-15, 1986. During that mission, the 42nd ECS provided three EF-111As plus two spare aircraft to jam the Libyan radar network.

Under an Air Force contract awarded in January 1987, Grumman and TRW Inc. developed the Avionics Modernization Program (AMP) kit for the EF-111A. These kits provided the EF-111A with improved terrain following and navigational radars, a ring laser gyro inertial navigation system, the capability for using the global positioning system, two digital computers, improved cockpit displays, and upgraded communication systems. The first AMP kit was installed in EF-111A 66-0018 in January of 1989. Most existing EF-111As were later to receive this upgrade.

Eighteen EF-111A Ravens were deployed in support of Operation *Desert Storm* in 1991. They flew over 900 sorties. None were lost in combat, but one was lost in a non-combat related accident and both crew members were killed.

F-111B

The F-111B was the naval version of the TFX fighter project, which had been decreed by Secretary of Defense McNamara to be designed in common with the Air Force version, even though the requirements were completely different. In retrospect, this turned out to be a serious mistake.

The F-111A and B aircraft shared the same primary structure, the same fuel system, the same pair of Pratt & Whitney TF30-P-1 turbofans, and the same two-seat cockpit in which the two crew members sat side-by-side. However, the F-111B's nose was 8 feet 6 inches shorter than the F-111A's because of the need of the aircraft to fit on existing carrier elevator decks, and had 3 feet 6 inch extended wingtips in order to increase the wing area so that the on-station endurance time would be improved. The Navy F-111B version would carry a Hughes AN/AWG-9 pulse-Doppler radar and an armament of six Hughes Phoenix missiles.

The first F-111B (Bu No 151970) was assembled at Bethpage from components produced by both General Dynamics and Grumman. It was powered by the same pair of Pratt & Whitney TF30-P-1 turbofans that powered the F-111A. Pending the availability of the escape capsule, the first F-111B was equipped with a pair of conventional ejector seats. It was rolled out at Bethpage on May 11, 1965 and transported to Calverton. It made its first flight at Calverton on May 18, flown by Ralph "Dixie" Donnell and Ernie von der Heyden. Aside from a problem with compressor stall (as already experienced by the F-111A), the first flight was trouble-free.

The first Naval Preliminary Evaluation was held at NATC Patuxent River in October of 1965. The F-111B was already in trouble since it was seriously overweight. Takeoff weight for a fully-equipped aircraft was estimated at nearly 78,000 pounds, well over the upper limit of 55,000 pounds as required by the Navy.

The problems with the overweight F-111B were so severe that General Dynamics and Grumman were forced into a Super Weight Improvement Program (SWIP), most of the changes being incorporated into the fourth and subsequent F-111Bs. The fourth F-111B (BuNo 151973) was fitted with an escape capsule in place of the individual ejector seats that were fitted to the first three F-111Bs. However, the fitting of this capsule more than offset the weight reductions achieved by the SWIP, and the F-111B remained grossly underpowered. Range was also below specifications and could only be increased by adding more fuel, making the aircraft even heavier.

The third F-111B (BuNo 151972) was allocated to trials with the Phoenix missile system. Four Phoenix missiles were to be carried on swiveling pylons underneath the wings, with two Phoenix missiles being housed inside the fuselage weapons bay. The first successful firing of a Phoenix missile took place in July of 1967.

By October 1967, the Navy Bureau of Weapons was convinced that the F-111B would never be developed into a useful carrier aircraft and recommended that the project be terminated. In May of 1968, both houses of Congress refused to fund F-111B production. On July 19, 1968, a stop-work order was issued to General Dynamics, after $377 million had been spent on the program.

F-111C for Australia Royal Air Force (RAAF)

On October 24, 1963, the government of Australia agreed to purchase 24 F-111As. The Australian version is designated F-111C. It is still in operation after all other F-111 models have been retired by the US Air Force.

The F-111C is equipped with eight underwing pylons mounted on an F-111B-type larger span wing (span of 70 feet when fully extended). It was equipped with with an FB-111 type of reinforced undercarriage. The twenty-four F-111Cs were given the USAF serial numbers 67-0125/0148. Their RAAF serials were A8-125/148.

The first F-111C was delivered on September 6, 1968. However, the problems with the F-111A's wing carry-through box slipped delivery of the remaining 23 F-111Cs to late 1969. To make matters worse, the whole F-111 fleet had to be grounded pending verification of their overall structural integrity. The remaining F-111Cs awaiting delivery to Australia were stored at Fort Worth until the structural integrity of the F-111 could be confirmed. In April of 1970, a joint agreement between General Dynamics and Australia deferred the RAAF's acceptance of the F-111C pending the verification of their structural integrity. The RAAF was to lease F-4E Phantoms as an interim aircraft while new wing carry-through boxes were installed on all F-111Cs before being delivered to the RAAF. This refurbishment program began on April 1, 1972. In 1973 the F-111C was finally ready for delivery to the RAAF.

The F-111C carries the APQ-113 forward-looking attack radar, which is used for navigation, for air-to-ground ranging and for weapons delivery. In theory, this radar can also be used in the air-to-air mode in conjunction with the internal 20-mm cannon or Sidewinder missiles carried under-wing, although this is not the primary mission of the F-111C.

Four F-111Cs were converted in 1979 for the RF-111C reconnaissance role by General Dynamics and delivered to Australia. The reconnaissance "kit" comprises two KS-87C framing cameras, a KA-56E low-altitude and KA-93A4 high altitude panoramic camera, and an AN/AAD-5 Infrared Line-scanner. There is a TV viewfinder which assists with line up for the photo run. The RF-111C retains full conventional attack capability.

F-111D

F-111D was the designation given to a more advanced version of the F-111. It was powered by a pair of Pratt & Whitney TF30-P-9 engines, each rated at 20,840 lb.s.t. with afterburner. The aircraft were equipped with Mark II microprocessor avionics with improved air-to-air capability. This system was a first generation version of what later came to be known as a "glass" cockpit.

In addition, the F-111D was provided with Triple Plow II air intakes, which were intended to correct the F-111A's remaining problems with compressor stall above Mach 2.2, and in high angle of attack maneuvers. The Triple Plow II intakes were mounted four inches farther from the airframe (with the splitter plate removed entirely) than Triple Plow I in order to prevent the fuselage boundary layer from being ingested by the inlet, and the translating cowl was replaced by a series of blow-in doors. These blow-in doors were a set of auxiliary inlets which enabled extra airflow to reach the inlet duct during takeoff or when the engine is at full power but the aircraft is moving slowly. They are normally sealed closed by spring-loaded doors which are pushed open by air pressure when additional air flow is needed.

The Mark II system included 7 major components--an inertial navigation set and attack radar built by the Autonetics Division of North American Rockwell, an IBM computer system, converter and panels by the Kearfott Division of Singer-General Precision, Inc., an AN/AVA-9 integrated display set by the Norden Division of United Aircraft Corporation, a Doppler radar by the Canadian Marconi Company, a horizontal situation display by the Astronautics Corporation of America, and a stores management set by the Fairchild Hiller Corporation. The main forward-looking attack radar of the F-111D was the APQ-130, with MTI, Doppler beam sharpening, and illumination for radar-guided AAMs.

Ninety-Six F-111Ds were ordered by USAFon May 10, 1967. The first F-111D (68-0085) flew on May 15, 1970. It was equipped with the new P-9 engines but did not have a complete Mark II system. It was delivered to the Air Force on June 30, 1970.

The F-111D with Mark II Avionics went through a rather protracted development cycle before it was deemed fit for service. There were difficulties in integrating the various complex electronic components with each other. The Autonetics attack radar needed several improvements in its initial design, and the Norden integrated display set required extensive changes. The radar problems required that the radar doppler unit be redesigned, which in turn caused interface problems with the Norden integrated display set. By late 1969, the Mark II system was still not ready. By mid-1970, the problems with the Norden integrated display set were still not resolved.

Development problems with the F-111D's advanced avionics caused so many delays that the Air Force decided to acquire 94 of the simpler F-111E with Mark I avionics. The F-111E is basically an F-111A with the Triple Plow II inlet system.

It was not until November 1, 1971 that the first F-111D was delivered to the 27th TFW at Cannon AFB in New Mexico, the third TAC Wing to receive the F-111. This aircraft was the sixth F-111D produced (68-0090). It was equipped with a full Mark II avionics system, featuring one of Norden's early IDS productions. The initial operational capability with the 27th TFW was in September 1972. Eventually, the F-111D equipped the 522nd, 523rd, and 524th Squadrons of the 27th TFW.

Throughout the rest of 1972, TAC's few F-111Ds continued to be crippled by avionics problems. The horizontal situation display was prone to frequent failures, delivery of field ground equipment was late, and depot support was poor. Operational readiness remained low all throughout 1973, and the abort rate of the F-111D was higher than that of other F-111s. It was not until January of 1974 that the F-111D was finally declared operationally ready.

96 F-111Ds were delivered between June 30, 1970 and February 20, 1973. The serials were 68-0085/0180.

F-111E

Because of late delivery and protracted development of the F-111D, 94 F-111Es were ordered with simplified avionics and the TF30-P-3 turbofan engine, but with the Triple Plow 2 air intakes of the F-111D. They were ordered in 1968. Even though the F-111E had a later series letter than the F-111D, the E preceded the D into service.

The first flight of an F-111E took place on August 20, 1969, and deliveries to the Air Force took place from 1969 to May 28, 1971.

F-111Es of the 20th TFW were used in Operation *Desert Storm* in early 1991, flying out of bases at Incirlik, Turkey. They lacked the precision guided munitions capability of the later F-111F, and so they carried mainly Mk 82 or Mk 84 standard conventional bombs and other conventional ordnance against targets in the northern part of Iraq. None were lost in combat.

F-111F

The F-111F was the final F-111 version produced for the Tactical Air Command (TAC). It was ordered on July 1, 1970. It carried the Mark IIB avionics suite which combined F-111D and FB-111A navigational and digital computer systems (but excluding the F-111D's AN/APN-189 Doppler radar navigation set) plus numerous other FB-111A components such as the AN/APQ-144 attack radar and some simpler, less costly avionics systems used by earlier F-111s. This lower cost Mark II avionics suite is designated Mark IIB. The APQ-144 attack radar of the F-111F has a new 2.5-mile display ring made possible by a 0.2 s pulse-width capability. The F-111F also featured an improved landing gear. It was powered by a pair of 25,100 lb.s.t. TF30-P-100 turbofans. There were some initial problems with the TF30-P-100 engine --- difficulties were encountered with afterburner stalls in cold weather, with tail-feather seal leakage, and with inlet guide vane cracking. 106 F-111Fs were produced for the US Air Force. The last F-111F was delivered to the USAF in September of 1976.

Many F-111Fs carry the Ford AVQ-26 *Pave Tack* pod semi-recessed in the weapons bay. The Pave Tack is equipped with a laser designator and forward-looking infrared (FLIR) which are used for the delivery of laser-guided bombs with pinpoint accuracy. The laser and FLIR are bore-sighted in a powered turret giving magnified clear pictures of targets integrated with the cockpit avionics displays and weapons-aiming systems. Although all of the F-111 marks can drop laser-guided bombs, only the F version has the laser suite to designate targets.

24 F-111Fs from the 48th TFW based at Lakenheath spearheaded the US attack on Libya on the night of April 14, 1986, striking targets in Tripoli with laser-guided and retarded bombs. One F-111F was lost to ground fire during the attack.

During *Desert Storm* in 1991, 67 F-111Fs of the 48th TFW operated from air bases in Saudi Arabia. Because of their ability to deliver precision-guided ordinance in all-weather conditions, they played a key role in the destruction of the Iraqi command and control structure and in the elimination of key targets in the Kuwait theatre of operations. These aircraft flew 2500 sorties, destroyed 2203 targets, including direct hits on 920 tanks, 252 artillery pieces, 245 hardened aircraft shelters, 13 runways, 113 bunkers, and 12 bridges. A total of 5500 bombs were dropped. Almost 85 percent of these bombs were precision guided munitions. When Iraqi forces deliberately opened an oil pumping station manifold to allow oil to leak into the Persian Gulf, an F-111F was selected to deliver the GBU-15 electro-optically guided bomb against the manifolds to stop the flow.

On the last night of the war, two F-111Fs delivered 5,000 lb GBU-28 deep-penetrator "bunker-buster" bombs against Iraqi command and control bunkers. These bombs could penetrate over 100 feet of earth or 22 feet of concrete.

