F-111 Case Study




Boon Seh Choo
Daniel Craig
Benjamin Dupuy
Dan King
Matthieu Verani
©All rights reserved

16.885J December 9, 2003

Acknowledgements:

We would like to thank Jim Phillips, of Lockheed Martin, for his invaluable guidance and insight into the F-111. We would like to thank Dain King, Ken Worrell, and Jerry Fetter, three retired F-111 pilots and/or WSOs, for spending the time to share some of their extensive operating experience in the F-111. We would like to thank www.f-111.net for providing flight manuals and other material.

We would also like to thank Professors Earll Murman and John Hansman for their help and support with this project.

Table of Contents

List of Figures

List of Tables

Acronyms

AAA	Anti-Aircraft Artillery
AC	Alternating Current
AFB	Air Force Base
AMARC	Aircraft Maintenance And Regeneration Center
AMCS	Airborne Missile Control System
CO	Commanding Officer
CPLT	Cold-Proof Load Test
DC	Direct Current
DDR&E	Department of Defense Research and Engineering
DOD	Department of Defense
ECM	Electronic Countermeasures
EW	Electronic Warfare
FAD	Fleet Air Defense
GAO	Government Accounting Office
GD	General Dynamics
GDFW	General Dynamics Fort Worth
GOR	General Operating Requirements
ICBM	Intercontinental Ballistic Missile
LRAAM	Long-Range Air-to-Air Missile
NDI	Non-Destructive Inspection
RAAF	Royal Australian Air Force
SAC	Strategic Air Command
SAO	Systems Analysis Office
SDR	Systems Development Requirements
SOR	Specific Operating Requirement
TAC	Tactical Air Command
TFS	Tactical Fighter Squadron
TFX	Tactical Fighter Experimental
TP I	Triple Plow I
TP II	Triple Plow II
US	United States
USAF	United States Air Force
V/STOL	Vertical and Short Takeoff and Landing

1.0 Introduction

Few aircraft have been as controversial as the F-111. Intended to be the first joint fighter development program, the F-111 was the biggest, most expensive aircraft program of its time. It also came about during an era of drastic change in military strategy, program management, DOD acquisition strategy, and technology. As such, a case study of the F-111 presents insights into all those changes as well into knowledge gained and used on later aircraft programs.

The F-111 was a swing-wing twin-engine single-tail two-seat fighter/bomber. Conceived in the 1950's as an instrument of nuclear retaliation, it was specifically designed to fly low and fast. In the 1960's, however, American military strategy shifted its emphasis to more conventional warfare, involving missions such as air superiority and ground attack.

As military strategy radically shifted, so did the management techniques in the Defense Department. Secretary of Defense Robert S. McNamara, who came into office in with President John F. Kennedy in 1961, instituted a revolution in acquisition policy in the form of "systems analysis." McNamara strove to make military procurement reflect actual military strategy and to do so in the most cost-effective way possible. Over strong objection from the services, one of those cost-effective measures was a common aircraft for the Air Force and the Navy. Unfortunately, in his zeal for change, McNamara underestimated political and bureaucratic limits. The problems of managing a joint program plagued the F-111 until the Navy finally withdrew from the program in 1968.

When the joint program was launched in 1961 as the TFX, the F-111 was intended to serve as a multi-role fighter for both services. The much of technology existed at the time to build tactical fighters similar to the very successful F-15 and F-16 of the 1970's, but the F-111 remained a child of the 1950's preoccupation with the nuclear mission. While designated a Fighter, it is actually a Bomber or Attack aircraft as defined by its requirements. The difference between the requirements and the intended use of the F-111 produced confusion as to its role. Furthermore, the requirements for the F-111 escaped rigorous analysis, tradeoffs, or prioritization, leaving little design space for the primary contractors General Dynamics and Grumman.

Despite the constraints, the F-111 succeeded in meeting or coming close to meeting its difficult set of requirements. The F-111 could fly at tree top level at supersonic speeds while also being able to take off from short airfields or aircraft carriers. It could carry a significant payload over long distances and performed admirably for the United States from Vietnam through the first Gulf War. It is still in service in Australia.

Technically the F-111 incorporated many innovative features. It was the first operational aircraft to use a swing-wing and afterburning turbofan engines. Its avionics package was also revolutionary, utilizing an effective terrain-following radar system. Many lessons learned from the F-111 would be incorporated into the design of the F-14, F-15, and F-16.

Given the poorly compiled requirements, the F-111 was a well-designed attack plane that was also intended to serve as a joint multi-role fighter. It proved highly capable in the attack mission, but because of its weight and lack of maneuverability, the F-111 fell short in the air-to-air mission and as a result was never used in that role. Its schizophrenic nature reflects more on the confusion of the policy-makers and requirements-setters than on the technical merits of the aircraft. The experience of the F-111 impacted not only its immediate successors, the F-14 for the Navy and the F-15 for the Air Force, but also the most recent venture into joint programs, the F-35 Joint Strike Fighter.

2.0 High Level Aircraft Overview

2.1 Primary Mission and Market

The F-111's intended mission was to serve as a joint-service fighter/bomber that could fulfill each service's distinct missions while allowing commonality to save costs. For the Air Force, the F-111's primary mission was to serve as a transoceanic supersonic nuclear bomber capable of deep penetration into Soviet air space. The Air Force also hoped it would serve as a supersonic air-to-air fighter. For the Navy, the F-111's mission was fleet defense against Soviet bombers that could launch anti-ship missiles.

As a joint aircraft, the F-111 was to be sold to the United States Air Force and Navy, as well as the armed forces of the Western Allies, such as Great Britain and Australia. The Air Force desired to replace its existing fleet of F-100, F-101, and F-105 fighter/bombers while the Navy intended to replace its F-4 and F-8 fighters. In all, the original contract called for nearly 900 aircraft between the two services.

2.2 High Level Metrics

As detailed in the timeline, the TFX program started in the late 50's. It finally led to the production of 562 F-111's in several variants.

Production of the F-111 prototype began in the fall of 1963 and the first F-111A rolled out on October 15, 1964 for a first flight in December 1964. The first operational aircraft was delivered in October 1967, even though testing had not yet been completed. On August 30, 1969, the last F-111A was delivered. Later, the obsolete F-111A's were converted to **EF-111A**'s, with radar jamming equipment for electronic warfare. A complete table of the various models is presented in Table 1. A more detailed description can be found in section 8.5.

Table 1: Variants of the F-111 (from [47])

Model	Number built	Purpose	User	Comments
F-111A	159	Strike	USAF	First production aircraft including 18 pre-production
F-111B	7	Fighter	US Navy	Built for carrier operations - cancelled
F-111C	24	Strike	RAAF	Hybrid version containing fuselage of F-111A and wings of FB-111A
F-111E	94	Strike	USAF	Improved A model
F-111D	96	Strike	USAF	Improved E model Enhanced and complex avionics
F-111F	106	Strike	USAF	Similar to F-111D but with simplified electronic systems and most powerful engines
FB-111A	76	Bomber	USAF	Strategic bomber version
FB-111H	0	Bomber	(cancelled)	Longer fuselage, larger engines than FB-111A, but cancelled in favor of B-1B
RF-111A	1	Reconnaissance	USAF	Reconnaissance aircraft – cancelled Converted from F-111A
RF-111C	4	Reconnaissance	RAAF	Photo-reconnaissance aircraft
EF-111A	42	Jamming	USAF	Raven - conversions from F-111A Electronic counter measures aircraft
F-111G	60	Strike	RAAF	Converted from FB-111As with F-111F systems
YF-111A	2	Strike	USAF	Re-designated pre-production of the canceled United Kingdom F-111K

Below is a summary of the specifications of the F-111A according to [1] and [2]. Detailed descriptions of the features and subsystems of this aircraft may be found in section 5 of this report.

FEATURES

Type	Two-seat variable-geometry multi-purpose fighter
Primary Function	Multipurpose tactical fighter bomber
Contractor	General Dynamics Corporation
Crew	2, pilot and weapon systems officer
First Flight	21 December 1964
Production	159 delivered
Inventory	none, retired in 1996
Power Plant	F-111A, 2 Pratt & Whitney TF30-P-3 turbofans
Thrust	F-111A, 18,500 pounds (82.3 kN) each w/ afterburners

DIMENSIONS	
Length	73 feet, 6 inches (22 meters)
Height	17 feet, 1 ½ inches (5.13 meters)
Wingspan	63 feet (19 m) full forward, 31 feet 11 ½ inches (11.9 m) full aft.
Wing area	525 sq feet (spread)
PERFORMANCE	
Speed	Mach 1.2 at sea level, Mach 2.2 at 60,000 feet
Service Ceiling	60,000 feet
Range	over 3,165 miles with maximum internal fuel
TO Run	under 3,000 feet (915 m)
Landing run	under 3,000 feet (915 m)
WEIGHTS	
Empty	46,172 lbs
Max. Takeoff Weight	98,850 lbs
ARMAMENT	Tactical fighter versions carry one M61 mult-barrel 20mm gun or two 750-lb bombs in internal weapons bay. External stores are carried on four attachments under each wing.
UNIT COST	~ $75 million

Figure 1 presents a three-view of an F-111. The sweep angle could vary from 16 degrees (full forward) to 72.5 degrees (full aft). With the wings forward, the span was 63 ft and the total wing area was 525 sq ft. With wings swept fully back, the span reduced to 32 ft 11.4 but because of accounting for the glove area, the area increased to 631.2 sq ft. A more detailed description of the aircraft is presented in Section 5.7.

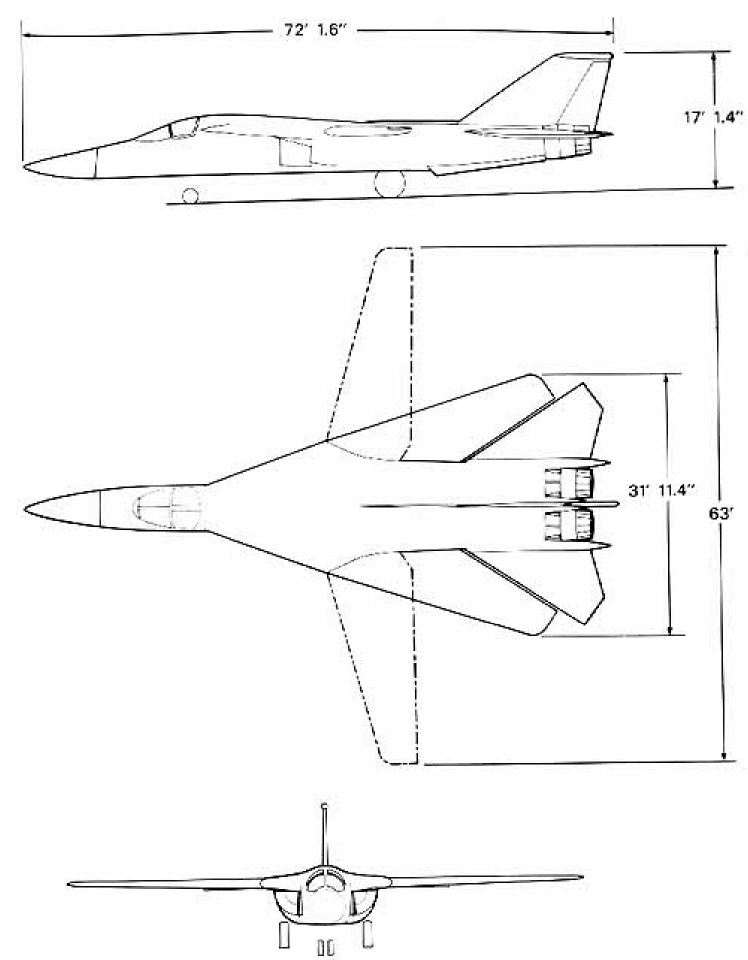


Figure 1: 3-view of the F-111A (from [3])

3.0 Program Overview

3.1 Timeline

This section presents a brief timeline of the F-111 program, from the origin of the requirements to the aircraft's retirement. The key events and milestones are shown in bold. A more detailed timeline will be found in sections 3.4 and 5.1.

Mid to late 50's	**Tactical Air Command (TAC) of USAF expresses a need for a replacement of the fighter bombers currently in service. The fighter should be able to carry two nuclear bombs across the world.**
March 27, 1958	Air Force issues General Operational Requirement (GOR) Number 169, calling for Weapon System 649C.
March 29, 1959	Air Force recognizes that a fighter w/ such performances is simply not feasible.
Feb 16, 1961	**New Secretary of Defense Robert McNamara directs that the Services study the development of a single aircraft for both AF and Navy. The project is known as the Tactical Fighter Experimental, or TFX.**
Sept 29, 1961	Request for proposals. TFX will be called F-111A for the AF version, F-111B for the Navy.
January 1962	None of the proposals were acceptable, but Boeing and General Dynamics are asked to give further details.
May 1962	Second proposals rejected. The Air Force endorses the Boeing Proposal in late June, the Navy is unhappy with it and refuses.
November 24, 1962	**The Defense Department announces that the General Dynamics design is selected.**
December 21, 1962	Procurement of 18 F-111As and 5 F-111Bs for research, development, test and evaluation.
October 15, 1964	**First test F-111A.**
1965	Cost rises from an estimated \$4.5 to \$6.3 million per aircraft. The Defense Department cuts the F-111 program sharply (50% reduction).