FB-111A Strategic Bomber

The FB-111A was the all-weather strategic bombing version of the F-111, intended as an interim successor to early models of the B-52 and the B-58s of the Strategic Air Command. It was initially developed as Weapon System 129A. The development of the FB-111A was prompted by the slow progress of the Advanced Manned Strategic Aircraft (AMSA) program (which would become the B-1) and by fears that fatigue failures in the B-52 fleet might come earlier than expected. A proposal to resume production of the Convair B-58 Hustler was rejected as being too costly. In the spring of 1963, the Air Force turned to General Dynamics for a solution to its problem. In November of 1963, General Dynamics responded with a suggestion for two strategic versions of the F-111A. In order to hasten availability, the Air Force decided on June 2, 1965 that the least modified version was the one that they would go with. The designation FB-111A was applied.

The FB-111A differed from the F-111A primarily in having a longer fuselage (75 feet 7 inches as compared to 73 feet 5 1/2 inches) to accommodate the additional fuel required for its strategic mission. In order to provide a longer range and greater load-lifting capability, the FB-111A had the extended wing of the F-111B (unfolded span of 70 feet as compared to 63 feet). It also had a stronger undercarriage and landing gear, and was powered by TF30-P-7 turbofan engines (20,350 lb.s.t. in afterburner). It featured the Mark IIB avionic subsystem, same as the F-111F. The FB-111A was the first F-111 version to fly with the new Triple Plow II air intakes. The primary weapon of the FB-111A was to be the Boeing-designed AGM-69A Short-Range Attack Missile (SRAM).

A modified RDT&E F-111A (serial number 63-9783) was converted as the prototype of the FB-111A and flew for the first time on July 30, 1967. It achieved Mach 2 on its first test flight.

The first production FB-111A aircraft flew on July 13, 1968. It was accepted by the Air Force on August 30, 1968. A second FB-111A was delivered on October 25. Problems with the Mark IIB avionics slowed further deliveries, with the Air Force not accepting its next FB-111A until June 23, 1969. FB-111A testing of the SRAM began on March 27, 1970. Initial test started poorly --- in almost a year, there were only seven successes out of 11 launches. However, by early 1961, the results began to get better, with the final score being 15 successes out 19 launches during the entire test series.

A total of 263 planes were projected when the FB-111A program began. This was reduced to 126 on November 28, 1968 because of rising costs and production delays with the basic F-111 program. The final cut took place on March 16, 1969, with the total FB-111A order being reduced to 76. The last production FB-111A (68-0291) was delivered to SAC on June 30, 1971.

The FB-111A could carry two AGM-69A SRAMs in the internal weapons bay along with two more on the inner underwing pylons. Typically, four 600-US gallon drop tanks were carried on the outermost underwing pylons, although the SRAMS carried underneath the innermost underwing pylons could be replaced by another pair of 600-gallon drop tanks, bringing the total number of drop tanks to six. The non-swiveling outer pylons are intended for subsonic flight only and are jettisoned when wing sweep exceeds 26 degrees. Alternatively, up to 24 750-pound conventional bombs could be carried externally. The FB-111A could also carry six gravity nuclear weapons or a B77 nuclear bomb. A total offensive load of 35,500 pounds could be carried.

As the Rockwell B-1B Lancer came into service, the FB-111A became redundant to SAC needs, and 34 FB-111As were converted to F-111 Gs to serve in the Tactical Air Command. For the F-111G program, the FB-111A's short range attack missile (SRAM) system for stand-off nuclear delivery was retained, and a conventional weapons release system was installed to provide for dual-role capability. Other improvements included the installation of a Have Quick UHF radio and a new ECM system. On June 29, 1993, Australia announced that it was going to purchase 15 surplus F-111G aircraft. They would join 18 F-111Cs and four RF-111Cs already in RAAF service.

F-111K for the RAF - Cancelled Before Delivery

On February 1, 1967, the Royal Air Force ordered 46 F-111K strike fighters and four TF-111K proficiency trainers. These were intended to fill the gap left by the cancellation of the BAC TSR-2.

However, the Royal Air Force order was cancelled at the beginning of 1968, the reason being given that they were much too expensive.

Summary

The General Dynamics F-111 is one of the most controversial aircraft that ever flew. It suffered a protracted development cycle in which numerous serious problems had to be identified and repaired, and cost overruns came to be a serious concern. Of the several thousand that had originally been planned, only 562 production models of seven different variants were completed.

However, after a prolonged gestation period in which many, many problems had to be identified and fixed, the F-111 turned out to be one of the most effective all-weather interdiction aircraft in the world. Although vilified by some as being an unsafe and dangerous plane, the F-111 series of combat aircraft established the best safety record of any of the aircraft in the Century Series of fighters --- only 77 aircraft being lost in a million flying hours. There was no other aircraft in service with the USAF at the time which could carry out the F-111's mission of precise air strikes over such long ranges in all-weather conditions. The last USAF F-111s were retired from service in 1996. It is still in service with the Royal Australian AF today.

Sources:

The **primary source** for this Appendix is General Dynamics F-111 History, Joe Baugher, www.F-111.net, Sept 2001 e-mail jbaugher@worldnet.att.com. See Also Joe Baugher's Encyclopedia of American Military Aircraft

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F-111 Variants

F-111 Variant	F-111A	EF-111A	F-111B	F-111C	F-111D	F-111E	F-111F	FB-111A
Length	73ft 6in	74ft 0in	66ft 9in	73ft 6in	73ft 6in	73ft 6in	73ft 6in	73ft 6in
Height	17ft 0½in	20ft 0in	15ft 9in	17ft 0½in	17ft 0½in	17ft 0½in	17ft 0½in	17ft 0½in
Span @ 16°	63ft 0in	63ft 0in	70ft 0in	70ft 0in	63ft 0in	63ft 0in	63ft 0in	70ft 0in
Span @72.5°	31ft 11in	31ft 11in	33ft 11in	33ft 11in	31ft 11in	31ft 11in	31ft 11in	33ft 11in
Gross weight (normal)	91,300lb	88,950lb	79,002lb	114,300lb	100,000lb	91,300lb	100,000lb	114,300lb
Engine (TF30 X 2)	P-3/-103	P-109	P-12	P-3	P-9/-109	P-3/-103	P-100	P-7/-107
Maximum thrust (each)	18,500lb	20,840lb	20,250lb	18,500lb	20,840lb	18,500lb	25,100lb	20,350lb
Triple Plow Inlets	TP I	TP I	TP I	TP II	TP II	TP II	TP II	TP II
Mission avionics and special ordnance	Mk. I	Mk. I/TJS	Phoenix	Mk. I	Mk. II	Mk. I	Mk. IIB	Mk. IIB
Attack radar set*	APQ-113	APQ-160	AWG-9	APQ-113	APQ-130	APQ-113	APQ-144	APQ-114
Doppler radar	-	-	-	-	APN-189	-	-	APN-185
Terrain-following radar	APQ-110	APQ-110	-	APQ-110	APQ-128	APQ-110	APQ-146	APQ-134

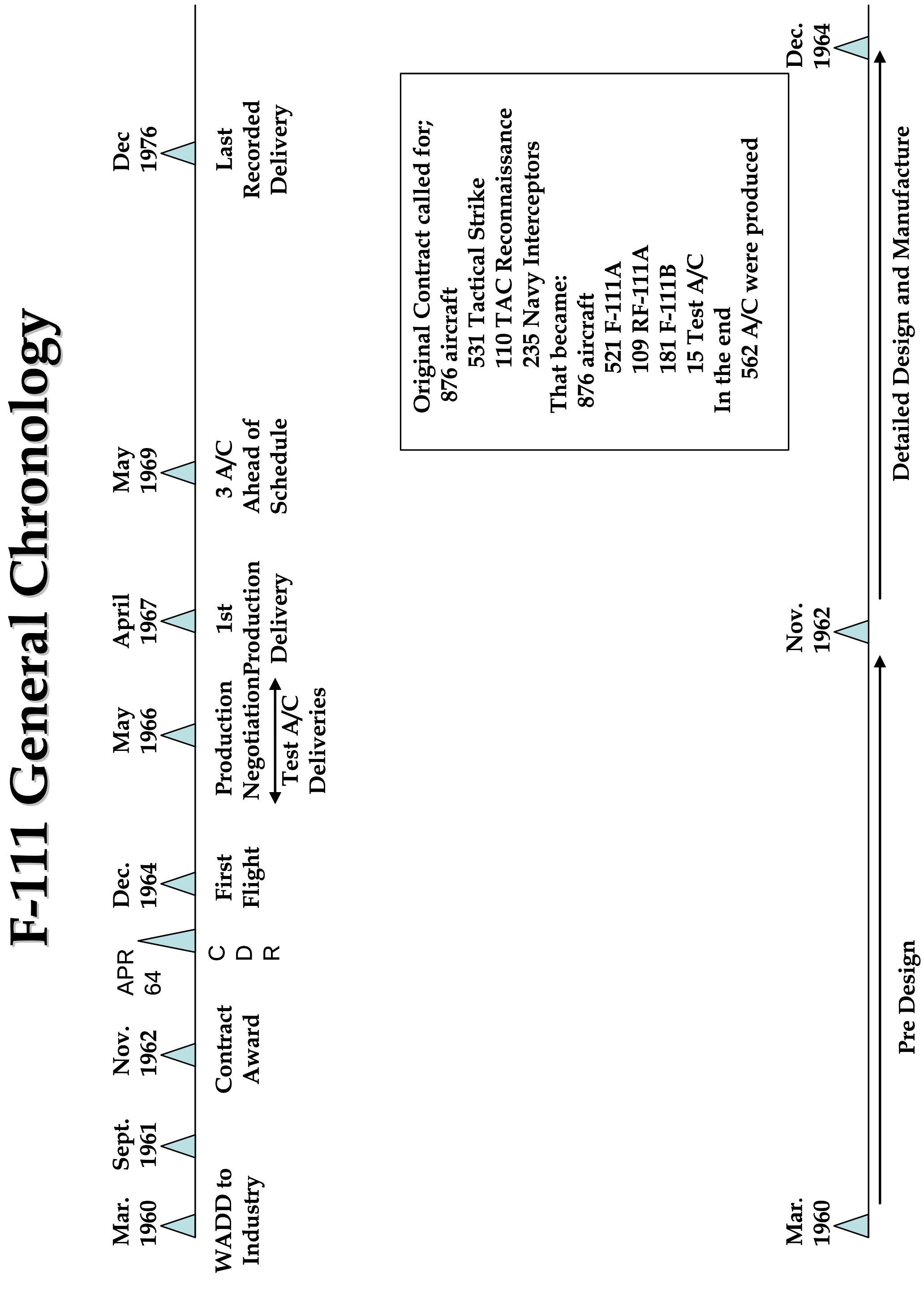
F-111 Variants (Cont'd)