1966	The Royal Australian Air Force (RAAF) orders its first F-111
July 17, 1967	**First delivery of F-111A**
1968	**(March) Navy pulls out of F-111 program** (September) First Australian F-111 delivered
August 30, 1969	**Last of the 158 F-111As delivered.**
1982	4 F-111As are transferred to the Royal Australian Air Force to cover attrition of their F-111C fleet.
1996	**Surviving F-111As transferred to AMARC in Arizona for storage. Some of them are being stored for possible transfer to Autralia to keep their F-111Cs operating for another 10 years. Others have been scrapped.**

3.2 Political Context of the F-111

3.2.1 Geopolitical Context

The F-111 was conceived during the height of the Cold War in the 1950's as a nuclear strike bomber. During Cold War, the United States relied on its nuclear weapons to counter the overwhelming conventional military superiority of the Soviet Union at the time. Even before the Cold War, the United States relied on such "asymmetry," from production capacity during World War II to nuclear capability during the Cold War, as a way to avoid the expense of an enormous standing army [4]. As the nuclear arms race progressed, the US settled upon a strategy known as "massive retaliation" whereby the US threatened a full-scale nuclear counterattack against the Soviet Union for attacking the West with either nuclear or conventional weapons. The Eisenhower administration, in particular, chose the nuclear strategy as the most affordable option and accordingly deemphasized conventional weaponry.

3.2.2 Military Strategy

Before the birth of intercontinental ballistic missiles (ICBM's), the backbone of America's nuclear deterrence was the Air Force's Strategic Air Command. SAC's heavy bombers flew higher and farther than airplanes had ever flown, capable of striking the heart of the Soviet Union from bases within the United States. The SAC bombers flew at very high altitudes at high subsonic speeds, attempting to stay out of range of enemy defenses. But as early warning radars and surface-to-air missiles improved dramatically, the United States had to choose an alternative tactic: flying below the radar. Since radars still saw only to the horizon, the lower, and presumably faster, an aircraft could fly, the deeper it could penetrate into enemy airspace.

3.2.3 Service Politics

Within the Air Force, under the umbrella of the massive retaliation strategy, priority went to programs with nuclear capability. To maintain relevance within the Air Force, the Tactical Air Command (TAC) began development of an aircraft to deliver tactical nuclear weapons under enemy radar [5]. With a tactical nuclear aircraft, TAC could compete with SAC and its new nuclear ballistic missiles for political footing within the Air Force.

The Navy also had its own identity and conception of its place in the American force posture. While the Air Force planned for a quick nuclear exchange, the Navy envisaged a protracted, yet still nuclear, war fought on the seas. Since central planning was not emphasized in the DOD at that time, neither service coordinated its battle plans with the other.

3.2.4 National Level Politics

Around the same time as the Air Force began its new fighter-bomber program, the Navy began planning for a new fleet defense and close ground support aircraft [6]. By the end of the Eisenhower administration, the Air Force and the Navy had independent projects that they hoped to fund. But Eisenhower, famously wary of what he termed the military-industrial complex, chose not to commit to any new weapons systems and to leave the decision to the incoming President John F. Kennedy.

Kennedy brought two important changes regarding what would become the F-111. First, the Kennedy administration reintroduced to concept of symmetrical response to the Soviet threat, under the name Flexible Response [4]. The administration saw massive retaliation as too limiting and unusable against any aggression short of a massive invasion of Western Europe or a nuclear attack on the United States. In limited and proxy wars, the US was ill-equipped to counter smaller threats. This switch in strategy brought conventional weapons, including the multi-purpose fighter aircraft, back into prominence.

The second key attribute of Kennedy and more importantly his Secretary of Defense Robert S. McNamara was a disdain for inefficiency [6]. Under Eisenhower, the three services had strict budget limits but were left to spend what they had as they pleased [4]. The result was dramatically inefficient spending on weapons that did not always match the tasks required by the military strategy. McNamara swiftly changed the planning process, introducing “systems analysis” or “cost-effectiveness” techniques for quantifying cost and utility of new weapons and allocation of resources.

3.2.5 Political Effects of the Joint Program

In terms of fighter aircraft, McNamara and his team of “whiz kids” specifically sought to eliminate duplication of design, manufacturing, and maintenance [6]. Since the beginning of military aviation, the services procured different aircraft suited to their own needs and bureaucratic desires. These aircraft rarely contained any common parts or maintenance procedures. McNamara's new Tactical Fighter Experimental (TFX) program sought to remedy the incompatibility problem by creating the first joint-service aircraft. Air Force and Navy variants were to serve their service's individual needs, yet allow for common parts, maintenance, and training as well as the bulk purchasing power that would be possible with buying the massive quantity of aircraft originally envisioned.

In trying to use cost-effectiveness techniques, McNamara chose to combine multiple aircraft programs into one large one. The intention was to create an economy of scale for greater efficiency. The secondary effect, though, was one very expensive program and items with these price tags tend to attract significant Congressional oversight. The TFX program was tremendously controversial, prompting a congressional investigation known as the McClellan Hearings [6]. Due to the program's vast size, many believed it was politically motivated for someone's benefit, either a member of Congress or Vice President Lyndon Johnson, but the investigations turned up no evidence to indicate it.

Another effect of the large single program was to threaten the prides and identities of the services. Each service had its own specific requirements and peculiarities. For instance the Navy needed carrier capability and wanted a side-by-side cockpit, whereas the Air Force needed terrain-following and wanted supersonic low-altitude dash. The services had to compromise, and although the Air Force was the lead service and got most of what it wanted, some of the Navy features remained in what ended up as an Air Force-only project.

3.3 Technical Highlights of the F-111

The F-111 is part of the "century series" of aircraft designed in the 1950's and 60's, such as the F-100, F-101, F-105, F-106 etc. that utilized new supersonic technology. The "centuries" all incorporated advances in aerodynamics, propulsion, and control systems that made supersonic warplanes possible. Specifically, the F-111 employed each of these new technologies [6]. Aerodynamically, the F-111 was the first operational aircraft to use variable-sweep wings. Swept wings were standard on the other century series aircraft, but most were optimized for high subsonic and supersonic speeds and as a result had very long takeoff distances. The F-111, on the other hand, was supposed to fly from smaller airfields and off the decks of aircraft carriers, so variable sweep was the only way to come close to meeting all the requirements.

The second new technology used on the F-111 was advanced turbofan engines. Earlier turbojet engines provided the thrust needed for supersonic flight, but at low speeds they lose efficiency. Turbofans are much more efficient in that regime, and therefore were a good choice for short field and carrier aircraft.

Lastly, the F-111 utilized advanced electronic control systems. The earlier century series aircraft experimented with automatic flight and fire control, allowing the pilot to fly lower and faster as well as fire on targets further away from the aircraft [7]. The F-111 continued this trend with an advanced avionics system with terrain-following radar that facilitated the low altitude supersonic dash.

3.4 Contract Competition

The competition for the contract to develop the F-111 ran from late September of 1961 through November of 1962. There were actually four separate competitions run during this time period. With such a complicated set of requirements for a range of capabilities never seen before in an airplane, the contractors had an understandably difficult time with their proposals. It took four redesigns to get the competitor's designs and the government's requirements to match (see Section 5.0 Requirements).

There was a fundamental difference between the typical Air Force and Navy selection process, and that led to internal tension between the services. The Air Force's goal was to determine which competing source was the best choice to develop that system [5]. The Air Force process was intended to choose the most promising source (contractor or team) early on, even if the design was incomplete. With this, the Air Force avoided long and expensive competitions and could get to work early with a single source. The Navy put more emphasis on the design and demanded that it be complete before committing to a program; the source was less important than the design [5]. The services did not typically work with competitors to help with requirements definition, so it was not until the end of a competition that a contractor would find out if it met the requirements [5].

Because the Air Force was the lead service on the program, its System Source Selection Process was used. A diagram of this process is shown in Figure 2. At the bottom of this process was the Evaluation Team. This group evaluated the proposals in four areas: technical, operations (including carrier-suitability), management (including cost realism), and logistics. In the detailed evaluation, each area was broken up in various ways and points were assigned to the proposal in sub-areas and summed for a total score in each area. The analyses and scores were sent up to the Source Selection Board. The Source Selection Board reviewed the analyses and weighted the scores based on what area (technical, logistics, etc…) it thought was important. The Board then sent its own recommendation up the chain-of-command to the Air Force Council and to various Air Force and Navy Commands. The Air Force Council advised the Air Force Chief of Staff, helped formulate Air Force objectives, and reviewed major programs. Because the it was a joint program, several Naval representatives were added to the council for the TFX. The Council made a recommendation and sent it up to the Air Force Chief of Staff and the Chief of Naval Operations. The Chiefs made recommendations and sent them to the Secretaries of the Navy and Air Force. Finally the civilian Secretaries of the Navy and Air Force made a recommendation and sent the whole package of analysis and recommendations from 6 levels to the Secretary of Defense, Robert McNamara [5].

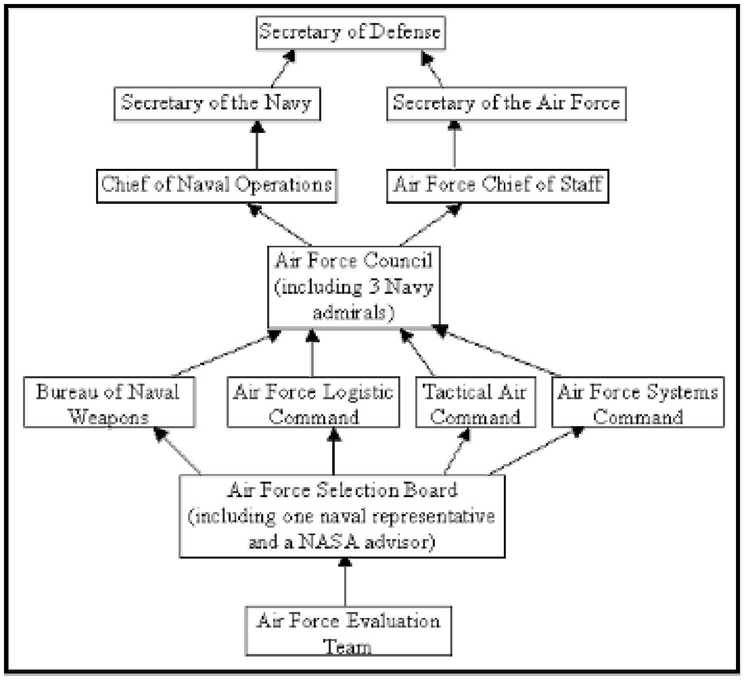


Figure 2: F-111 Source Selection Architecture [5]

3.4.1 Competition Phases 1-3

In September/October 1961 requests for proposals were sent out to industry. In December of 1961, 6 bids were submitted individually by Lockheed, North American, and Boeing; and by teams of General Dynamics and Grumman, Republic and Chance Vought, and McDonnell and Douglas (as separate companies). Three factors made it difficult for the companies to deliver a bid that satisfied the requirements:

1. The requirements were difficult to meet
2. There was not much time allotted for the competition
3. McNamara demanded identical aircraft for both services [5].

The evaluation team found that although none of the bids were acceptable, two warranted funding for further study, Boeing and General Dynamics/Grumman [5].

Three engines were allowed for the competition: the Allison AR-168, the Pratt and Whitney TF-30, and the GE MF-295. The MF-295 was in an early phase of development but promised significant size, weight, and performance advantages. All the bids except General Dynamics' bid used the MF-295 engine. General Dynamics designed their airplane around the TF-30. In the end, the evaluation team decided that because of the MF-295's early stage of development, it was too big of a risk to bank on it being ready in time for F-111 operations. Engine choice was not the only factor considered but it helps show how General Dynamics gained an advantage [5].

Despite betting on the wrong engine, Boeing had an advantage over its competitors. Boeing had been working on a variable-sweep aircraft for 2 years, long before anyone else. It had even been developing a variable-sweep airplane around the TF-30 before switching to the MF-295 for the competition. General Dynamics used the right engine, but had problems elsewhere. The primary reason their design was found unacceptable was that it failed carrier suitability with a high wind-over-deck[κ] requirement. The evaluation team recommended that Boeing redesign their airplane around the TF-30, and that General Dynamics reduce the wind-over-deck requirement to an acceptable level (5).

The Source Selection Board, to save time and money spent in competitions, selected Boeing as the overall winner and sent up its recommendation. The Air Force Council sided with the evaluation team and thought that the Selection Board's decision was premature. McNamara followed the Air Force Council's recommendation and awarded Boeing and General Dynamics 90-day contracts for a second competition [5].

The second competition proposals were submitted in May, 1962. Neither company was able to meet the Navy wind-over-deck requirement. Boeing struggled because of the weight increased with the engine change, and General Dynamics still could not meet the requirement. The Navy still said neither design was acceptable, but the Source Selection Board and the Air Force Council both voted to recommend Boeing as the winner (with Naval members of each board dissenting). This reflects back to the earlier discussion of the Navy and Air Force selection processes. The Navy wanted to see a complete design that fulfilled requirements, and the Air Force wanted to select the best source with an incomplete design [5].

The difficulty in meeting the requirements was coming from the requirement for identical airplanes. McNamara gave both competitors another chance with a third competition, and gave in to allowing some variation in Navy and Air Force designs. He stipulated that a high degree of commonality was still very important to the final award [5].

The third competition only lasted 3 weeks, with only 5 days for the government to evaluate the proposals. This turned out to be too short and a fourth competition was given to both companies. Boeing and General Dynamics received $2.5 million for a further 60-day study and the evaluation period was set to be 45 days [5].