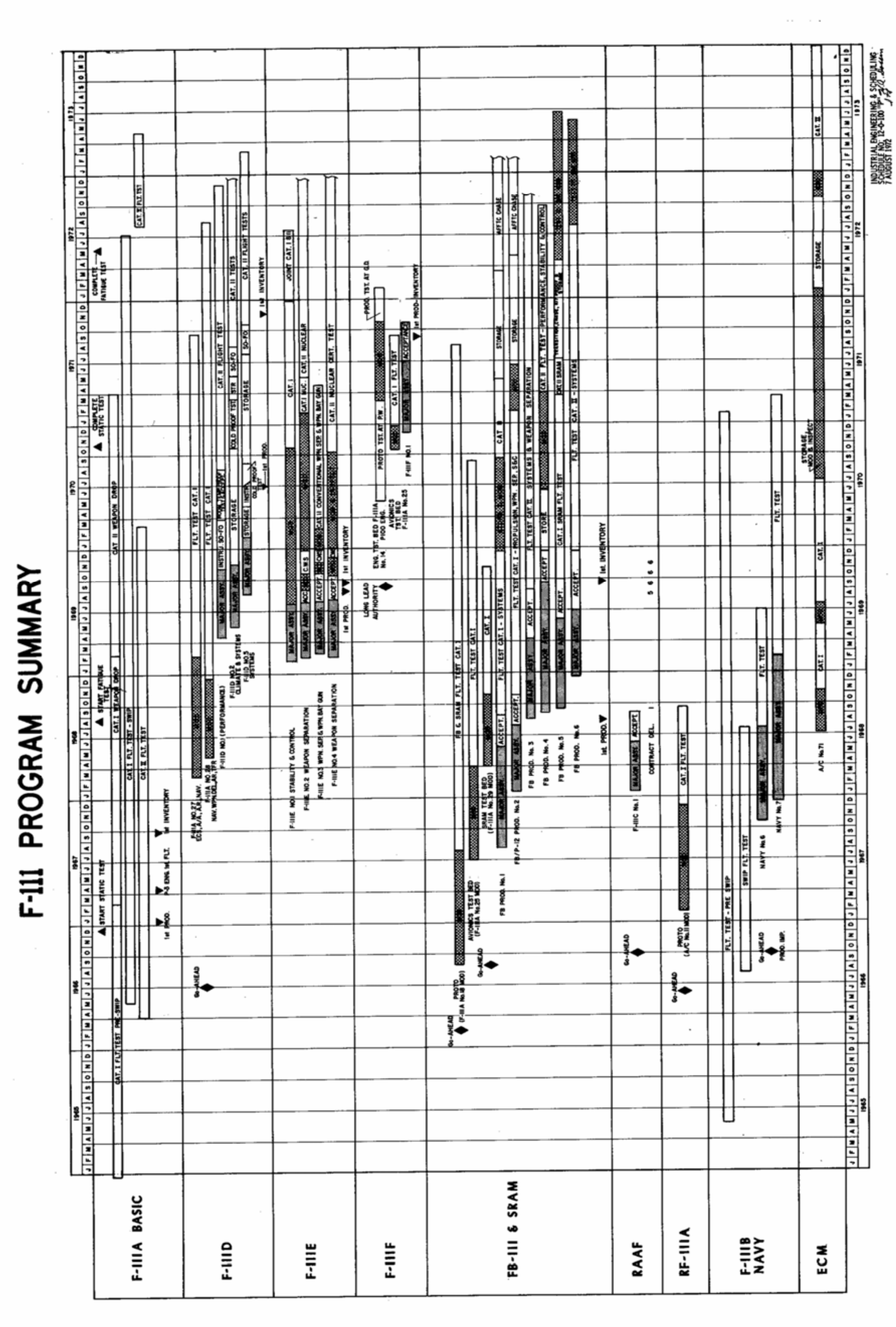
F-111 Variant	F-111A	EF-111A	F-111B	F-111C	F-111D	F-111E	F-111F	FB-111A
Inertial navigation and ballistics system	Mk. I; AJQ-20A, BCU	Mk. I; AJQ-20A, BCU	LN INS, CP741	Mk. I; AJQ-20A BCU	Mk. II; AJN-16 AYK-6	Mk. I; AJQ-20A, BCU	Mk. IIB; AJN-16, AYK-6	Mk. IIB; AJN-16, AYK-6
Special equipment	-	ALQ-99E, JSS	IRSTS, V/HUD displays	AVQ-26, Pave Tack	AVA-9 displays	-	AVQ-26 Pave Tack	ASQ-119 Astrocompass
Special weapons	B61	-	AIM-54 Phoenix	AGM-84 Harpoon, AGM-88, HARM, GBU-15, Paveway laser	B61	B61	B61, GBU-15, Paveway laser	B61, AGM-69, SRAM
Self-protect jammer	ALQ-94	ALQ-137	-	ALQ-94	ALQ-94	ALQ-94	ALQ-94	ALQ-137
Radar warning receiver	ALR-62	ALR-62	-	ALR-62	ALR-62	ALR-62	ALR-62	ALR-62
Countermeasures receiver	AAR-34	-	-	AAR-34	AAR-34	AAR-34	AAR-34	AAR-34
Countermeasures dispenser†	ALE-28	ALE-28	ALE-29	ALE-28	ALE-28	ALE-28	ALE-28	ALE-28
Strap-on ECM	ALQ-131	-	-	-	ALQ-131	ALQ-131	ALQ-131	-
Conversions	1 to FB-111A; 1to RF-111A; 4 as F-111C; 42 to EF-111A; 1 to NASA	-	-	4 to RF-111C	-	-	-	60 to F-111G
Nos. built	159	42	7	24	96	94	106	76
RDT&E and pre-production	30	(2)	7	-	-	-	-	2

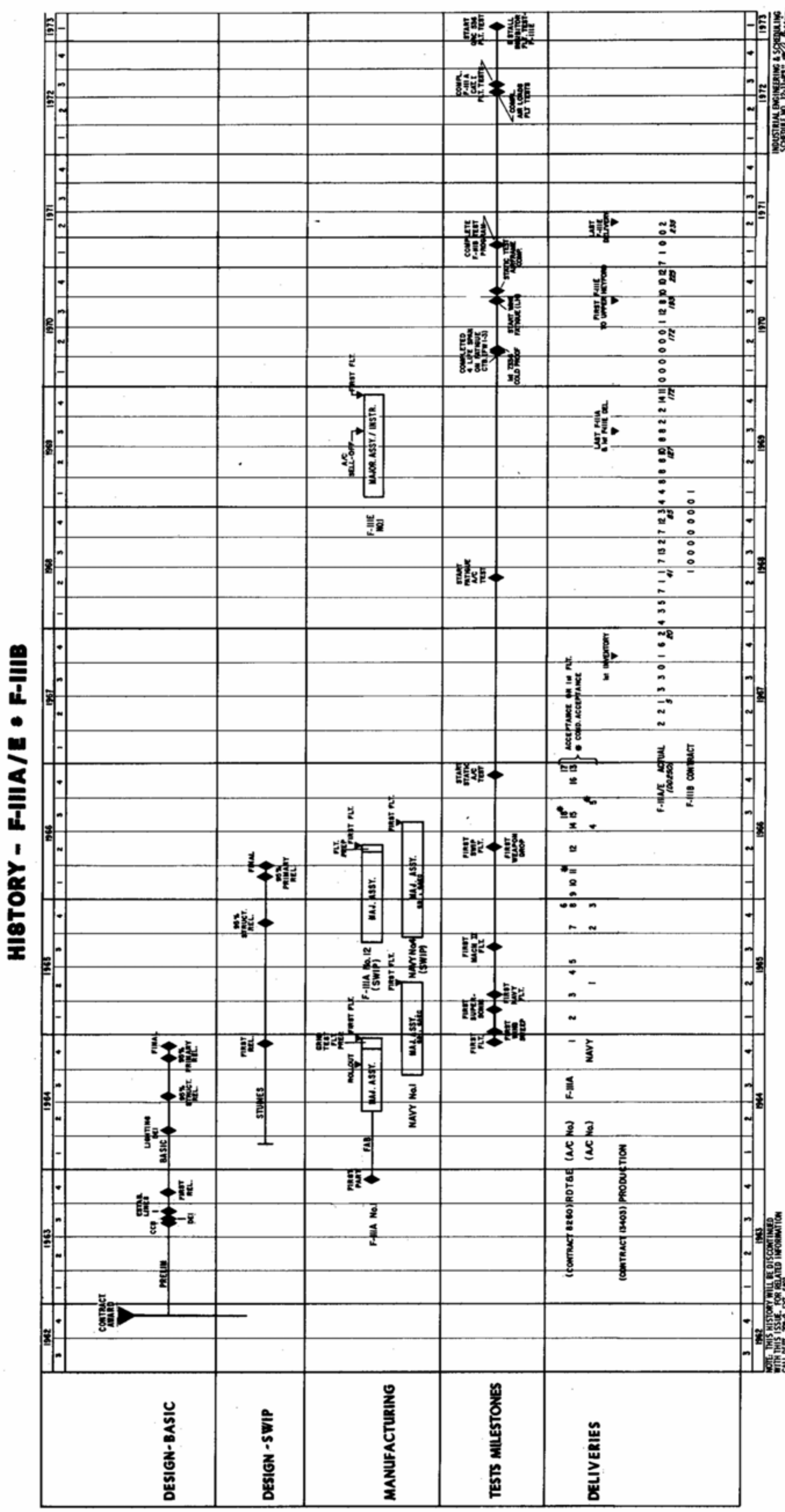
*Replaced with the AN/APG-67 during AMP. †Replaced with the AN/ALE-40 during AMP.

Appendix 4

Program Milestone Charts




F-111 PROGRAM SUMMARY
F-111A BASIC
F-111D
F-111E
F-111F
FB-111 & SRAM
RAAF
RF-111A
F-111B NAVY
ECM


HISTORY – F-111A/E • F-111B
DESIGN-BASIC
DESIGN-SWIP
MANUFACTURING
TESTS MILESTONES
DELIVERIES

Appendix 5

F-111 Combat Operations

Operational Experience

Based on the results of the *Combat Bullseye I* tests of the spring of 1967, the Air Force decided to send a small detachment of F-111As to Southeast Asia under a program known as *Combat Lancer*. This program was preceded by the *Harvest Reaper* program of June 1967 which was intended to identify known F-111A shortcomings and to prepare the aircraft for combat. It was anticipated that the *Harvest Reaper* modifications would enter the F-111A production lines if they were successfully proven in combat.

Six 428th Tactical Fighter Squadron F-111As were allocated to the *Combat Lancer* program, and departed Nellis AFB for Thailand on March 15, 1968. By the end of that month, 55 night missions had been flown against targets in North Vietnam, but two aircraft had been lost. Two replacement aircraft arrived from Nellis, but the loss of a third F-111A on April 22 halted F-111A operations. The surviving five aircraft returned to Nellis AFB on November 22, 1968.

It turned out that three F-111A losses were not due to enemy action but were caused by a tail structural defect or other problems. One of the *Combat Lancer* crashes has been traced to a malfunction of the aircraft's tail servo actuator which could cause a sudden and uncontrollable pitch-up. The AF SPO and GD took appropriate action to correct the deficiencies from this initial operational experience.

The F-111A returned to Southeast Asia in September of 1972. Two F-111A squadrons (the 429th and 430th) left Nellis AFB for Thailand. They participated in the *Linebacker II* aerial offensive against North Vietnam. They flew bombing missions against targets in North Vietnam and Laos in the midst of the monsoon season. They flew without electronic countermeasures escort aircraft or KC-135 tankers. On November 8, 1972, they flew 20 strikes over North Vietnam in weather that grounded other aircraft. Four F-111As could deliver the bomb loads of 20 F-4s. The 429th and 430th TFS flew some 4,000 combat missions with excellent success rates in hitting targets even when visibility was near zero. Only six aircraft were lost in action. (A 0.15% loss rate) from ground fire and some anomalies in the terrain following radar.

When the F-111As returned to Nellis there were a few modifications made to them. The Electronic Counter-Measures (ECM) suite was updated and a target-offset box was added. The main impact was on training. In Vietnam, the Air Force learned how to use the F-111. The 4,000 sorties flown in Vietnam became the basis of all F-111 operations and training thereafter. Although the F-111 was originally designed as a high speed/low altitude penetrator carrying its weapons internally, the actual operational use of the F-111 in Vietnam and other operations was often at much slower speeds and higher altitudes where the F-111 could be "loaded up" with multiple bombs in a saturation bombing role. Using all the wing pylons, and NOT sweeping the wing beyond 26 degrees, the F-111 could carry up to 48 Mk 82 (500 lb) bombs (Figure A5-1). Thus the F-111 had several times the ordnance-delivering capacity of other fighter-bombers such as the F-4. Often, a weapon system is designed for one purpose and actually used in a different role. The flexibility of the F-111 design served the Air Force well to provide needed operational flexibility.

Figure A5-1. Forty Eight Mk82 Bombs on USAF F-111

Other Operations

Twenty four F-111s from the 48th TFW based at Lakenheath spearheaded the US attack on Libya on the night of April 14, 1986, striking targets in Tripoli with laser-guided and retarded bombs. One F-111F and crew was lost to ground fire during the attack.

Desert Storm 1991 (IRAQ)

During *Desert Storm* in 1991, 67 F-111Fs of the 48th TFW operated from air bases in Saudi Arabia. Because of their ability to deliver precision-guided ordinance in all-weather conditions, they played a key role in the destruction of the Iraqi command and control structure and in the elimination of key targets in the Kuwait theatre of operations. These aircraft flew 2,500 sorties, destroyed 2,203 targets, including direct hits on 920 tanks, 252 artillery pieces, 245 hardened aircraft shelters, 13 runways, 113 bunkers, and 12 bridges. A total of 5,500 bombs were dropped. Almost 85 percent of these bombs were precision guided munitions. When Iraqi forces deliberately opened on oil pumping station manifold to allow oil to leak into the Persian Gulf, an F-111F was selected to deliver theGBU-15 electro-optically guided bomb against the manifolds to stop the flow. One the last night of the war, two F-111Fs delivered 5,000 lb GBU-28 deep-penetrator “bunker-buster” bombs against Iraqi command and control bunkers. These bombs could penetrate over 100 feet of earth or 22 feet of concrete.

Current Operations

All USAF F-111s were retired from active service in 1996. The Royal Australian Air Force (RAAF) still operates F-111Cs, RF-111C reconnaissance pod-equipped aircraft, and F-111G models which were converted from USAF FB-111As. The RAAF currently plans to operate the F-111 until about 2020.

Appendix 6

F-111 Transonic Drag

It was well known (in the 1950's) from aerodynamic theory and test that Mach 1.2 could be within the "transonic drag rise" which occurs when an aerodynamic body accelerates from about Mach 0.7 to about Mach 1.4. This Mach range (dependent on body cross-sectional area distribution and ratio of body length to diameter) is where the shock waves are nearly perpendicular to the surface and the resultant pressure distribution on the body creates the most drag. See Figure A6-1 for shock structure on a wing alone.

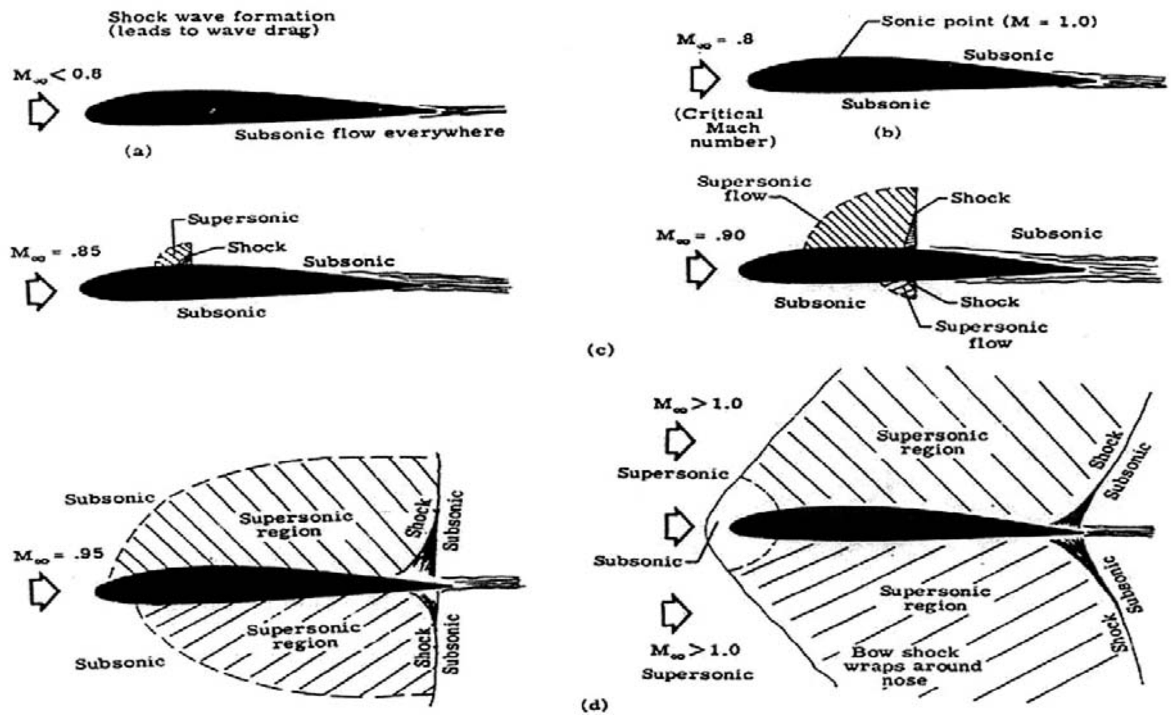


Figure A6-1. Subsonic and Supersonic Shock Structure on Wing

Below transonic drag rise (about Mach 0.9 for the wing shown in Figure A6-1), the shocks are localized and weak, and do not cause high drag. At Mach numbers greater than 1.0 (again, for the wing shown in Figure A6-1), the shocks are more oblique to the body surface and the pressure distribution creates less drag, but still more drag than at subsonic conditions.

For a wing-body shape like the F-111, the flight speed where the drag is higher tends to be over a wider Mach number range than for the wing alone, and may extend up to Mach 1.4. Figure A6-2 is illustrative of the transonic drag rise for a "generic" aircraft, but it illustrates the drag rise problem. Phi (ǿ) is the vehicle angle of attack. Note the drag increase for ǿ =0 degrees between Mach 0.75 and Mach 1.2.

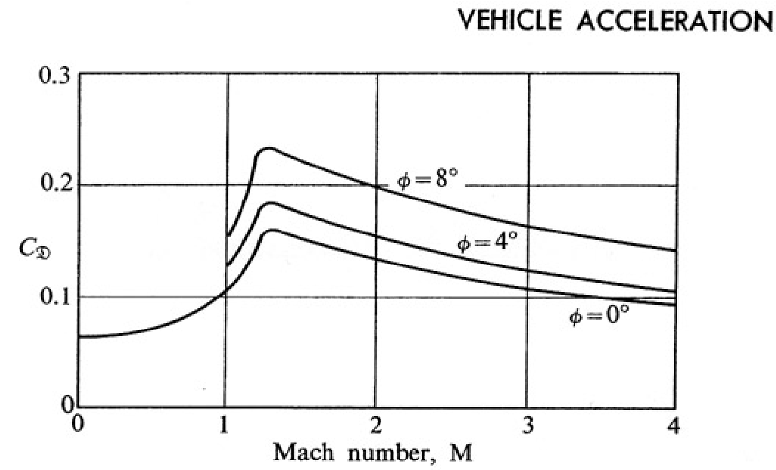


Figure A6-2. Typical Drag vs Mach Number for a Generic Aerodynamic Vehicle

A typical drag curve for a wing with various wing sweeps is shown in Figure A6-3. Higher wing sweep reduces drag, as expected, but there is still a drag increase at Mach numbers above about 0.95, even at the highest sweep. GD and the government knew that variable sweep would reduce the transonic drag, but they over-estimated the drag benefit of the swing-wing when integrated into an aircraft.

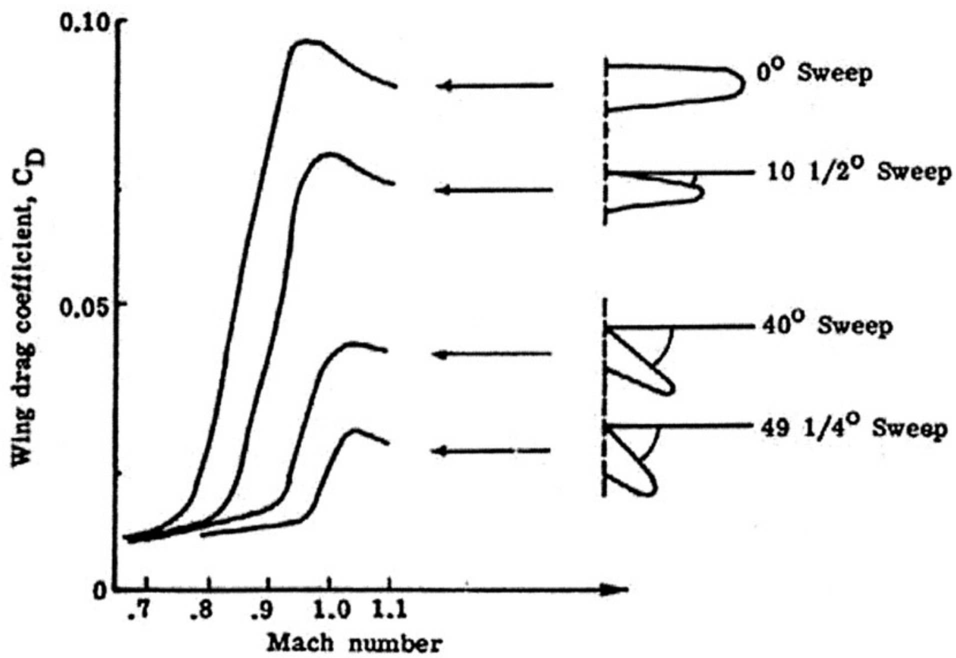


Figure A6-3. Wing Drag vs Mach Number for Various Degrees of Wing Sweep

General Dynamics knew the drag at Mach 1.2 would be high but their analysis, based on data from a small scale model in the Cornell Aeronautical Lab transonic tunnel, indicated that the 200 NMi dash requirement could be met. NASA Langley had tested an F-111 model in their larger transonic tunnel and the drag was indicated to be considerably higher. Using the NASA data, the 200 NMi dash would be less than 100 NMi. Eventually the NASA data was shown to be more nearly correct, and when all the flight test data was in, the predicted dash distance was only 39 NMi.

The Air Force was also concerned but various drag-reduction techniques were ineffective; for one reason, the nozzle-afterbody drag was double that expected due to separated flow in the nozzle area and poor performance of the blow-in door ejector nozzle, which is suitable for clean flow, but had decreased thrust and higher drag at Mach 1.2 in the complex F-111 configuration (Figure A6-4). Flight test data showed that the complex flow field caused some of the blow-in doors to be closed at subsonic cruise, when they were supposed to be open to enhance nozzle performance.

Figure A6-4. F-111 Nozzle-Afterbody

In summary, although drag at the supersonic low altitude was identified as an issue, the impact that the contractor had on mitigating the risk and solving the issues was minimal. The design was "locked in" by Critical Design Review (CDR) in 1964, even before first flight, to meet the disparate AF and Navy mission requirements, and the contractor did not have a good enough understanding of aerodynamics on a complex, tightly integrated configuration. This is not the fault of the contractor. The state of the art of complex aerodynamics was not as well understood in the 1960's as it is now, with the advent of Computational Fluid Dynamics (CFD) analysis methods.

Appendix 7

F-111 Inlet-Engine Compatibility Problem

During development of the F-111, there was a problem with flow incompatibility between the inlet and engine compressor of the TF-30. It was well known at the beginning of the F-111 program that a high level of inlet flow distortion at the inlet exit/compressor face plane could cause compressor stall where the compressor blades, which are like small airfoils, encounter local regions of low pressure air, which increases the lift coefficient required to maintain pressure ratio to an unacceptable (compressor blade stall) level. A partial compressor stall (also called a rotating stall) could then propagate to other blades and cause the entire compressor to stall. The fuel control system would sense this loss of pressure and shut down the engine. A re-start procedure would be necessary when the inlet flow distortion is reduced, usually by lowering the aircraft angle of attack or air speed.

What was not known prior to F-111 development was that high performance engines, such as the TF-30 afterburning turbofan, are sensitive to **time-dependent** inlet flow distortion where the inherently unsteady flow in the inlet duct can produce regions of distortion that are much higher than the time-averaged distortion that is measured by slow-acting pressure rake surveys in the duct. If the higher unsteady distortion region lasts long enough for all the fan/compressor blades to pass through it once, the compressor will stall just as if the distortion were steady state. This is known as time-dependent distortion/engine incompatibility. Certainly time-dependent distortion had been present in every supersonic inlet developed during the 1950's in fighter aircraft preceding the F-111, but the engines were less-sensitive pure turbojets and the inlets were in most cases less integrated with the aircraft than the F-111 design. Thus the severity of the unsteady distortion/engine compatibility problem was unknown to the contractor or the government at the beginning of the F-111 program.

The baseline F-111A inlet (Figure A7-1) had been tested extensively in wind tunnel tests using scale models of the inlet/fore-body/wing glove of the F-111, but the tests had used slow-response (steady) pressure transducers to survey the flow patterns at the inlet duct exit. A distortion parameter called K_D (Figure A7-2) had been developed by Pratt and Whitney where if the inlet flow distortion was below a certain critical value of K_D, the compressor would not stall. This critical K_D had been determined by testing the TF-30 engine/compressor behind mesh screens which generated different patterns of steady flow distortion. The K_D parameter was based on the depth and radial extent of the pressure deficit. So for a given distribution of inlet exit flow from a wind tunnel test, the value of K_D could be computed and compared to the critical K_D value. By testing the inlet over a range of Mach numbers and aircraft angle of attack or slide-slip, the inlet K_D values could be mapped out to ensure compatibility between inlet and engine in flight. The F-111 inlet was known to have somewhat high flow distortion from the wind tunnel tests, but the data indicated the K_D was less than the critical value, so no compressor stalls were expected.