3.4.2 Competition Phase 4

The first three competitions were run in the standard way at the time where companies were in the dark from government feedback in preparing proposals. For the fourth round, McNamara allowed the evaluation team to work closely with each competitor to point out deficiencies and make recommendations during the competition. In this manner it was much less likely that either proposal could come out unacceptable. This process is similar to the "Integrated Product Team" concept used today [5].

The proposals for the final competition were submitted in September of 1962. The total competition scores computed by the evaluation team were very close, less than one-percent different in a partially subjective evaluation process. General Dynamics was significantly better in the technical and management areas, and Boeing was significantly

[κ] Wind-over-deck (WOD) is the wind felt standing on the deck of an aircraft carrier. The WOD requirement is the minimum wind-over-deck required for an aircraft to land on an aircraft carrier safely.

better in the operational area and a very small amount better in logistics. The evaluation team concluded that both designs were acceptable, both competitors were capable of carrying the program out, and the airplane would provide a "markedly improved capability" to both services [5]. At the Source Selection Board level, the Air Force favored the Boeing design. The Navy, finding both proposals to be acceptable, agreed to go along with the Air Force preference. This recommendation was repeated up the chain of command to the Secretaries of the Navy, the Air Force, and Defense [5].

The question that must be answered is if the two designs were so similar, why did the military chain-of-command unanimously favor the Boeing design? Though both aircraft met the requirements set, the Boeing proposal contained extra features that promised abilities beyond what the requirements asked for. Three main differences in the designs of the aircraft stood out to the services. For a braking system, supersonic aircraft of the time needed something more that just wheel-brakes and flaps. General Dynamics proposed using the standard and proven set of spoilers, speed brakes, and a drag chute. Boeing proposed thrust reversers for braking. The company was developing reversers for commercial aircraft and proposed to develop them for the F-111. In addition to providing brake power for landing, thrust reversers could be used in flight for dramatic improvements in maneuverability. The Air Force favored the possibility of improved performance. The second difference was that General Dynamics had gone with engine inlets under the wings and Boeing was using inlets over the wings. Boeing's design prevented debris ingestion and flameout, appealing to the Air Force's desire to rough field use. The third difference was that the General Dynamics design used a standard steel/aluminum wing carry-though structure and the Boeing design saved weight with an advanced titanium structure. For these reasons and others, the Source Selection process unanimously recommended Boeing through the chain-of-command in early November of 1962. At the end of November, however, McNamara announced that the General Dynamics/Grumman team was awarded the development contract [5].

3.4.3 Reasons for McNamara's Decision

This section will summarize why McNamara chose General Dynamics against the recommendations of the Navy and the Air Force. To start with, McNamara was very skeptical of any cost estimates given by the companies or the services. The detailed reasons for this are too complicated to be described in detail here, but in brief the reasons are that companies could benefit from under-bidding a development contract and making up for it with a separate production contract. The services could justify starting a project with low proposed costs more easily, and once invested, could justify continuing even as the costs rise. From this point McNamara evaluated the proposals based on cost-effectiveness; looking at which proposal was most likely to fulfill the needs of the services for minimal cost [5].

From a cost-effective point-of-view, extras beyond requirements were not worth it. The three differences above that made the Air Force favor Boeing were the same reasons that made McNamara favor General Dynamics. General Dynamics braking system was used and proven. Boeing's thrust reversers needed to be developed. Developing technology causes inevitable delays, increased testing, increased costs, and increased risk. McNamara and the other Secretaries believed that the variable-sweep wing was enough advanced technology risk for this aircraft. They saw no reason to risk the success of the program on a bonus feature that wasn't really necessary. Again with the location of the inlets, McNamara sided with General Dynamics under-wing inlets because he perceived their risk to be lower. The Boeing design solved the foreign debris problem only to leave undetermined problems and undetermined risk, by moving the inlets to an unproven configuration. The wing carry-through structure was a similar story. Boeing was proposing to use a fairly new material in a thickness never used before for a primary aircraft structure. Air Force Secretary Zuckert sought out an engineer on the Lockheed A-11*, a "black" Mach 3 plane made with a lot of titanium, that none of the companies and most of the officers involved in the F-111 knew about. The engineer advised Zuckert that it wasn't worth it to use titanium in such a way. From this recommendation and from the added risk and development costs of testing a new material used in a new way, McNamara again favored General Dynamics over Boeing [5].

To get within the wind-over-deck requirement the companies had to either make their planes lighter or increase the wing size. General Dynamics chose to increase wing size by what were essentially "bolt-on" wingtip extensions. Boeing chose to reduce weight by "hogging out" parts on the Air Force plane that were beefed up for the 1.2 Mach on the deck requirement. "Hogging out" is cutting material out of individual parts, either physically or in the design, to reduce weight. What the services saw in the Boeing proposal were airplanes that went further to reduce the constraints imposed by the other service. Boeing went further towards the services' desires for their own separate airplanes, and this was exactly why McNamara put up another strike against Boeing. In "hogging out" the airplane, Boeing reduced commonality. By reducing commonality, the possibility of saving money with a joint program was decreased, negating the whole reason why McNamara forced a joint program on the services. By numbers of parts, the General Dynamics airplanes were 83.7% identical, and the Boeing airplanes were only 60.7% identical. As a further measure of how close the airframes were, General Dynamics was 92% common by structural weight, and Boeing only 34% common. By having more common parts and a more common airframe, McNamara believed that General Dynamics could save the Department of Defense money by reducing process duplication throughout the entire process of development, testing, analysis, production, and operational support [5].

McNamara chose the most cost-effective proposal that still met the requirements with acceptable risk. The military picked the proposal that offered the most potential performance. Boeing met the requirements set, but had too many risky development items that could delay the program and increase its costs. General Dynamics met the requirements with mostly proven designs and minimal risk [5].

---

* The engineer whom the Secretary sought was Kelly Johnson, one of the greatest aeronautical engineers of all-time. Johnson set up Lockheed's "Skunk Works" during WWII. His developed the SR-71 from his A-11 mentioned above.

4.0 Value Propositions

The F-111 program was very extensive, and involved a huge number of stakeholders, such as the Department of Defense, the military services, contractors and manufacturers for the various sub-systems. However, a few key stakeholders can be identified among them. These major stakeholders were the Department of Defense, the Air Force, the Navy, the prime contractor, General Dynamics, and the main subcontractor, Grumman.

4.1 Value Expectations and Propositions

The Department of Defense wanted an aircraft to fulfill military requirements in a more cost-effective way. To do this, Secretary McNamara ordered the Air Force and Navy to combine their requirements into a program for a single aircraft. This is the economy of scale for greater efficiency. A combined program would save money with a single design, development, and testing program; a shared logistical program; and reduced cost per aircraft through bulk acquisition.

The Air Force wanted the F-111 to be a more versatile aircraft capable of conventional and nuclear bombing as well as air-to-air combat missions. For bombing missions, value would come from a long range and from flying 1.2 Mach below radar for deep penetration. At the same time, they expected the capability to fly 2.5 Mach to give them an edge in air-to-air combat.

The Navy wanted a more effective aircraft for fleet defense. Value would come from long-range detection with better radar and high-speed intercept capability. Additional value would come from a long range and loiter time. As difficult as it was to fulfill each service's individual requirements, the program sought to combine them into a single aircraft and this eventually created numerous design difficulties. This requirements flow-down will be presented in further detail later in this report.

General Dynamics and Grumman expected a profitable long-term program. The F-111 was expected to be the largest aircraft program to date [5]. Besides money, value for GD and Grumman would come from the expertise gained from a huge defense program leading to future contracts and additional financial security. Grumman added value to the contractor team with its experience in working with the Navy and designing for carrier operation.

From a value perspective, the F-111 was a Swiss-army knife of aircraft. The F-111 combined the functions of many aircraft into one, just like a multi-tool. And just like a multi-tool, the F-111 was expected to be more cost effective to buy the whole package rather than the individual tools. So the value proposition for the military was to get all the tools in one aircraft, even if the Air Force and the Navy got more functions than they really wanted.

In the end, it may have had too many tools making it too bulky and less effective than something more specialized.

5.0 Requirements

5.1 Origins of the Air Force Requirements

Before describing the requirements in detail, it is useful to present some historical issues. On March 27, 1958, the Air Force issued General Operational Requirement (GOR) Number 169, which called for Weapon System 649C: a Mach 2+, 60,000 foot altitude, all-weather fighter capable of vertical and short takeoff and landing. This new aircraft was expected to be deployed by 1964 to replace the F-100, F-101 and F-105 fighter-bombers that were in service then. However, GOR 169 was cancelled only a year after, when the Air Force recognized that a V/STOL fighter capable of such performance was simply not feasible.

Figure 3: (counter-clockwise,from top-left) F-100 Super Sabre, F-101 Voodoo & F-105 Thundercheif

On February 5, 1960, a new set of requirements was written and the Air Force issued System Development Requirements (SDR) No. 17, eliminating the VTOL requirement. The general requirements of SDR-17 were brought together on June, 1960 into what was to be called Specific Operating Requirement Number 183, or SOR-183. Generally, the aircraft had to be capable of achieving a Mach 2.5 performance at high-altitude, and a low-level dash capability of Mach 1.2. It also had to be capable of operating out of airfields as short as 3000 feet long. The low-level radius was to be 800 miles, including 400 miles “on the deck” at Mach 1.2. The un-refueled ferry range had to far enough such that the aircraft was capable of crossing the Atlantic Ocean. It had to have a 1000-pound internal payload plus a lifting payload between 15,000 and 30,000 pounds.

5.2 Origins of the Navy Requirements

During the same period, the Navy had issued a requirement for a two-seat carrier-based fleet air defense (FAD) fighter to replace the McDonnell F-4 Phantom and the Vought F-8 Crusader. The requirements specified the ability to loiter on patrol for a much longer time with larger and more capable air-to-air missiles, and the capability to counter threats to the carrier group at much longer ranges than for the F-4 and F-8 (1,000 miles for the Crusader or 1,300 miles for the Phantom).

Originally, the Navy had planned to meet this FAD requirements with the Douglas F6D-1 Missiler, which was a subsonic aircraft powered by two 10,000 lbs static thrust Pratt & Whitney TF30-P-2 turbofans carrying a three-man crew (pilot, co-pilot and a weapons system operator). The Missiler had to be capable of remaining on patrol for up to 6 hours, tracking targets with a long-range Hughes pulsed-Doppler track-while-scan radar and carrying six long-range Eagle air-to-air missiles (warhead either conventional or nuclear).

Figure 4: F-8 Crusader (from [8])

Figure 5: F-4 Phantom (from [8])

The Missiler was considered to be too costly, too specialized and was also incapable of self-defense once its missiles have been launched. Thus the programs for the F6D and its Eagle missiles were both cancelled in December 1960, leaving the FAD requirements unfulfilled.

5.3 Joint Requirements

On February 16, 1961 McNamara directed that the Services study the development of a single aircraft that will fulfill the SOR 183 requirements and the FAD requirements. This study was known as Project 34. Project 34 had to review the overall problem of tactical type aircraft in the 1962-1971 time period, and recommend a single TFX project. The motivation behind this was, as previously mentioned, a substantive reduction of costs. Indeed, Project 34 reports showed that a single compromise design would be $1 billion less expensive than two individual programs. In June 1961, McNamara instructed the Air Force and the Navy to work closely to combine their requirements before issuing a joint Request For Proposal. The characteristics on which the Project 34 recommendation was based upon are displayed in the next table. The first column shows the Navy recommended design, the second column the Air Force expectations, while the DOD recommended compromise is shown in the third column.

Table 2: Design versions of Project 34, as written in TFX Characteristics 2-2-65, and used in a [9]

	Project 34, May 1961		
	NAVY	**AIR FORCE**	**DDR&E Compromise**
AIR FORCE VERSION			
Gross weight (lbs)	50,000	63,000	55,000
fuel-internal (lbs)	17,500	25,000	19,000
fuel-external (lbs)	4,000	0	0
lo-lo radius (miles)	555	800	340
dash speed (M)	1	1.2	1.2
dash distance (miles)	100	200	100
TO distance 50' (feet)	2,000	2,500	2,200
Alternate GR.WT (lbs)	57,000		68,200
External Fuel (lbs)	10,000		12,000
lo-lo-hi radius (miles)	625		830
NAVY VERSION			
Gross weight (lbs)	50,000	62,000	
fuel-internal (lbs)	17,500	19,000	
loiter time @ 150 miles (hours)	3,3	4.8	4.2
operate from	CVA-43		
length (ft)	56	83	66
span (ft)	50	68	60

radar antenna diameter (in.)	40	40	40
bomb bay capacity (lbs)	0	8,000	3,000
engines	2TF-30	2TF-30	2TF-30
No. of Aircraft	934	779	1708
NAVY/USAF	934/0	0/779	929/779

The following characteristics can be noted:

1. All designs used two TF-30 engines.
2. The Navy design emphasized holding size and weight to a minimum (e.g. for carrier fitting). The 56 ft. long airplane with a gross weight of 50,000 lb. carrying 6,000 lb. of missiles and 17,500 lb of fuel was questioned as being optimistic by DDR&E. This requirement was the most controversial and heavily questioned by DDR&E.
3. The Navy version had a radius of 555 miles on a Lo-Lo-Hi mission (see next part for explanations on missions), with a Mach 1.0 dash of 100 miles (555/1.0/100), compared to the 800/1.2/200 for the Air Force.
4. The recommended compromise design showed an Air Force radius of only 340 miles at Mach 1.2 dash of 100 miles, half that specified by the Air Force.

On August 22, 1961, the Secretary of Defense was informed that the single design was not technically feasible to meet the stated requirements of the two services. The 22 Aug letter repeated the basic and fundamental Navy requirements of a 55ft. long, 50,000 lb. airplane. In a spirit of compromise, a 55,000 lb, 56 ft. specification was offered as the maximum that could be accepted by the Navy. This design was to have a Mach 1.2 dash speed capability, but over a 100 miles dash distance. The Air Force remained firm with the 800/1.2/200. On August 30, 1961, DDR&E recommended the single design approach to the Secretary who directed implementation on Sept 1st (see section 5.5).

5.4 Mission Descriptions

A key factor that drove the requirements of the F-111 was the variety of missions it had to peform. As previously presented, the F-111's primary mission was to serve as a transoceanic supersonic nuclear bomber capable of deep penetration into Soviet air space. However, it also had to fulfill conventional missions like loitering missions, in the case of the Navy version, or ferry transport. These missions were specified in the early requirements, and it is important to describe them more precisely, since they have influenced key performances.

5.4.1 Nuclear Strike Missions

The key requirement aimed at fulfilling this mission was the capability to carry one 2000 lb. nuclear weapon. A sketch of this mission is presented in the figure below.

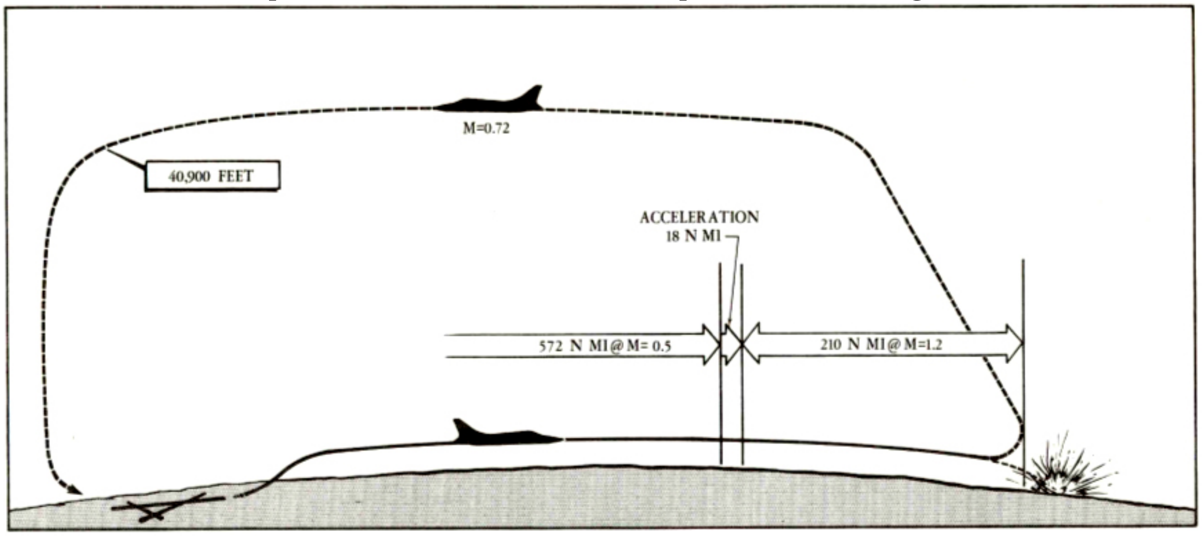


Figure 6: Sketch of a Lo-Lo-Hi mission, from [10]

This kind of mission is called a "Lo-Lo-Hi Mission" because of its division into three parts, the first two being at low level (cruise to target) and the last one being the return to base at very high altitude. The aircraft must fly at a high speed at low level to penetrate enemy defenses. The mission radius was required to be 800 miles with a dash speed of Mach 1.2. Since low altitude flight takes place in dense, turbulent air, the "Lo" mission requirements played a critical role in the design of the aircraft.

Another type of nuclear mission that had been included as a requirement was a Lo-Lo-Lo-Lo. In this kind of mission the aircraft maintained a low altitude and high speed (Mach 0.95 to Mach 1.2) throughout. The total mission radius was lower, on the order of 450 miles.

5.4.2 Conventional Missions

Conventional missions were those where the bombs were not nuclear, but regular M-117 general purpose bombs. For this type of subsonic mission, mission radius was at a maximum, since the aircraft would follow a Hi-Lo-Hi or Hi-Lo-Lo-Hi trajectory. The "Hi" parts correspond to the cruise to get to the target, and the cruise to get back to the base, whereas the "Lo" parts correspond to the dropping of payload. Total mission radius was on the order of 1000 miles, and the mission was typically an air-to-ground mission.

5.4.3 Loiter

Loiter is typically a Naval carrier-based mission. As outlined by the sketch of the mission in Figure 7, this kind of mission required the aircraft to loiter for a given time, at a given distance. Mission radius was on the order of 200 miles. A loiter time of 3.5 hours at 150 miles was required.

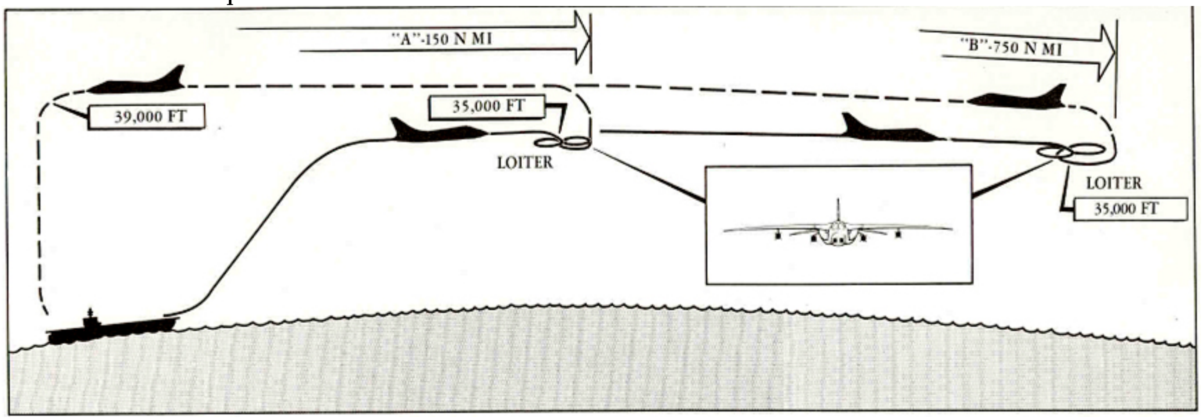


Figure 7: Sketch of a loiter mission extracted from [10]

5.4.4 Interception

The interception mission is not described in terms of "Hi" or "Lo", since the main purpose was to reach the enemy as quickly as possible, shoot it down and get back to base to be eventually refueled and rearmed for another mission. This kind of mission was also key in the set of requirements, since a very high speed is necessary, typically Mach 2.5 for the F-111.

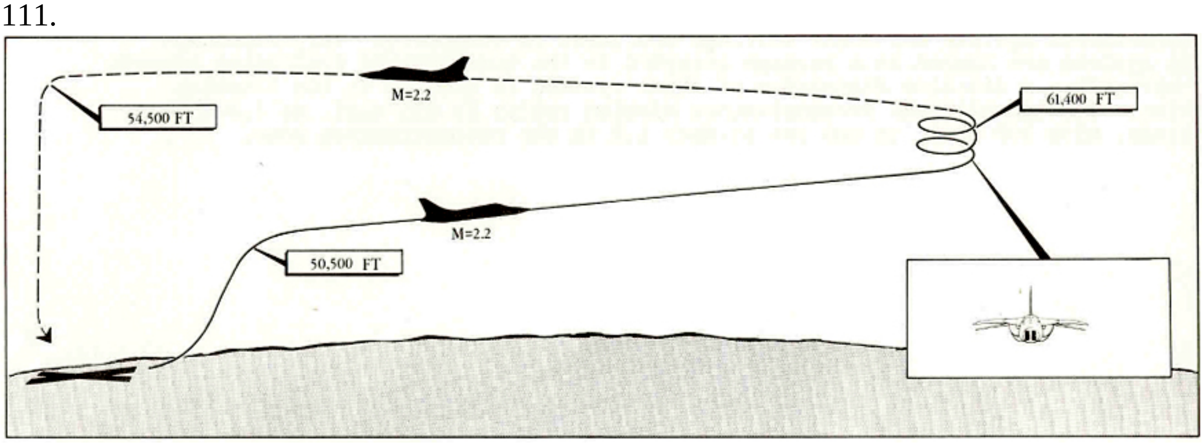
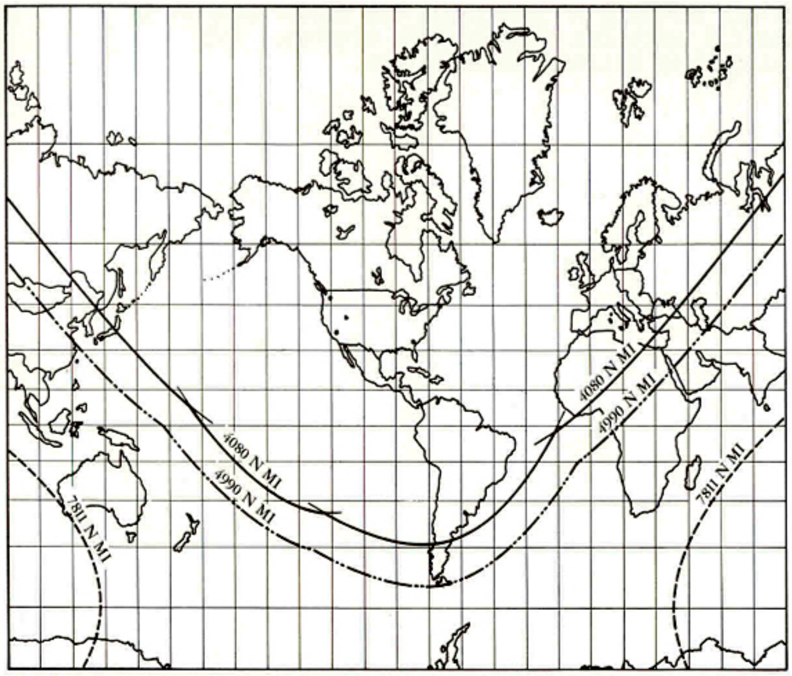


Figure 8: Sketch of an interception mission from [10]

5.4.5 Ferry

For this kind of mission the aircraft would be equipped with six 450-gallon external tanks. The maximum range with such a configuration was on the order of 5,000 miles, without refueling. This last requirement didn't really drive any important design considerations. As seen on the next figure, the aircraft could reach every point in the world with only one inflight refuel.



RANGE	FUEL
4080 N MI	• FULL INTERNAL
4990 N MI	• EXTERNAL FUEL • (4) 400 GAL TANKS
7811 N MI	• ONE INFLIGHT REFUEL • NO EXTERNAL FUEL • BUDDY OUT WITH KC-135

Figure 9: Range of a ferry mission for various fuel loads, from [10]

5.5 Final Specific Requirements

5.5.1 Top Level Requirements

In the search for a baseline set of requirements, the DOD chose to build on the Air Force's plans originally intended for the supersonic fighter-bomber replacement of the F-105. These requirements, listed in SOR-183, called for an aircraft that could perform the following: [6]

- Unrefueled ferry range of 3300 miles.
- Lo-Lo-Hi mission radius of 800 miles
- Within the Lo-Lo-Hi radius, perform a 400 mile sea level dash at Mach 1.2
- Operate from short, unprepared airstrips

SOR-183 was written before the joint TFX project began, so it included none of the Navy's requirements. During negotiations between the two services to come up with a set of joint requirements, the Navy introduced its own desires for a carrier-capable aircraft that could loiter for long periods of time and could act as a long range missile and radar platform for fleet defense. These negotiations produced the document titled the Memorandum of September 1st, which stated that the TFX should also have [6]

- 36 inch diameter radar
- Maximum length of 73 feet
- Maximum weight of 60,000 pounds (Air Force) and 55,000 pounds (Navy)

- 2,000 pounds of internal storage
- 10,000 pounds of conventional ordnance
- Two 1,000 pound air-to-air missiles stored internally or semi-submerged
- Ability to loiter from a carrier for 3.5 hours with six 1,000 pound missiles
- Aircraft carrier capability

Though this list represented the high level requirements for the Navy, they are clearly very detailed, even specifying the length and radar diameter. The diameter requirement came from the Navy's desire to use the radar developed for the cancelled Missileer program. The length requirement related directly to handling the aircraft on the tight confines of an aircraft carrier. Specifically, any aircraft on a carrier must be able to be stored below deck and raised to the deck on the carrier's elevator. The tight space restrictions of the elevator can be seen clearly in Figure 10.