However, there were compressor stalls on the very first flights of the F-111A beginning in December 1964, both in flight and, in some cases, on the ground during engine run-up. The test pilots learned to advance the throttles gingerly as they took the F-111A down the runway to take off. In the early F-111A flights there were numerous compressor stalls during maneuvers, both subsonic and supersonic, and compressor stalls in non-maneuvering flight at Mach numbers greater than about 2.0 (Figure A7-3). The original F-111 inlet had reduced performance and high compressor face flow distortion at Mach numbers approaching 2.0 (Figure A7-2). Note the sharp increase in compressor face flow distortion above Mach 1.8. This is because the external compression inlet is starting to go supercritical. There were also compressor stalls during afterburner light-offs. It turned out that the turbofan bypass duct flow is subsonic, so the pressure pulses associated with the afterburner staged ignition were propagated forward, and increased the back-pressure on the fan. This in turn could cause fan stall which then became a full-fledged compressor stall.

Needless to say, the compressor stalls restricted the test program to evaluate maneuvers, loads, handling qualities, etc., and the stalls were clearly unacceptable to future operations of the F-111. Even though the problem was un-anticipated, swift corrective action was needed to develop a compatible inlet-engine system, and the problem soon elevated to the attention of the Air Force, Navy leadership and to SECDEF, Mr McNamara. The F-111 SPO, led by Mr Fred Rall, and the contractor team, led by Mr Cal Porcher, began to immediately search for solutions. Through various iterations where an inlet configuration change would be evaluated in the wind tunnel and then flight-tested, the original inlet (Figure A7-1) was modified into what is known as Triple Plow I (Figure A7-5) with a modified cowl lip, bulged splitter plate, modified boundary-layer bleed, duct vortex generator pattern, etc. When improvements in flight were less successful than expected from the wind tunnel tests, which indicated reduced K_D with the re-designs, another cause of the incompatibility was sought. Through a series of special teams chartered by the SPO, including propulsion and inlet experts from the Air Force Labs and Arnold Engineering Development Center (AEDC), it was postulated in 1967, over two years after first flight, that the root cause of the problem was the unsteady flow distortion and that a time-dependent critical K_D needed to be considered, or at the very least, a "turbulence factor" (T_u – Figure A7-4) added to the steady K_D in order to evaluate inlet configuration changes. In 1966 and 1967, the F-111A test aircraft number 14 and 15 were instrumented with at least some unsteady pressure transducers, and the wind tunnel test inlet models were similarly instrumented. When the unsteady distortion patterns were replicated as distortion screens in the engine tests, there was improved correlation between critical K_D and engine stalls which verified the unsteady distortion postulate, but there were still cases in flight tests where the engine would stall at values less than the critical K_D.

The Triple Plow I inlet (Figures A7-5,7,8,) opened up the stall-free envelope to about sixteen degrees angle of attack at subsonic maneuvers, allowed moderate maneuvers at up to Mach 2.0, and greatly reduced the occurrence of compressor stalls at take-off. The Triple Plow I inlet is used on all F-111As, including the F-111As converted to the EF-111A configuration, all Australian F-111Cs, and the few F-111Bs produced.

In early 1967, when it was apparent from numerous compressor stalls in flight test that the Triple Plow I inlet still had high distortion at higher angles of attack where the fuselage boundary layer ahead of the inlet thickened more than the depth of the splitter plate, and that at Mach numbers greater than about 2.3 the terminal shock was entering the inlet (going supercritical), the SPO and General Dynamics designed a more radical inlet re-design known as Triple Plow II (Figure A7-6) where the entire inlet was moved outboard 4 inches, the splitter plate was removed entirely, and a new (18 inches longer) inlet spike was installed with a revised bleed pattern and spike movement/cone angle schedule (Figures A7-7,8). This required a modification of wing glove structure, and re-tooling of the production F-111s.

Wind tunnel testing showed a dramatic reduction of time-dependent distortion and subsequent flight test verified that the aircraft could fly stall-free to Mach 2.5, with full maneuverability at Mach 2.2 and below. The hydraulically actuated translating cowl (used to provide extra air at take-off) on Triple Plow I was replaced by three suck-in doors on each Triple Plow II inlet (Figure A7-9) which operated on airflow demand rather than positive control, thereby improving safety since no mechanical control was required.

Triple Plow II was installed on all USAF F-111D, E, F and G models and on all but the first production FB-111 aircraft. Fifteen F-111Gs (modified from FB-111As) with Triple Plow II inlets and TF-30 P-7 engines were sold to Australia and delivered in 1993/1994 to keep the RAAF F-111 fleet operational to 2010. The transonic drag (Mach 1.2) was somewhat higher with Triple Plow II, but by 1967, the transonic sea level dash distance was so far reduced from the original 200 NMi specification that the SPO agreed that having a stall-free aircraft was preferable to losing a few more miles of dash distance.

Impact on Later Inlet-Engine Compatibility Solutions

After the F-111 inlet-engine compatibility problem, the Air Force Propulsion and Flight Dynamics Labs, AEDC and NASA began an intensive research program in 1967 to evaluate inlet designs and compressors on the basis of true **instantaneous** distortion indices using unsteady pressure data filtering techniques, which were eventually processed in a dedicated analog computer system called DYNADEC, to convert unsteady pressure data from a 40- probe array at the inlet duct exit/compressor face plane to a series of total pressure maps which would then be used in compressor tests.

A little before this time, wind tunnel and flight tests of the XB-70 aircraft had produced hints of the unsteady distortion (inlet turbulence) phenomena. These early hints of compatibility problems came in the form of un-anticipated compressor stalls, not understood at the time. The stalls were not as frequent nor anywhere near the program show-stopper that was experienced with the F-111. However, they were a problem and Dr William Kimzey of AEDC and Richard Lewis of General Electric developed a special engine test rig for the XB-70's YJ93 engine to explore this problem. The rig used an axisymetrical venturi (converging-diverging duct) with a translating center body operating super critically. It produced unsteady distortion from the shockwave and boundary layer interactions in the divergent flow channel and was called an "Aircraft Inlet Turbulence Generator". This device, in effect, crudely reproduced the terminal shock system of a supersonic aircraft inlet. The strength of the interaction and severity of the resulting time-dependent distortion could be regulated by changing the pressure ratio across the device and/or changing the center body position. An improved version of this device was later applied at Pratt and Whitney with the TF30 engine supporting the F-111 program by Gary Plourde of Pratt and Whitney and Brian Brimlow of the Air Force Propulsion Laboratory. It was from a combination of these experiments that the nature of time-dependent distortion, its effect on engines and methods to test and correlate results were first developed. Following these experiments, a more controllable test rig using an array of individually controlled small jets in the duct upstream of the engine in ground tests of compressors or engines was developed to better represent time-dependent distortion. This device was computer controlled and allowed desired patterns to be "dialed in". The concept was proposed at AEDC by Kimzey and the system developed by Glen Lazalier, Wade Stevenson and William Overall also of AEDC. By duplicating the inlet flow patterns from the inlet tests in a full scale engine test with the selection of the proper jet efflux pattern, it was shown that there was good correlation between separate ground tests of the inlet and engine with actual flight test of inlet and engine. Various versions of other similar devices and test methods were employed at AEDC, NASA, Glenn (Lewis) Laboratory, at Allison Engines and at other locations that contributed to the overall solution of this problem. Also, with the understanding provided by the above described work, computer programs were developed at AEDC that allowed the **instantaneous maximum severity distortion pattern to** be designed into a simple wire mesh distortion screen placed in the duct in front of the engine. A few different screens were often needed to cover the desired range of aircraft operating conditions. In many programs, this less expensive approach coupled with compression system and engine stability math models was sufficient to validate compatibility for a particular inlet-engine combination and operating range. If a great number of different patterns were needed, the air jet system was the most economical solution. This process was used extensively in the F-15, F-14, F-16, B-1 and all subsequent supersonic inlet development programs. The inlet-engine compatibility problems fully came to light during the F-111A development, but all aircraft programs, both in the US and overseas, are the beneficiary of the research spawned from the F-111 experience.

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Interview, Robert Widmer

Personal recollections G.K. Richey

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NASA TN D-6679 Flight-Determined Characteristics of an Air Intake System on an F-111A Airplane, D.K. Hughes, J.K. Holzman and H.J. Johnson, NASA Flight Research Center, Edwards, CA

AIAA Paper 95-0950, 1995 Wright Brothers Lectureship in Aeronautics, AIAA Journal of Aircraft Vol. 33, Number 4, pp. 649-679, "*Marrying Airframes and Engines in Ground-test facilities – An Evolutionary Revolution,*" Robert E Smith, Jr.

Figure A7-1. Original F-111A Inlet. Note Flat Splitter Plate and Wedge-shaped Ducts Next to Fuselage and Wing that Capture Boundary Layer and Duct it Aft.

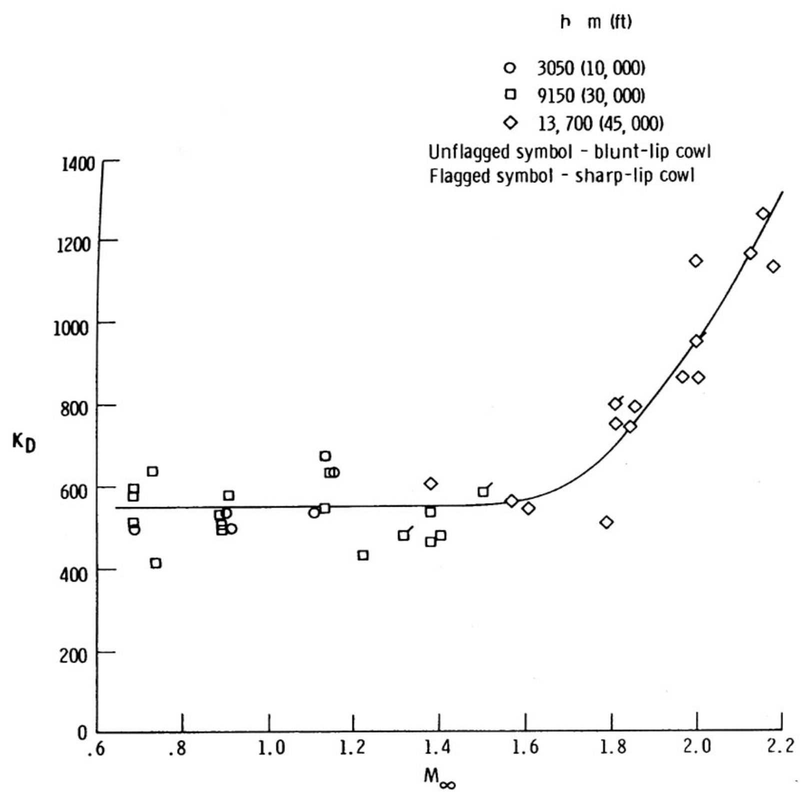

Figure A7-2. F-111A Inlet Flow Distortion Kd vs Mach Number (Flight Data)