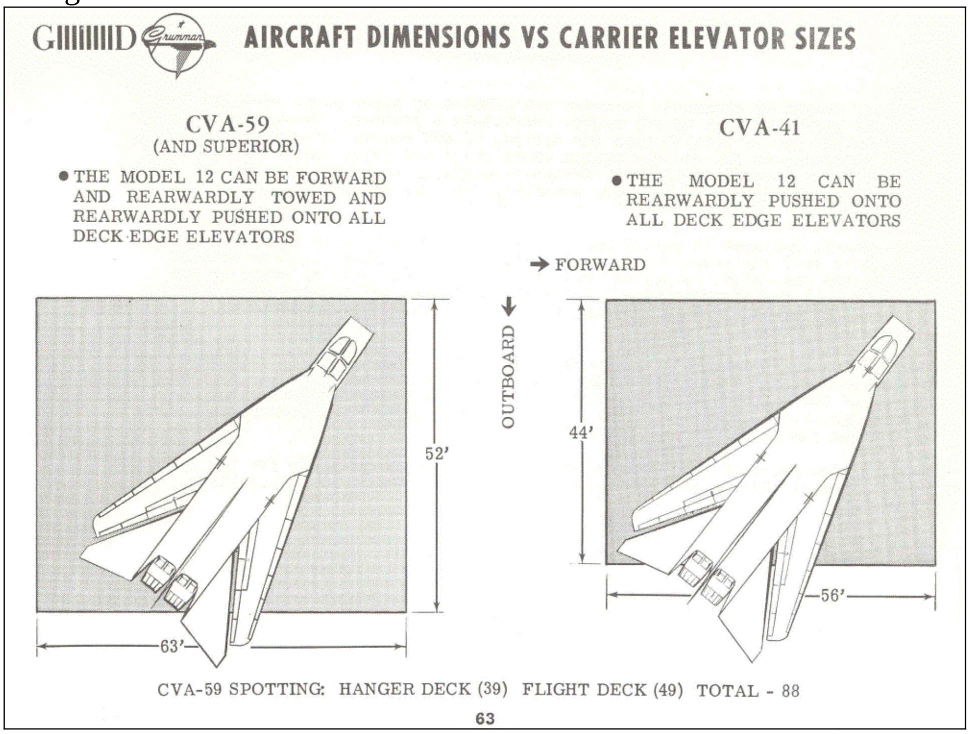


Figure 10: Aircraft Carrier Elevator Sizes [10]

Rather than attempt integration of the two different, and in some cases conflicting, sets of requirements, the services chose simply to concatenate the two because they could not agree on a compromise [6]. Furthermore, neither the services nor the DOD ever prioritized the requirements, leaving the key design trade-offs up to the contractor. If this lack of prioritization did not pose a difficult enough problem, each service continued to press its own particular requirements over the other service's on the contractor whenever they could [6].

5.5.2 Additional Requirements

In addition to the twelve requirements specified in SOR-183 and Memo of September 1st, the services added their own lower-level requirements. In particular, the Navy insisted on the side-by-side arrangement of the crew as well as the capsule escape pod [6]. The Air Force, on the other hand, insisted on a high altitude top speed of Mach 2.5.

Outside of the services, the DOD required as much commonality in parts and design as possible, often trading off performance. Lastly, partly because of the culture of the defense aviation industry at the time, and partly because of the high profile of the TFX program, the DOD also insisted on meeting the development schedule and producing the aircraft quickly, even before testing was complete.

Table 3: Major Requirements Documents (data from [6])

Documnt	SOR-183 (Air Force)	Memo of Sept. 1 (Navy)	Add'l Requirements
Date	July 1960	September 1, 1961	1961-1962
Req'mts	Unrefuelled Ferry Range of 3300 miles Lo-Lo-Hi radius of 800 miles In Lo-Lo-Hi, sea level dash for 400 mi at Mach 1.2 Short, grass airstrips Internal nuclear weapons	36" radar Max length 73 ft Max Weight AF 60,000 lbs With internal fuel, 2000 internal payload Max Wt Navy 55,000 lbs 10,000 lbs conventional bombs Two 1000 missiles internally, semi-submerged Carrier operations Six 1000 lbs missiles for 3.5 hour loiter at 150 mile range	Side-by-side crew Escape pod Max speed Mach 2.5 Commonality Fast development program

5.6 Requirements Flow Down

Between SOR-183 and the Memorandum of September 1st, no fewer than 12 very detailed requirements were in place for the TFX. Some requirements were general, such as the maximum weight, while others were extremely specific with regard to hardware, such as the 36 inch radar, or specific to a particular mission, such as the Lo-Lo-Hi requirements. It soon became very clear that the F-111 was over-constrained, leaving the designers little flexibility other than to make a nuclear fighter-bomber that could land on a carrier [6].

Of the twelve major requirements in SOR-183 and Memo of Sept 1, four requirements had the most profound impact on the final design: Mach 1.2 at sea level, carrier/short field capability, maximum range, and maximum payload. A requirements flowdown diagram for these four key requirements is shown in Figure 11.

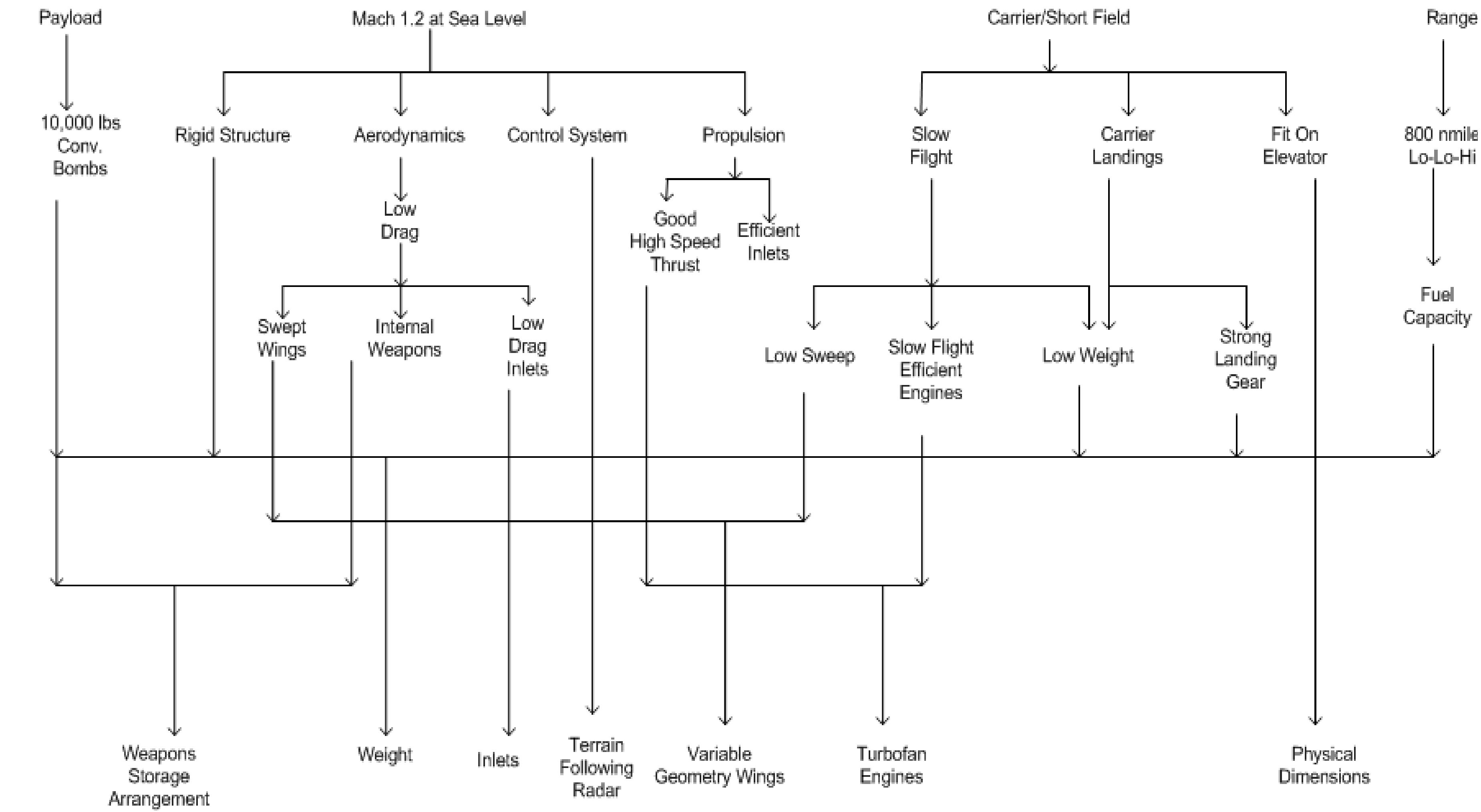


Figure 11: Flowdown of Four Key Requirements

5.6.1 Mach 1.2 Sea Level Dash

The most important requirement that affected nearly every component on the F-111 was the capability to fly at Mach 1.2 at sea level as part of the Lo-Lo-Hi nuclear penetration mission. This requirement drove the structure, the avionics, the aerodynamics, and the propulsion system of the F-111.

Low altitude supersonic flight imposes heavy buffeting on an aircraft as it flies in the turbulent lower atmosphere, necessitating a stiff structure capable of withstanding such heavy and erratic loads. The sea level dash speed was not the F-111's top speed. At high altitude, it could fly at much faster speeds, up to Mach 2.5, while under less structural load because the air is less dense and less turbulent. Had the low altitude dash been specified at high *subsonic* speeds, the structural requirement would have been much easier to meet.

To achieve high speeds required low drag and high thrust. At transonic and supersonic speeds, straight wings produce large amounts of wave drag due to compressibility effects. Swept wings reduce the Mach number normal to the wing, reducing this wave drag. Swept wings do impose more structural constraints and are less efficient at low speeds, such as takeoff and landing, but are necessary to achieve supersonic flight without unacceptable drag.

Another source of drag on an aircraft is externally stored weapons and fuel tanks. Because they would produce too much drag to achieve the supersonic sea-level dash requirement, the F-111 needed both internal weapons bays capable of storing the 2,000 pound nuclear weapon, as well as enough internal fuel storage to accomplish that mission.

To counter all the drag at supersonic flight, high performance engines with afterburners were required. Afterburners inject more fuel into the hot exhaust creating large amounts of additional thrust, but they are also inefficient and burn tremendous amounts of fuel. The afterburner fuel consumption, then, drove the amount of fuel the F-111 needed to carry, and thus its overall weight.

The inlet design also affected the engine performance as it determined the total pressure recovery (magnitude and distribution) of the entering air. Note that not only is more pressure recovery better, but also the distribution of total pressure at the compressor inlet has a significant effect on engine performance. Regions of low total pressure can lead to compressor stall and thereby limit the capability of the engine.

Lastly, since flying at such high speeds near the ground without striking terrain is virtually impossible for a pilot to accomplish manually, the low-level dash required an avionics system capable of sensing and following the terrain. Automatic control systems had been designed before, but the F-111 was the first operational aircraft to use low altitude, high speed automatic control.

5.6.2 Carrier/Short Field Capability

After the supersonic sea level dash requirement, carrier and short field capability imposed the second most important constraint on the design. The F-111's predecessor the F-105, required 10,500 feet of runway, limiting it to a handful of airports in Europe that were easy for the Soviets to target and attack. In order to use the more numerous shorter airports, the Air Force wanted takeoff distances closer to 3000 feet. Such short distance meant the F-111 needed to accelerate quickly and lift off at slow speeds. Landing on a carrier proved an even greater challenge in reducing speed, requiring a 115 knot approach. Carrier capability also drove the landing gear and physical dimensions of the F-111.

Slow flight has several necessary conditions. An aircraft must have a low aerodynamic stall speed, which is primarily driven by the wing shape. By adding camber, or curvature, to the wing, it can produce more lift per given speed. At high speeds, though, this additional camber and the lift it produces, cause unacceptably high amounts of drag. Therefore, to achieve good high speed performance as well as slow stall speeds, the F-111 had flaps and slats (leading edge flaps) to vary the wing geometry.

Wing sweep angle also drives stall speed. When a wing is swept, the lift is a function of the speed of the air flowing normal to the wing. For transonic and supersonic speeds, sweep is absolutely necessary in order to reduce the normal speed in order to reduce wave drag. At slow speeds, however, the wing needs as much normal air speed as possible, meaning a straight wing.

To achieve short takeoff distances, not only must the aircraft be able to fly at slow speeds, but it must also be able to accelerate to those speeds quickly, requiring good engine performance at slow air speeds. In general, the best slow speed performance come from propellers, but as freestream speed increases propellers lose thrust. For supersonic flight, the F-111's predecessors, including the F-105, all used turbojet engines. The turbojet derives all its thrust from the high speed exhaust out of the turbine stage of the engine. Because the propulsive efficiency decreases as the ratio between exhaust speed and inlet speed increases, turbojet engines are very inefficient during takeoffs and produce less static thrust. The turbofan engine, on the other hand, circumvents that problem by tapping the energy in the exhaust to drive a large bypass fan that blows air out at speeds much closer to inlet speeds. As a result, propulsive efficiency improves dramatically at slow speeds and stays high as the aircraft gains speed. For the F-111, the only way possible to achieve high supersonic speeds as well as quick takeoff acceleration was to utilize the newly developed turbofan engine.

In addition to slow flight, the F-111 also had to be able to withstand aircraft carrier takeoff and landings. In a carrier takeoff, a pneumatic catapult attached to the nose wheel accelerates the aircraft very quickly to get the aircraft just up to stall speed after it leaves the deck. The force exerted by the catapult thus required landing gear capable of withstanding such high loads.

Carrier landings are no less violent, both on the landing gear and on the carrier itself. In a normal landing, the aircraft slams hard on the deck close to stall speed, then the throttle is pushed to full thrust in case a go around is required, until the tailhook catches the arresting wire quickly bringing the aircraft to a halt. If the tailhook were not functional, a net is strung across the deck to catch the aircraft. In either case, the arresting wire and capture nets must be able to withstand the force exerted by the quickly decelerating airplane. Since force is proportional to mass, the arresting wire stress limits set the maximum weight of the Navy's version of the F-111.

Finally, since carrier aircraft are stored below deck, the aircraft must be sized to fit on the elevator. This requirement set an absolute limit on the length of the F-111. Since most Navy aircraft have wingspans greater than the elevator limit, many with fixed geometry wings actually have hinges on the top of the wings and they fold vertically. Variable sweep wings, on the other hand, can be swept back to fit within the width limits.

5.6.3 Range

The defining range requirement was the 800 mile radius Lo-Lo-Hi mission. Under that mission, the F-111 would carry a 2,000 pound nuclear bomb and would fly at high subsonic and low supersonic speeds at sea level. Being one of the most high drag missions required, and therefore one of the most demanding on the propulsion system, it also requires the most internal fuel storage, since external tanks add too much drag. Thus, the 800 mile Lo-Lo-Hi mission set the fuel capacity of the F-111.

5.6.4 Payload

The maximum payload required of the F-111 was 10,000 pounds of conventional bombs. While no range or speed was specified for this requirement it could only be for a subsonic conventional mission, most likely the Hi-Lo-Hi mission, which is assumed to have a radius of 1000 miles. With a full complement of ordnance and external fuel tanks, the F-111 in this configuration has its highest possible weight set. More important, though, was that this payload required use of the outboard, non-movable pylons, making it impossible to sweep the wings.

5.6.5 Summary of Major Design Choices

Given all the requirements, the design choices of the F-111 were indeed constrained very early. A summary of the reasons for each choice follows.

- Variable Sweep: Chosen to allow supersonic flight, short field/carrier take off and landing, and to fit on an aircraft carrier elevator. Added weight and structural complexity.
- Flaps and Slats: Chosen to provide high lift configuration for short field. Added weight.
- Turbofan engines: Chosen to provide short field and supersonic capability.
- Engine inlet: Assumed to be optimized for sea level supersonic dash. Not optimized for high angle of attack flight.
- Structure: Sustain sea level supersonic dash. Added significant weight.

- Landing Gear: Heavy duty to sustain carrier takeoff and landing. Added more weight than standard Air Force landing gear.
- Internal Weapons Bay: Reduce drag enough for supersonic flight. Added weight.
- Weight: Carrier arresting wire strength.
- Dimensions: Carrier elevator restrictions.
- Terrain Following Radar: Low level penetration missions.
- Side-by-Side Pilots: Navy insists.
- Crew Escape Pod: Navy insists. Added 500 lbs.
- Twin Engine: Standard Navy requirement for lost engine capability
- Single Tail: The literature does not specify, but probably chosen for minimal weight versus a twin tail.
-

5.7 Commonality of Systems

The combined requirements imposed on the design of the aircraft eventually led General Dynamics to design an aircraft that was about 84% common between the Air Force and Navy versions before production. For example, the structure, wings and sweep mechanism, crew module, engines and engine inlets were all identical between the two versions. The major differences were in the nose, landing gear, and wing tips. The Navy version had a shorter and foldable nose radome to facilitate dimension requirements for carrier operations. The Air Force landing gear was lighter, whereas the Navy landing gear was designed for greater structural strength to withstand catapult take-offs. Also, additional 3.5 ft “bolt-on” wing tips were incorporated in the Navy version for take-off and loiter mission requirements. These differing components can be seen in Figure 12.

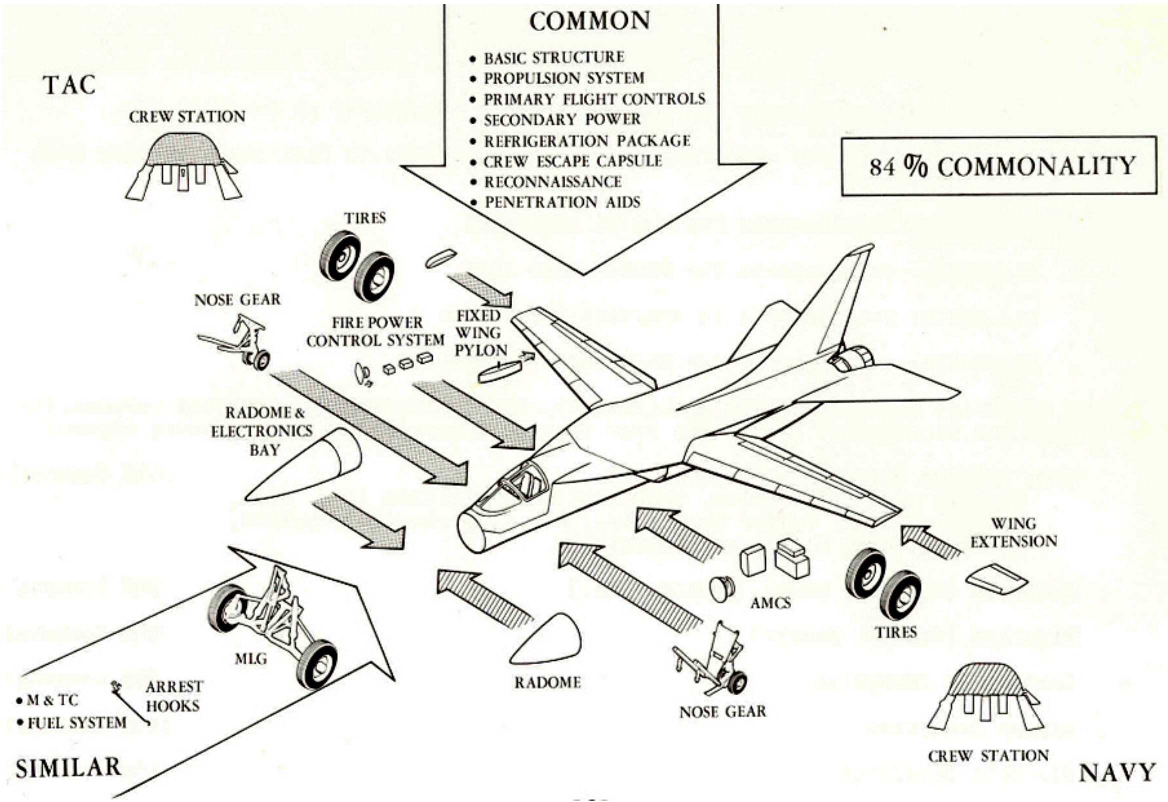


Figure 12: Air Force and Navy commonality [10]

Other differences include the firepower control system, outboard pylons, and crew stations. The firepower control systems differ due to different mission priorities. The primary Air Force mission was Air-to-Ground interdiction, while the primary Navy mission is Air-to-Air interception. Particularly, the Navy version was designed to use the Airborne Missile Control System (AMCS) and Long-Range Air-Air Missile (LRAAM) being developed by Hughes. The additional outboard pylons on the Air Force version were designed to allow greater weapon fuel capacity. The crew stations differed in terms of the design and location of some controls, displays, instrument subsystems and air data subsystems, but overall remained considerably similar.

6.0 Detailed vehicle description

6.1 Configuration

The F-111 had variable-sweep wings whose angles went from 16 degrees (full forward) to 72.5 degrees (full aft). The wingspan was between 63 ft and 33 ft respectively. This allowed the pilot to fly at the different regimes required: it could reach Mach 1.2 at sea level, Mach 2.2 at high altitude (up to 60,000 ft) with wings fully swept back, and nevertheless it could have a slow approach velocity (115 kts) with wings fully extended and then it could take off and land in about 2,000 ft.

For lower supersonic drag area-ruling concepts were used to pull together the engines at the rear of the airplane. The equivalent cross-sectional area distribution of the plane was close to the Sears-Haack rule.

Another particularity of the F-111 is that the two crewmembers sat side-by-side. The main reasons argued for this arrangement were allowing an optimum inter-crew communication and also avoiding the need of another plane to train new pilots. The cockpit also served as an escape module.

The F-111 could carry both conventional and nuclear weapons. To achieve a lower drag, it carried up two nuclear bombs in its internal bay, or it could replace them by additional fuel tanks for longer missions. It also could be equipped with M61 guns and could externally carry bombs, missiles and fuel tanks. A pivot system allowed the load nearest the fuselage to move in order to stay parallel to it when the wings swept.

Avionics of the F-111 were characterized by the Terrain-Following Radar, which was able to keep the plane flying at constant altitude, following the contours of the terrain. It could work day and night and for all weather conditions. The avionics system was also composed functions such as navigation, communication target acquisition, radar bombing for bad weather conditions, etc.

The airplane general arrangement shown in Figure 13.

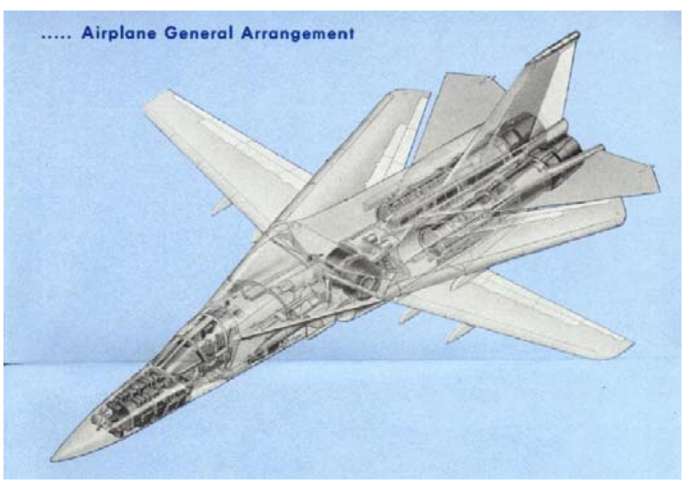


Figure 13: F-111 general arrangement [12]

6.2 Performance

6.2.1 Flight envelope and engine performance

Performance data from flight tests (F-111A performance document T.O. 1F-111(Y)A-1A) was not available for this study. The F-111A flight manual contains limited performance information on operating limitations, but all the data is estimated. The F-111F manual has operating limitations based on flight test, making it the best resource for performance charts. These performance charts can be supplemented with known F-111 performance numbers.

Altitude performance:

The F-111F altitude performance from the F-111F manual is shown in Figure 14.

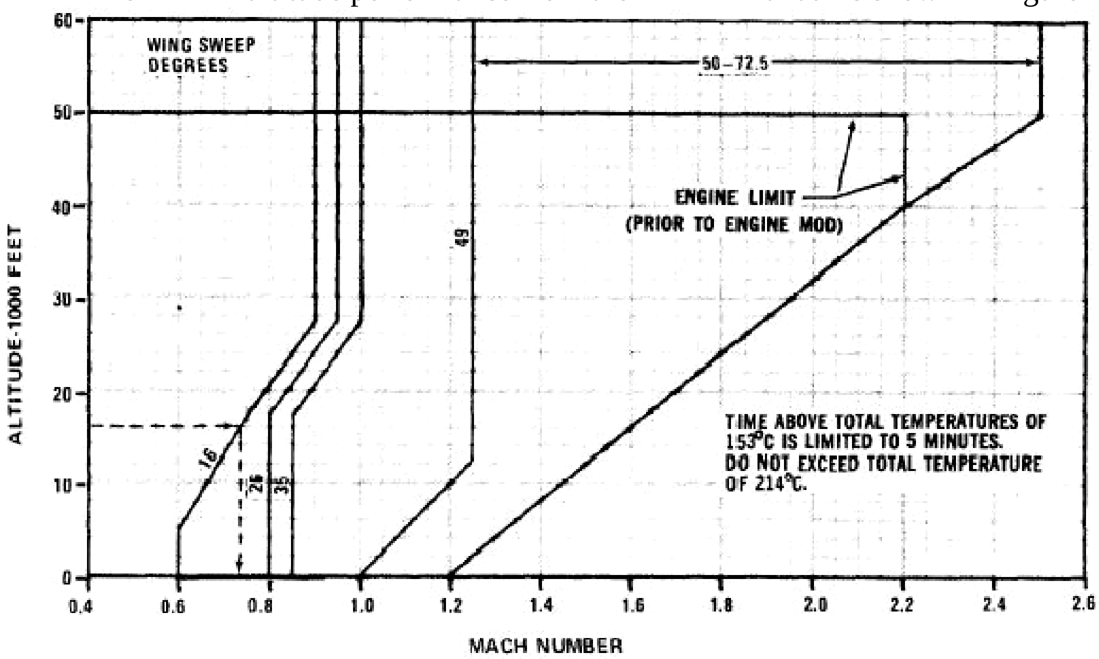


Figure 14: Altitude-speed performance of F-111F [13]

The 50,000 ft limit shown is not seen in published performance numbers. The ceiling for the F-111 was 60,000 ft. At 60,000 ft, the F-111A could operate up to 2.2 Mach, meeting the altitude requirement but failing the Mach 2.5 requirement. The figure also shows that the F-111 could fly at 1.2 Mach at sea level, fulfilling its requirement. Speed limitations in the figure are shown for various sweep angles as well.

Distance to clear a 50 ft obstacle:

Data on the distance to clear a 50 ft obstacle was not available, however the F-111 achieved its requirement of a less than 3,000 ft take-off run.