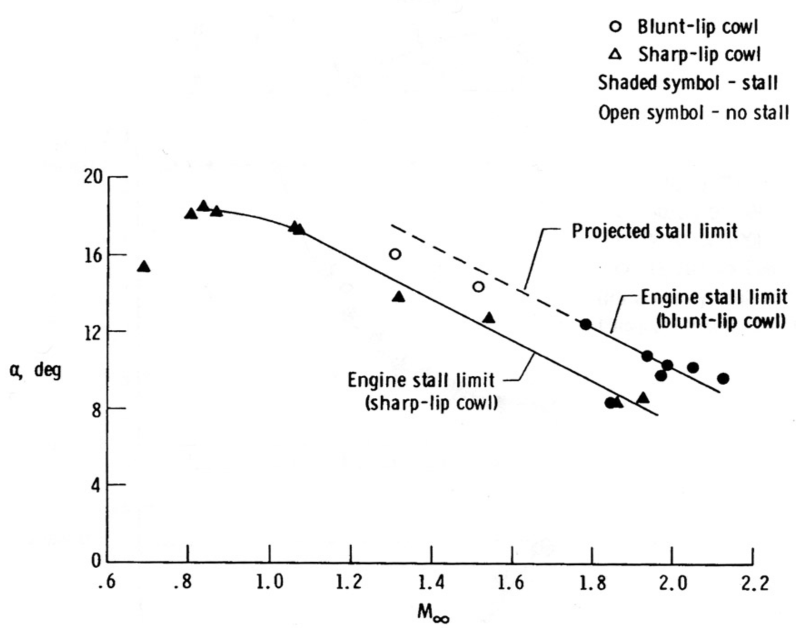

Figure A7-3. F-111 Compressor Stall Envelope

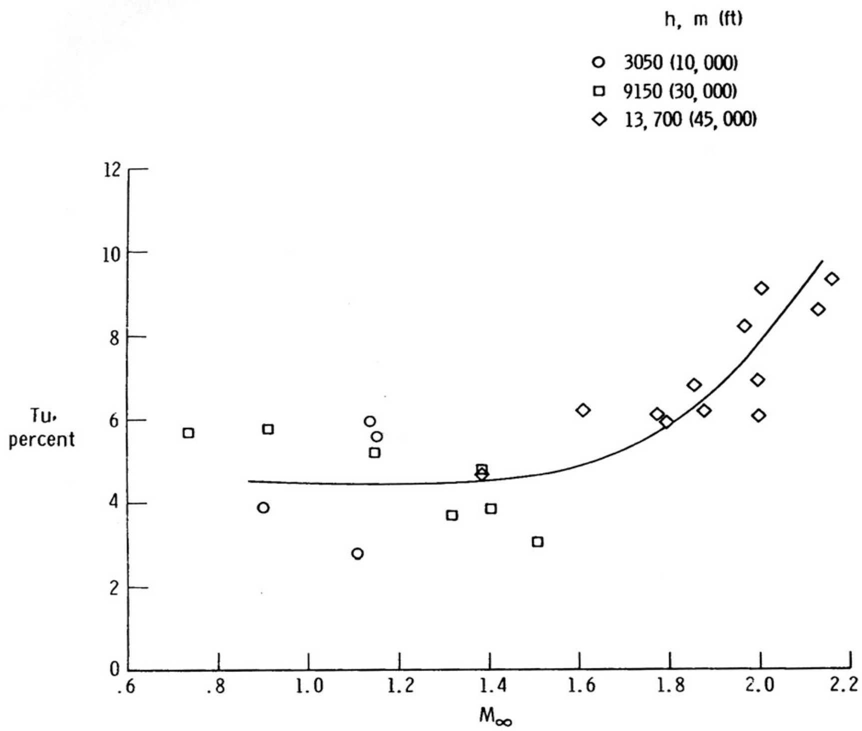

Figure A7-4. F-111 Inlet Flow Turbulence (Flight Test Data)

Figure A7-5. Triple Plow I – Note Bulged Splitter Plate, Plows to Divert (Not Capture) Fuselage and Wing Boundary Layer and Thickened Lower Cowl Lip

Figure A7-6. Triple Plow II – Note Wider Distance from Fuselage, No Splitter Plate

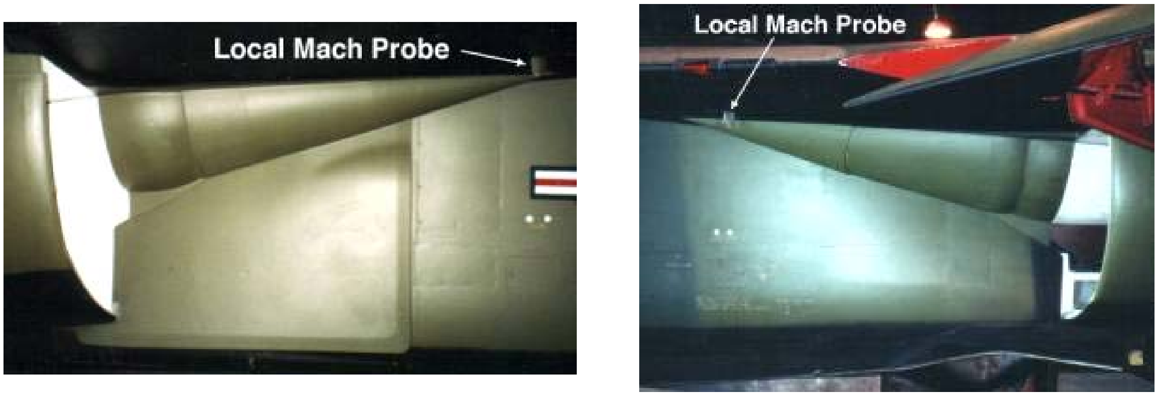

Figure A7-7. Triple Plow I Inlets (left) were most easily distinguished by the large splitter plate. Note how the inlet spike barely reached the local Mach probe. Triple Plow II inlets (right) eliminated the splitter plate and the inlet spike was 18 inches longer than on the earlier inlet, extending well past the local Mach probe.

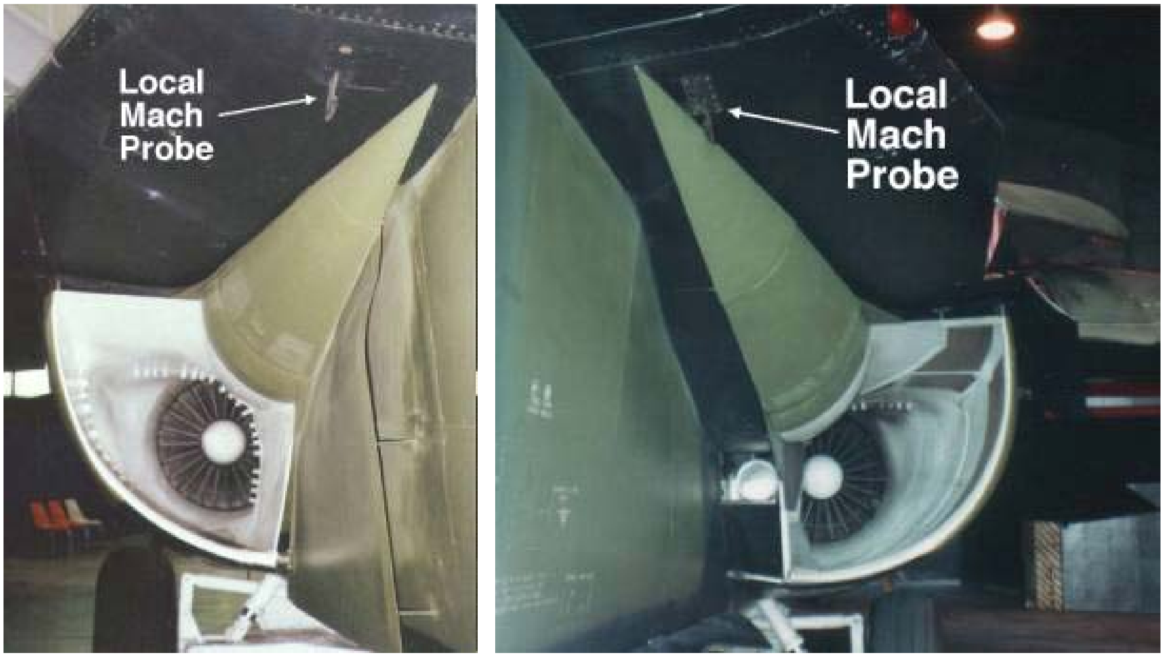

Figure A7-8. Triple Plow I and Triple Plow II: This head-on view of the Triple Plow I inlet on the left clearly shows the warped shape of the splitter plate. Note how far inboard of the local Mach probe the spike is. The Triple Plow II inlet on the right shows that the splitter plate has been removed and the entire inlet moved outboard 4 inches (note how close it is to the local Mach probe).

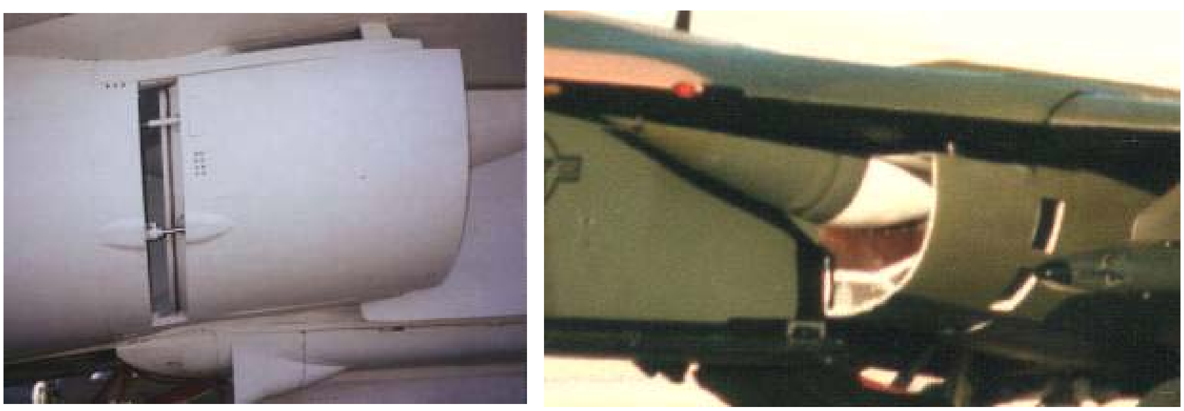

Figure A7-9. The Triple Plow I translating cowl (left) and the three suck-in doors of the Triple Plow II inlet (right).

Appendix 8

Wing Carry Through Box Failure and Impact on Subsequent Aircraft Development

Description of Aircraft and its Mission

The F-111 aircraft, the first U.S. production swing-wing flight vehicle, was a supersonic all-weather multipurpose tactical fighter bomber developed as a result of the Department of Defense plan for a single aircraft to fulfill both a Navy fleet-defense inceptor requirement and an Air Force supersonic strike aircraft requirement (Figure A8-1). Its variable sweep wings enabled both short distance take offs and sustained low level supersonic flight. Serving as the baseline design, the U.S. Air Force F-111A proved to be too heavy to be tailored to the constraints of carrier-based naval operations. Thus the F-111B Navy version did not reach production status [Ref.1].

Figure A8-1. F-111A

The multiple roles and wide speed range of this aircraft placed significant requirements on its aerodynamic configuration and leaving a very minimum of volume space available to the structural designer [Ref. 2]. The resulting higher design unit loadings led to the requirement for a very high strength and high stiffness material. Based on a comparison of stress corrosion cracking resistance, fatigue properties, and fracture toughness index, D6ac steel, heat treated to 200-220,000 psi ultimate tensile strength, and some application at 260,000 – 280,000 psi, was chosen from among several other high strength steels. Figure A8-2 illustrates the principal critical F-111 structural components fabricated from D6ac steel. These included the wing pivot fitting, the wing carry through box (WCTB), major fuselage frames and longerons, as well as the more conventional nose and main landing gear. In addition, literally hundreds of small detail D6ac steel parts were used throughout the airplane. The total weight of steel in the airplane exceeded 7,000 pounds or approximately 30% of the structural weight. The majority was concentrated in the wing pivot fitting and the WCTB and wing supporting structure. Figure A8-3 shows a pivot fitting being readied for mating to a WCTB during manufacture. The remainder of the airframe structure was fabricated mostly from aluminum alloys. The design load factors (Nz values) were -3 g to +7.33 g, and the original design life goals were 4,000 flight hours and ten years of service.