Load factor and airspeed limitations for F-111F:

Figure 15 shows the limit load factor in 'g's as a function of gross weight for various configurations and maneuvers. The different configurations are the following [13]:

- Flaps and gear up:
  - (A) symmetrical maneuver at any wing sweep
  - (B) asymmetrical (rolling pullout) maneuver
  - (C) symmetric maneuver during wing sweep
- Gear up or down, slats only extended or flaps extended
  - (D) symmetric maneuver (16-26 degrees wing sweep)
  - (E) asymmetric maneuver (16-26 degrees wing sweep)

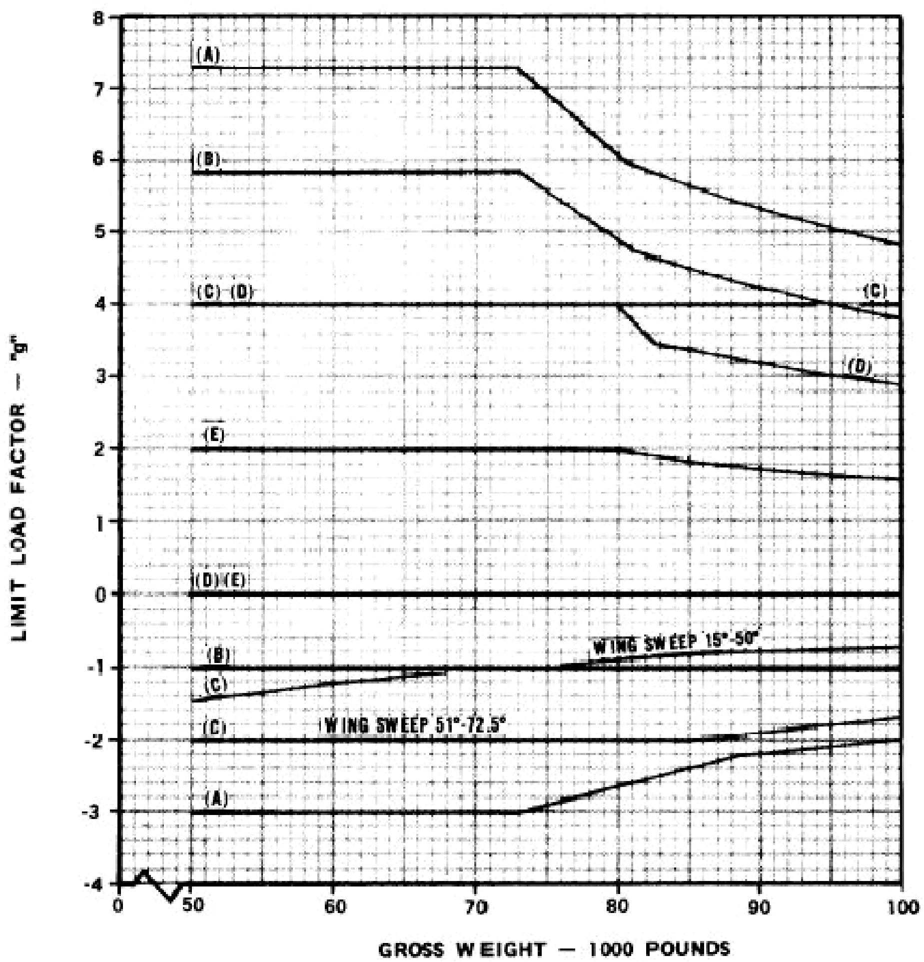


Figure 15: Load Factor as a Function of Weight for Various Configurations [13]

6.2.2 Missions

A quantitative way to determine with accuracy the performances of an aircraft is to analyze its capabilities in terms of mission. As explained in Section 5.4, the F-111 was designed to accomplish a certain number of particular missions allowing it to penetrate into the Soviet territory.

6.2.2.1 Lo-Lo-Hi Mission

This mission is described in section 5.4.1 and is summarized on Figure 16. This aims at dropping a bomb at low altitude and coming back at high altitude and very high speed.

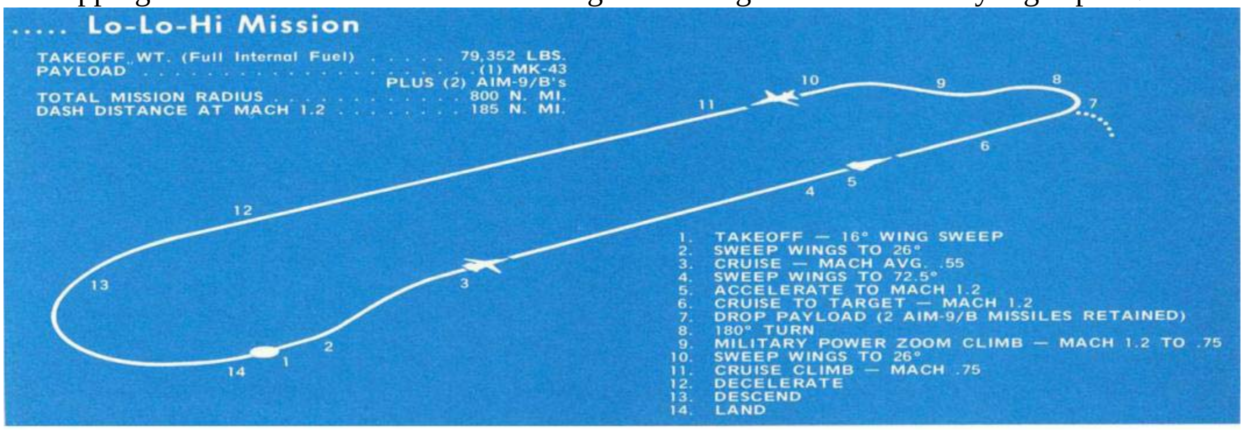


Figure 16: Lo-Lo-Hi Mission Profile [14]

As shown on Figure 17, the need for this mission is to be able to find a high performance tradeoff between the distance that you can reach at supersonic speed and low altitude (sea level dash distance) and the total mission radius. For a given total mission radius, the faster you fly, the smaller distance you can cover at high speed.

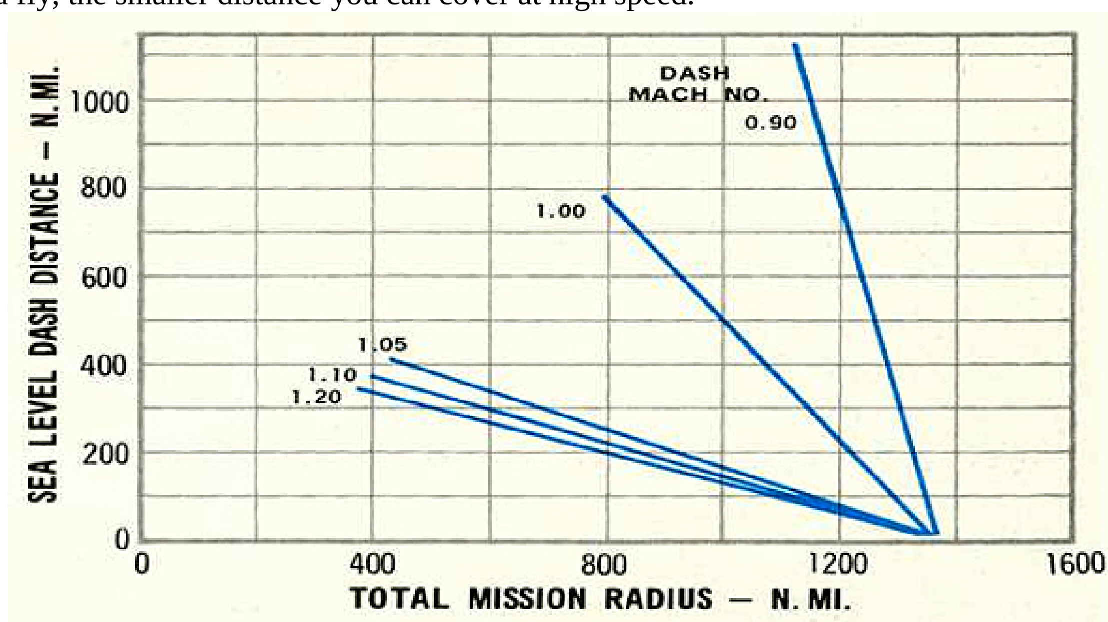


Figure 17: Tradeoff Between Sea Level Dash and Total Mission Radius [14]

The typical mission considered in the GD Proposal was an aircraft configured as in Figure 18: the airplane is has one 2000 lbs nuclear weapon and two AIM-9/B (Sidewinder) air-to-air missiles mounted internally in the weapons bay.

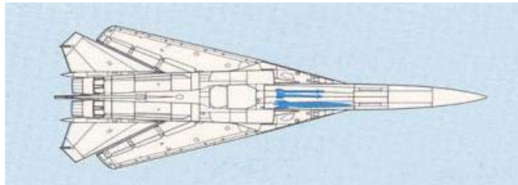


Figure 18: Lo-Lo-Hi Configuration [14]

In this configuration, the airplane is able to strike a target for a dash distance at Mach 1.2 of 185 N.Mi and a total mission radius of 800 N.Mi.

6.2.2.2 Lo-Lo-Lo-Lo Mission

It is the same kind of mission as the Lo-Lo-Hi one, but maintains low altitude throughout the mission (5.4.1). The mission is described in Figure 19.

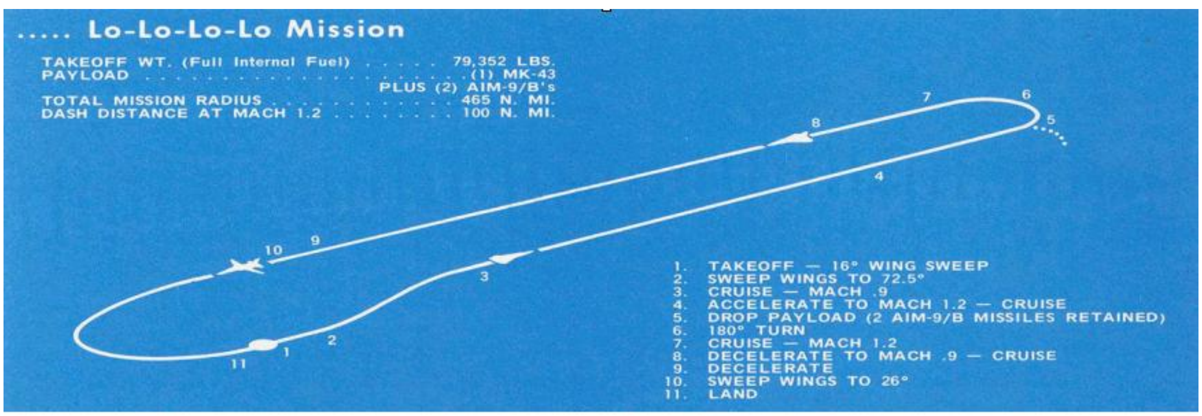


Figure 19: Lo-Lo-Lo-Lo Mission Profile [14]

The performance of this mission is measured by the combat zone radius (distance flown in supersonic flight) as a function of the total mission radius (Figure 20).

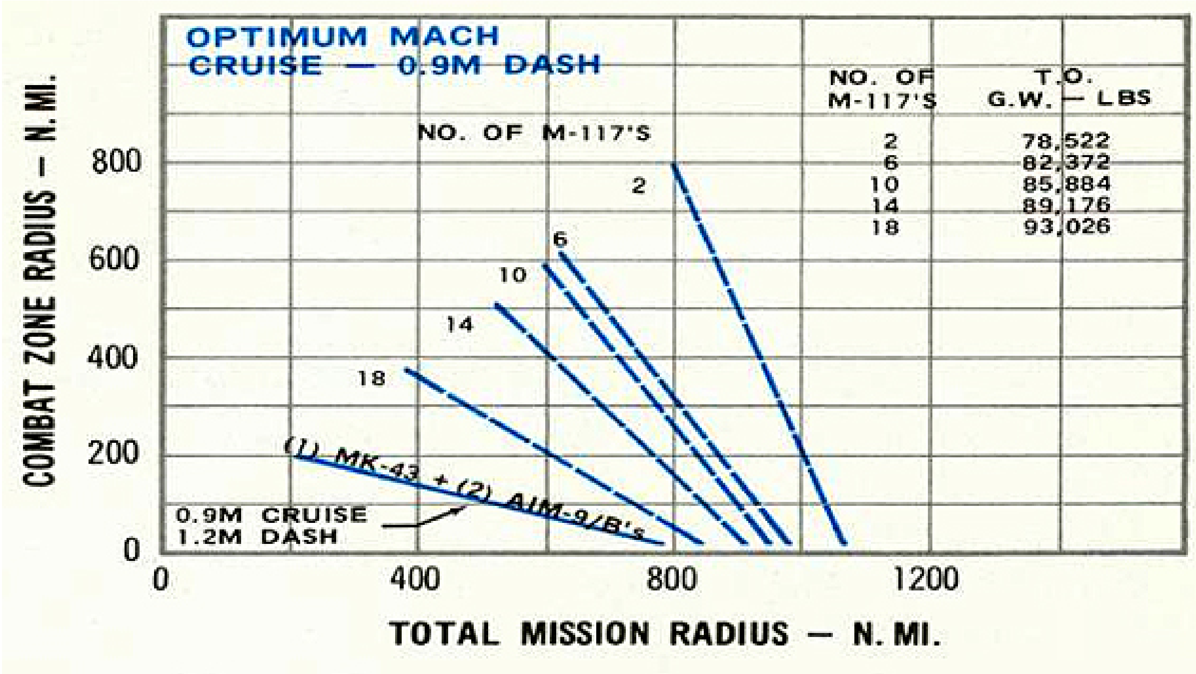


Figure 20: Tradeoff between Combat Zone Radius and Total Mission Radius [14]

Observations are the same as for Figure 17. F-111 can also carry M-117 missiles instead of nuclear weapons: then, increasing the payload decreases the combat zone radius. GD Proposal presents an airplane with the same configuration as for Lo-Lo-Hi mission (one 2000 lbs nuclear bomb and two AIM-9/B). For example, loaded as shown on

Figure 21 and for a total mission radius of 465N.Mi., the aircraft is able to strike a target for a dash distance at Mach 1.2 of 100 N.Mi.