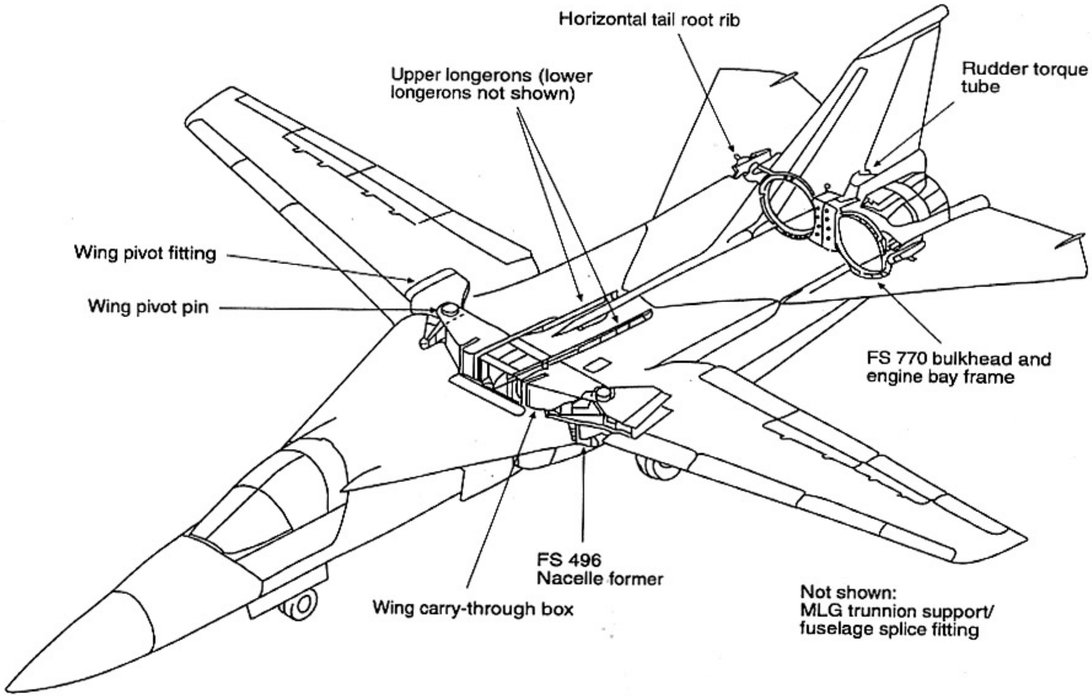

Figure A8-2. F-111 D6ac Structural Components

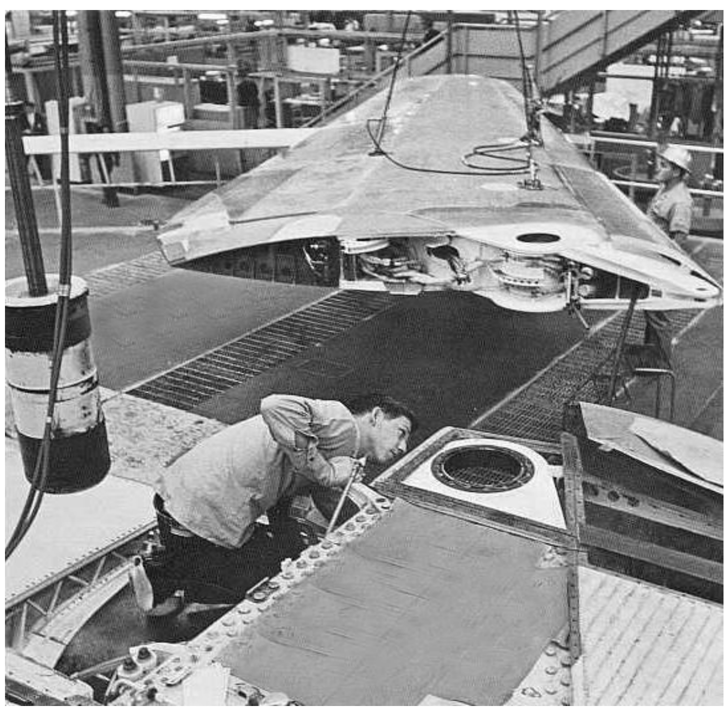

Figure A8-3. F-111 Wing Pivot Fitting and Wing Carry-Through Box Structure

Safe-Life versus Static Strength Criteria

The F-111A was among the first aircraft systems to be developed using the “safe life” design philosophy. Following several disastrous aircraft failures (e.g., De Havilland Comet transport fuselages, 1954 and AF B-47 bomber wings in the mid to late 1950s), which were later attributed to metal fatigue, the importance of adding the effect of cyclic fatigue loading to the traditional static strength model, and designing to a target safe fatigue life was recognized as an essential major design philosophy shift [Ref.3]. This design approach was introduced in the new Air Force Aircraft Structural Integrity Program (ASIP) methodology developed in the late 1950s and early 1960s [Ref.4]. Expanded data bases of fatigue tests of aircraft materials and representative component parts generally supported the upgraded design process. The safe-life methodology initially utilized a Minor’s rule fatigue analysis process incorporating the cumulative effects of cyclic loading on the subsequent strength and the remaining safe (fatigue) life of the airframe.

Structural Tests and Issues during Development

A full-scale static strength test program was conducted, and after several local redesigns to correct strength deficiencies, the test was completed successfully. Next, a full-scale fatigue test program was initiated in 1968, with the entire program lasting about six years. The goal was to demonstrate the original 4,000 flight hour safe-life design of the full F-111 airframe and various representative components to a safety factor of 4x, or 16,000 test hours, as required by ASIP, using a relatively severe block-type spectrum loading [Ref. 2]. However, after less than 600 cyclic test hours, failure occurred unexpectedly in the WCTB at approximately 80% simulated flight usage. As a result of the severe damage to the test article, the test program was revised to continue testing on separate major components (i.e., wing, fuselage, etc.) rather than the complete airframe. This failure, which occurred on 26 August 1968, was the initial event in the series of subsequent F-111 structural problems. A fatigue crack initiated in a taper lok bolt hole, associated with fastening the rear spar web stressed door to the spar assembly, and failure progressed rapidly through the lower rear spar and lower box cover plate – causing complete failure of the WCTB. A thorough investigation concluded that the hole was cracked either before or during the installation of the taper lok bolt. A re-inspection of over 5,000 taper lok holes in all of the WCTBs manufactured by that time found no cracks; however, the quality of some holes required rework and improvement.

A second failure of the test article WCTB, which occurred in February 1969 after 2,800 test hours, originated in a 3/16 inch diameter straight through hole in the lower plate of the box. The hole, which was located at the intersection of a spanwise and a chordwise plate stiffening element, had been used to secure a mounting bracket for hydraulic lines. The small fatigue zone on the fracture face consisted of multiple origins on the interior surface of the hole, producing an effective crack length of approximately 0.6 inch and depth of 0.35 inch. Investigation revealed that small sharp indentations were present in the hole from post-heat treatment grit blasting. Cracking was initiated by local bending effects not accounted for in the original fatigue analysis. To correct this condition, the holes were taper-reamed and a taper lok bolt installed. Subsequently, all holes in the WCTB were inspected to reveal over half of the 23 holes similar to the above hole were cracked; thus, all received the corrective action.

Concern over the inability of available NDI/E practices to detect these cracks initially led the manufacturer, General Dynamics Corporation, to create a new patented technique named magnetic rubber inspection (MRI), a variant of the established magnetic particle inspection (MPI), which uses a fast-curing liquid rubber containing dispersed black magnetic particles. After the liquid is introduced into the area to be inspected, an applied magnetic field causes the particles to migrate through the liquid and concentrate in vivid dark lines at cracks in the test surface shown in Figure A8-4. Once cured, the solid reversed replica is removed from the test surface. The example shown is a reversed replica of an aircraft flap actuator that reveals cracks in the roots of several gear teeth when viewed under low magnification.

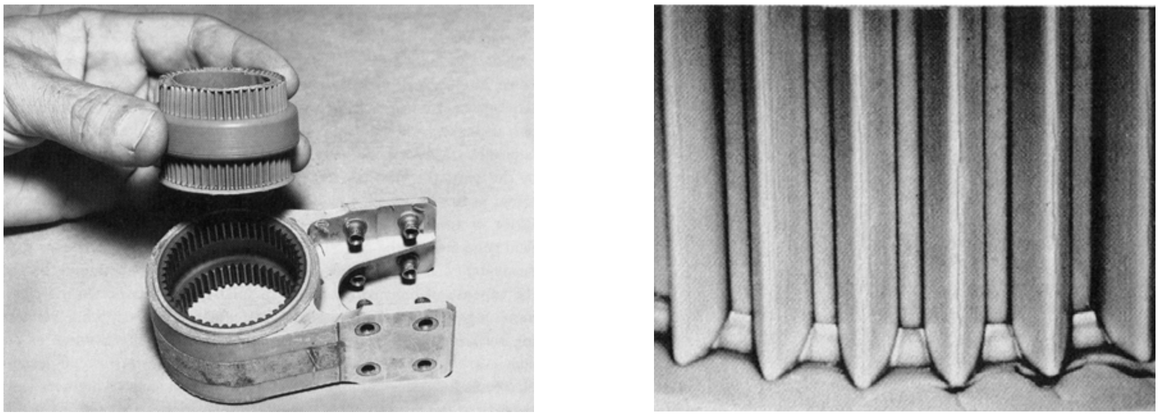

Figure A8-4. Magnetic Rubber Inspection Test Article

A new WCTB test specimen was fitted with all of the changes considered appropriate from the earlier test failures and underwent testing based on an improved fatigue analysis and a load spectrum more accurately reflecting programmed fleet usage. A failure occurred in June 1969 after demonstration of a test life equivalent to 8,000 hours of operation at the spectrum loads representing the projected TAC usage – with no scatter factor applied. This failure was located in the outboard closure bulkhead of the WCTB, in the return flange of the bulkhead at the rear spar. An investigation which included a strain survey in the failure location, revealed a very high strain gradient at the front and rear spar joints with the more flexible lugs. A very simple fix of eliminating two bolts through the flange at the front and rear spars permitted the upper plate to flex slightly with respect to the main box structure and eliminate the local area of very high strain which had led to the fatigue failure.

A fourth WCTB was modified incorporating all of the changes from the previous tests and tested to the latest spectrum described above. This structural configuration complied almost 20,000 test hours, equivalent to 5,000 flying hours for the predicted TAC usage. A planned extension to 24,000 test hours, or 6,000 hours service life was under consideration. It is noteworthy that modifications of the WCTB to reach the extended service life required a total of less than five pounds of additional material.

At 12,400 test hours, a failure occurred in the wing pivot fitting. This failure resulted in the development of a boron-epoxy-reinforced composite doubler modification, which was the first use of advanced composites to reduce the stress levels in metallic aircraft structures [Ref. 5]. The wing then completed the 24,000 test hours without any further significant events. This patch became a fleet fix. In 1994, a chordwise fatigue crack discovered in the lower wing skin of a RAAF F-111 was attributed to a local stress concentration in a fuel drain hole and secondary bending. A boron-epoxy bond patch repair was retrofitted successfully under the RAAF ASIP guidelines [Ref. 6].

F-111 In-Flight Failure and Discussion of Cause

The Air Force's F-111 program suffered a major setback when, on 22 December 1969, F-111A aircraft SIN 67-049 experienced a catastrophic failure and loss of the left wing during a relatively high load factor pull-up from a low altitude practice rocket-firing pass at Nellis AFB, Nevada. The accident was initially attributed to the presence of a defect in the steel pivot fitting. The Air Force immediately grounded the F-111 fleet pending the investigation into the causes and circumstances of the failure. The grounding eventually lasted for approximately seven months. As soon as the part containing the flaw was recovered from the field and examined by the manufacturer and Air Force experts, it was concluded that the failure originated from a pre-existing sharp-edged forging defect in the D6ac steel lower plate of the wing pivot fitting (dark half oval) as shown in Figure A8-5 [Ref. 2]. This 0.9 inch surface length defect evidently had passed undetected through numerous inspections during manufacture and grew a short distance by fatigue (narrow lighter band) to a critical size after a total of only 107 flying hours.

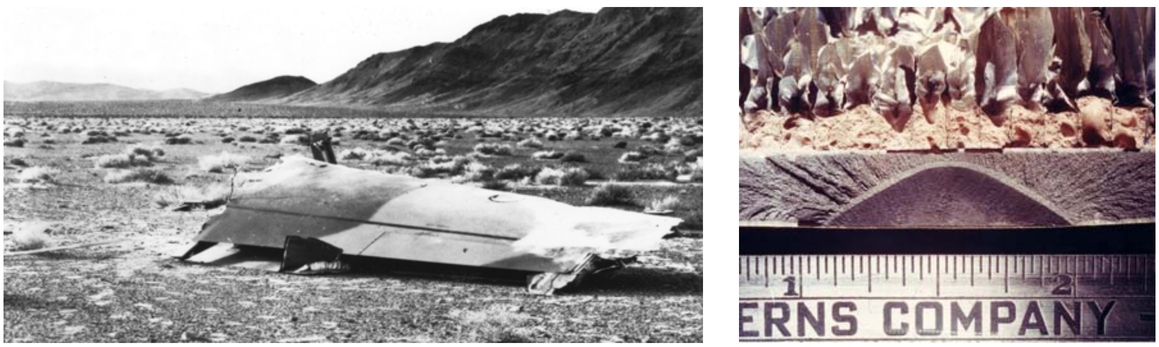

Figure A8-5. Failed F-111 Wing and Forging Defect in Wing Pivot Fitting Lower Plate

Subsequent investigations revealed that the ultrasonic and magnetic particle inspection procedures used during manufacturing NDI/E were incapable of detecting this flaw.

Startup and Implementation of a Recovery Program

As a result of the Nellis accident, the Air Force convened a special ad hoc committee of its Scientific Advisory Board to investigate the failure and recommend a "Recovery Program." [5, 7]. This committee representing a broad based expertise met with General Dynamics and the Air Force Systems Program Office frequently over a period of 18 months in 1970 and 1971. Early on it was apparent to the committee that it would be very difficult to assure the structural safety of the F-111 using the then available conventional nondestructive inspection and evaluation (NDI/E) methods and procedures because of the low fracture toughness of the D6ac steel and the resulting very small critical flaw sizes, and the even smaller flaw sizes that must be found to avoid more failures. Furthermore, very limited accessibility to some potential-flaw locations for effective NDI/E posed significant obstacles. The detailed evaluation of these procedures by the USAF NDI Review Team revealed numerous inadequate capabilities. These difficulties led the committee to recommend to the Air Force that every F-111 aircraft be subjected to a fracture-mechanics-based low-temperature proof load test [Ref.2, 5, and 7]. Subsequently, major improvements in ultrasonic, MPI and other methods were instituted. MPI flux field distributions were improved to better detect the F-111 target flaws. A new ultrasonic Delta Scan method developed by NASA, which greatly facilitates the detection of a crack oriented vertically to the part surface, was adapted to the critical F-111 parts. This modification subsequently led to the release of additional parts from dependence on proof testing [Ref. 7].

The proof test were scheduled to be repeated at periodic intervals to be determined from the predicted rate of crack growth in the individual aircraft based on its actual measured use obtained from the Individual Aircraft Tracking Program (IATP). This fracture-mechanics-based proof testing concept had been developed and successfully used for the pressurized structures in the Apollo space program as well as in other missile and space efforts.

The rationale for the proof test "inspection" was simply that any part containing a crack or flaw in excess of the critical size for the test conditions imposed would fracture under the peak load. By passing this "inspection," it could be assumed that a part contained only subcritical flaws or cracks, or none at all. In making the critical crack length determination, the objective was to get as small a length as possible – in other words, make the resolution of the inspection as fine as one could. It has been Air Force practice to allow laboratory proof tests of structures (load to design limit load) and still certify the aircraft for flight usage (assuming past test inspection revealed no permanent deformation). Any time a structure is loaded in a ground test to greater than limit load, the structure is usually not considered suitable for subsequent flight operation. Therefore, the maximum stress one could subject the critical component to is limit design stress. Thus one input parameter to the crack length determination was established. The fracture toughness index K_{IC} for representative parts from the critical structures areas in question had been determined as part of the previous test and flight failure assessment programs. In the case of high strength steels, K_{IC} varies with temperature – decreasing in value as temperature is reduced below ambient or room temperature. For instance, in the case of D6ac steel with a room temperature K_{IC} = 75 Ksi $\sqrt{in}$, the K_{IC} value at -60°F = 40Ksi $\sqrt{in}$, a reduction of approximately 46%. Again, to insure against as small a flaw as possible, it was desirable to conduct the proof test program as close to the lowest temperature called out in AF qualification specifications for the various components and equipments of the aircraft (-65°F). However, practical test problems limited this low temperature to -40°F which was used in the cold proof test program.

An extensive engineering analysis was made of the F-111 primary structure which established approximately 30 flight-critical D6ac parts. Of these, fifteen (15) individual D6ac steel parts (forgings) were identified as Class I critical items requiring immediate re-inspection. The location of these parts in the airframe is represented in Figure A8-2. The critical crack lengths, which, according to theory, would result in fracture, were also calculated in order to establish the required inspection levels. Meanwhile, a rigorous test program indicated a significant difference in material toughness between the coupons used in the original test program, and the forgings used on the aircraft. Unfortunately, the test specimens to determine the toughness of the steel had a section thickness different from the material placed on the aircraft. The material located on the aircraft had a toughness substantially lower, approximately half, than the toughness of the material used in the test program due to the difference in thermal behavior during heat treatment.

At the outset of the program, the NDI procedures in use were deemed inadequate to accomplish the necessary levels of inspection on 12 of the 15 critical parts [Ref. 7]. Thus the cold proof test was adopted as an alternate "inspection" technique. As confidence levels for the improving NDI/E continued to increase, more parts were included in the list to depend on NDI/E. However, pre-proof test NDI/E was still applied for the purpose of screening out all detectable flaws before proof loading to avoid any catastrophic failure of the entire airframe by proof loading a massively defective part. Thus, with the stress in the part determined, and the fracture index of the material (K_{IC}) selected, the critical crack length "a" was calculated for each of the critical D6ac forged steel parts. If all the critical parts were subjected to a proof test stress (limit design stress), at temperature of -40°F, and if no failures occurred, it would be assured that there were no flaws present at or greater than the critical size (a) calculated. Within a year after the accident, 11 of the 15 Class I critical items were released for conventional NDI/E and 4 remained for proof testing.

The remaining problem was then to develop a practical means to load the F-111 aircraft in order that limit stress could be applied to these critical areas. The structural arrangement of the F-111 was such that this could be done quite readily. The three pylon attach fittings (hard points) on each wing allowed the introduction of large local loads without danger of local overloading of the wings. These three load points, together with the application of a smaller load by means of a clamp towards the wing tip, - along with a specific wing sweep position – allowed the application of design limit bending moment (positive) at the wing pivot fitting and through the wing center box. Local load limitations prevented the application of full design limit bending moment (negative) from being applied. Only 90% design limit load (negative) was possible. At a load of +7.33g, wing tip deflection reached over two meters (Figure A8-6) [Ref. 8].

Figure A8-6. Load Test 7.33g Maneuver

By reacting the applied wing loads at the nose gear, main gear, arresting hook, and by means of special load fittings in place of the horizontal tail, it was possible to apply limit loads to the fuselage longerons, the nacelle bulkhead, and critical areas of the Fuselage Station 770 bulkhead. It was not possible to load the vertical tail; therefore, the rudder torque tube assembly was not loaded, and since the horizontal tails were removed during the test, the horizontal tail box beam fitting was not tested. It was necessary to rely on improved inspection techniques to ascertain the integrity and quality of these areas.

To insure positive test control, and to guard against any possibility of “overload” during the test, an elaborate and complex computer controlled load application system and test monitoring system was utilized. In addition – since the steel in the load jigs and fixtures would exhibit, to a limited extent, increased fracture sensitivity at the -40°F test temperature – it was necessary to construct the proof test set-up so that these loading jigs and fixtures were insulated to the extent that they remained above the temperature of +50°F. An important innovation utilized to enhance the monitoring of the cold proof test was the use of acoustic pickups to detect unidentified noise emissions during loading. Through this setup, it became possible to locate and replace many broken taper lok fasteners which otherwise would have gone unnoticed [Ref. 8].

The essence of the concept was that, if the structure successfully survived the cold proof test load, it could not have contained any flaws larger than the critical sizes at that load level. It had to be assumed then that it did contain flaws just smaller than the critical sizes at the cold proof test load level and reduced fracture toughness, and to cause failure in service they would have to grow to the larger critical sizes at the lower operational load levels, warmer temperatures and higher fracture toughness levels. The time for this to happen would then be calculated from the use spectrum generated from in-flight loading history recorders mounted in each airplane as part of the individual aircraft tracking program (IATP), discussed later In effect, the proof test is a potentially destructive inspection procedure that culls out any flaws that would cause an in-service failure. During the 25 year life of the cold proof test program, there were 11 failures recorded, including three in the Royal Australian Air Force fleet referenced earlier [Ref. 2, 5, 7, 9].

Adoption of Damage-Tolerant Design Methodology

The catastrophic wing failure and loss of and F-111 aircraft at Nellis Air Force Base, Nevada in December 1969 graphically highlighted the fundamental shortcomings of the safe-life approach that failed to account for any unknown or “rogue” flaws. It was this failure that provided much of the impetus for the Air Force to abandon the safe-life approach and adopt damage tolerance requirements on all of its aircraft in the early 1970s [Ref. 5]. This landmark shift was incorporated in the Air Force ASIP process. Featured in the revised ASIP plan were new durability and damage tolerance analysis (DADTA) tasks and an Individual Aircraft Tracking Program (IATP) upgraded to a program based on crack growth or fracture mechanics (although the proof test intervals had been based on crack growth predictions from the inception of the proof test program).

In summary, the Air Force specification MIL-A 83444 “Airplane Damage Tolerance Requirements” requires the detection of cracks before they propagate to failure [Ref. 10]. In designing a critical structural element or component, 83444 requires the demonstrated ability to consistently detect small initial flaws/cracks in both the manufacturing and in-service operational settings. Without such demonstrated capabilities, the existence of larger threshold flaws must be assumed initially and a more conservative (less efficient) damage tolerant design must be adopted [Ref. 11]. Inspection intervals for each critical element or component are established using crack growth calculations based on measured materials fracture properties, together with loading spectra and other usage information from IATP measurements, in order that a propagating crack will be detected before it causes failure.

In the late 1970s, a complete DADTA was conducted on the F-111 [Ref.5]. It initially considered over 400 potentially critical areas, which were subsequently scaled down to about

100 to be analyzed in detail. At the time of retirement of the remaining F-111 fleet in 1996, approximately 20 areas of the structure were being tracked and analyzed, which resulted in periodic updates to the Force Structural Maintenance Plan (FSMP) and adjustments in the inspection requirements to account for use changes and base reassignments. Although the first repeat proof testing of the F-111A/E/D aircraft fleet was set to occur at 1,500 accumulated hours, this interval was increased to 3,600 hours for subsequent proof tests based on the DADTA and force tracking data [Ref. 5]. During the course of the overall program, virtually all of the active F-111 aircraft were proof tested at least three times and some four times.

As part of the Air Force postproduction force management process, inspections and modifications derived from the ASIP tasks and results of DADTAs for active aircraft fleets have been implemented over the last three decades with marked success, and safety has been protected. These individual aircraft model updates, including FSMPs and IATPs about every five years, are considered important [Ref.5].

Post-Event Evolution of Related Advanced Technologies and Processes

Influenced by the F-111 incident, and the lasting attention it received, the Air Force, and the aerospace community in general, increased significantly research and development activities to produce new tools and methods to help assure the structural integrity of aircraft fleets. These included the following areas:

(a) Advanced structural analysis methods. The practical application of finite element structural analyses (FEA) received emphasis starting in early 1960s with the advent of high speed digital computers. Research focused on improving the mathematical definition of the elements used to represent the structure and extending the applicability of the finite element method to increasing complex structural configurations. The F-111 accident accelerated the development pace in the 1970s toward a more practical tool for local stress analyses, including fracture mechanics applications, which helped the transition to the new damage-tolerance design approach and adoption as a formal part of ASIP. As demonstrated by the late 1970s, increasing the polynomial degree of the shape functions beyond the first or second order, commonly called the p-version of FEA, yielded immense dividends in performing local stress analyses [Ref. 12] and assuring designs with adequate damage tolerance.

(b) Improved performance aircraft structural materials. The inadequacy of the safe-life design approach used for the F-111 aircraft, and the adoption of the damage tolerance methodology pointed to the need for broader and more accurate characterization of specific materials properties related to structural integrity, including fracture toughness, crack growth rate, fatigue life under appropriate loading, and others. Research concentrated also on overcoming limitations such as embrittlement and corrosion in some structural materials through improved processing techniques and heat treatments. In addition, efforts were increased to develop new and modified titanium alloys and processing methods resulting in improved fracture toughness, formability, weldability, corrosion resistance and lower cost.

(c) New and improved NDI/E capabilities. The general inadequacy of the NDE/I state of the art, as revealed in part by the F-111 incident, resulted in a significant increase in R&D efforts by the Air Force as well as the aerospace industry. Emphasis was placed on both improving capabilities of existing inspection methods and the creation of new approaches and supporting instrumentation and equipment to more reliably reveal smaller, more obscure structural cracks, hidden corrosion, and other defects related to structural integrity. These have included ultrasonics, electromagnetics, radiography, including computed tomography, thermal imaging, and several others. The major emphasis has been to transition these successful tool developments and improvements as quickly as possible to the operational maintenance environment.

Donald M. Forney, Universal Technology Corporation

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