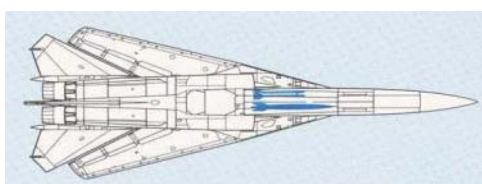


Figure 21: Lo-Lo-Lo-Lo Configuration [14]

6.2.2.3 Hi-Lo-Hi Mission

This is a conventional mission, which means that the airplane does not carry any nuclear weapon, but M-117 missiles. The cruises to the target and to return are done at high altitude, whereas the airplane delivers its payload at low altitude (Figure 22): the aircraft descends to sea level and a time of 3 minutes at military power is allowed for target acquisition. This mission has already been described in section 5.4.2.

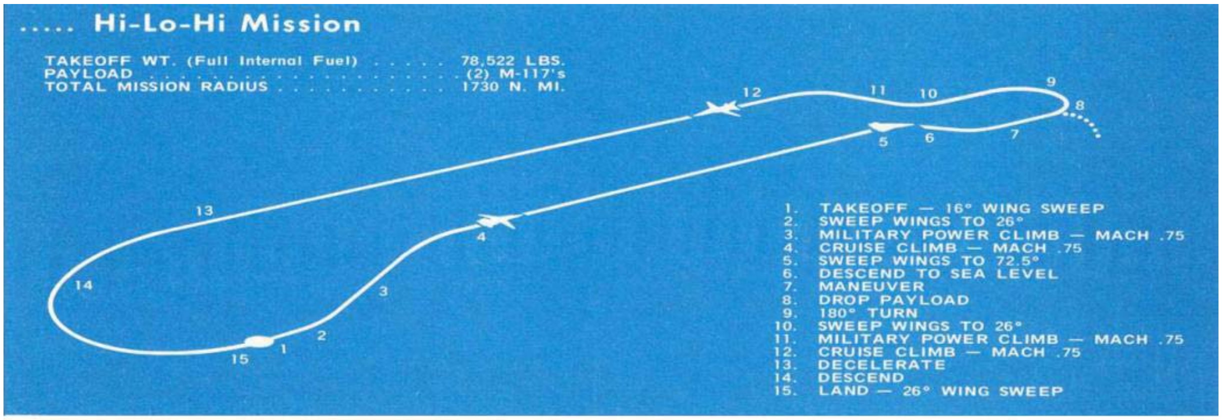


Figure 22: Hi-Lo-Hi Mission Profile [14]

The performance is given by the total number of M-117's as a function of the total mission radius (Figure 23). Obviously, when you increase the number of M-117 missiles, the payload is heavier and so the total mission radius decreases.

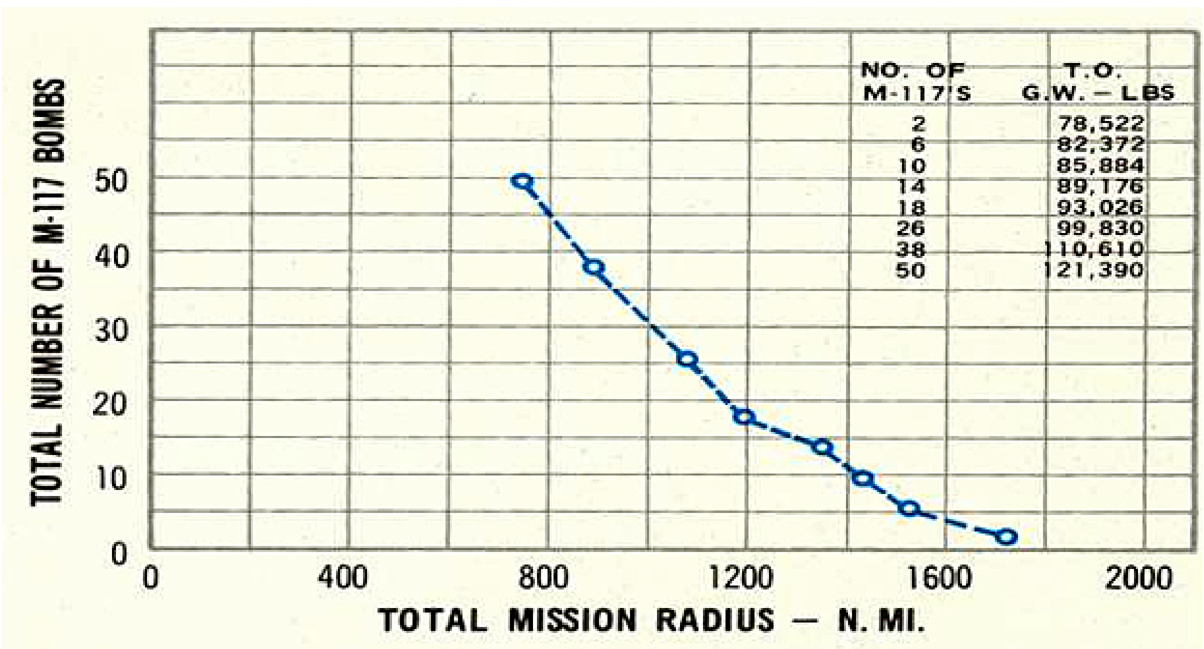


Figure 23: Tradeoff Between Number of Bombs and Total Mission Radius [14]

The proposed configuration is two M-117 general purpose bombs mounted internally in the weapons bay (Figure 24). An aircraft with such a configuration is able to accomplish a total mission radius of 1730 N.Mi.

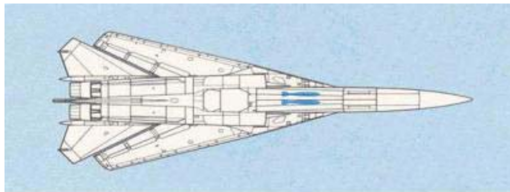


Figure 24: Hi-Lo-Hi Configuration [14]

6.2.2.4 Hi-Lo-Lo-Hi Mission

This mission is similar to the previous one, but dash to and from the target 200 nautical miles distance is accomplished at Mach 0.90 at sea level (Figure 25). This mission is described in section 5.4.2.

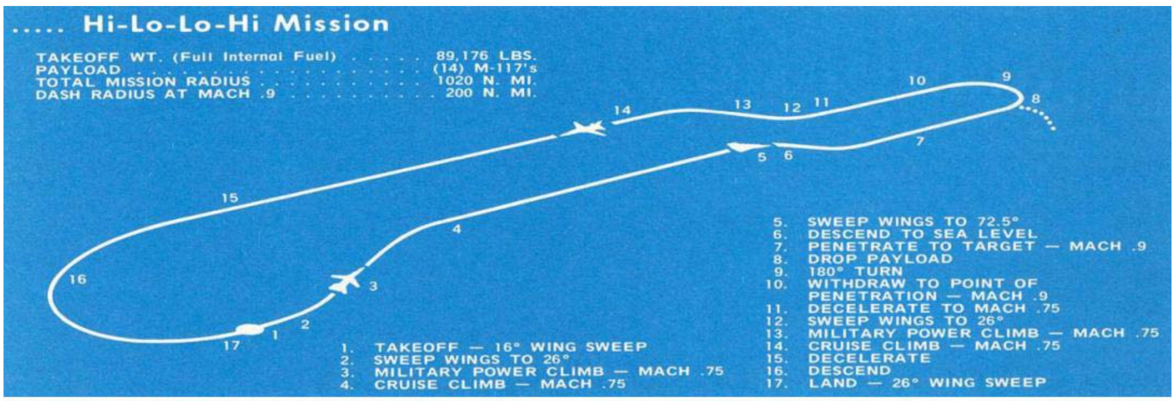


Figure 25: Hi-Lo-Lo-Hi Mission Profile [14]

The performance of the plane is expressed in terms of combat zone radius and total mission radius, depending on the payload (number of M-117's missiles on board). The results for F-111 are shown on Figure 26.

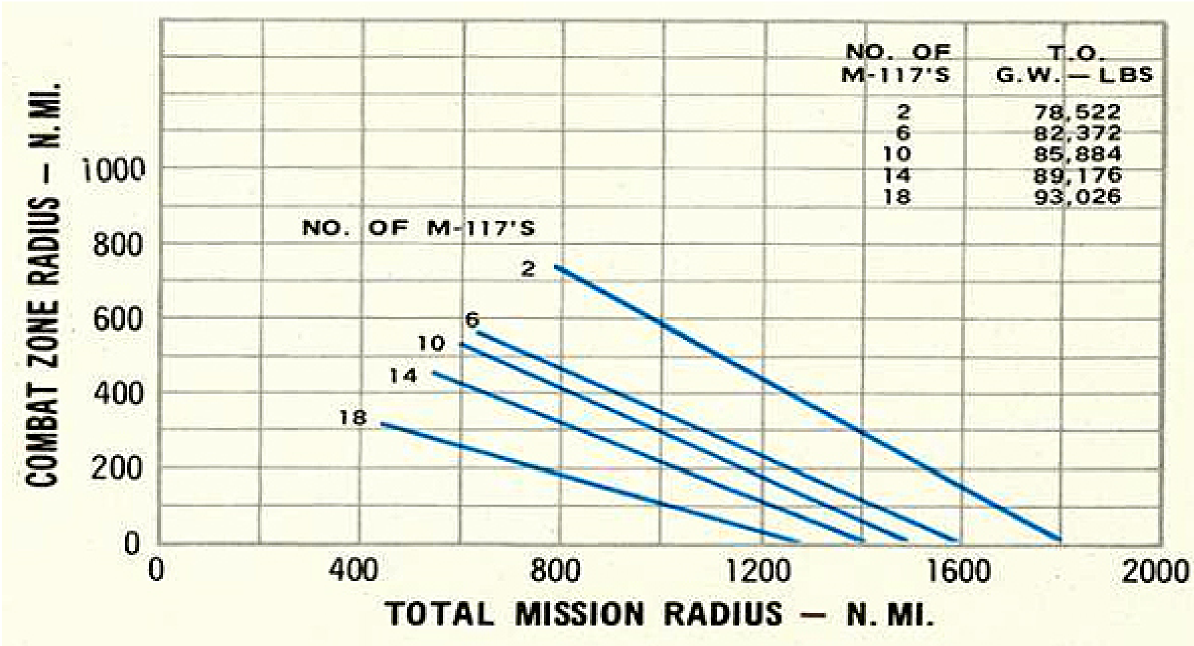


Figure 26: Tradeoff Between Combat Zone Radius and Total Mission Radius [14]

The typical configuration chosen by GD in its proposal is 14 M-117 general purpose missiles. Two are carried internally in the weapons bay and six are carried on each of the two outboard pivot pylons shown in Figure 27. For this kinds of mission and configuration, the aircraft has a dash radius distance at Mach 0.9 of 200 N.Mi. for a total mission radius of 1020 N.Mi.

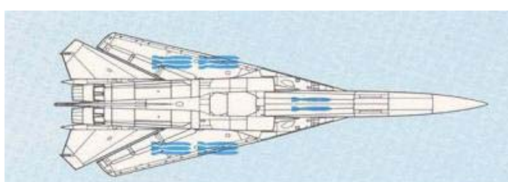


Figure 27: Hi-Lo-Lo-Hi Configuration [14]

6.2.2.5 Loiter Mission

This mission was required by the Navy (section 5.4.3). A description is given on Figure 28.

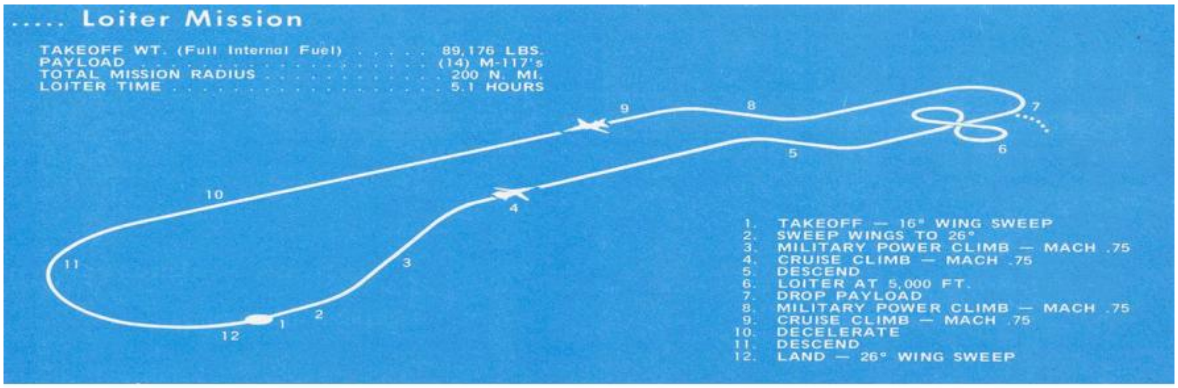


Figure 28: Loiter Mission Profile [14]

The loiter time as a function of the total mission radius for different numbers of M-117s is given by Figure 29. For a given total mission radius, this chart gives the decrease of loiter time when the number of M-117s missiles increases.

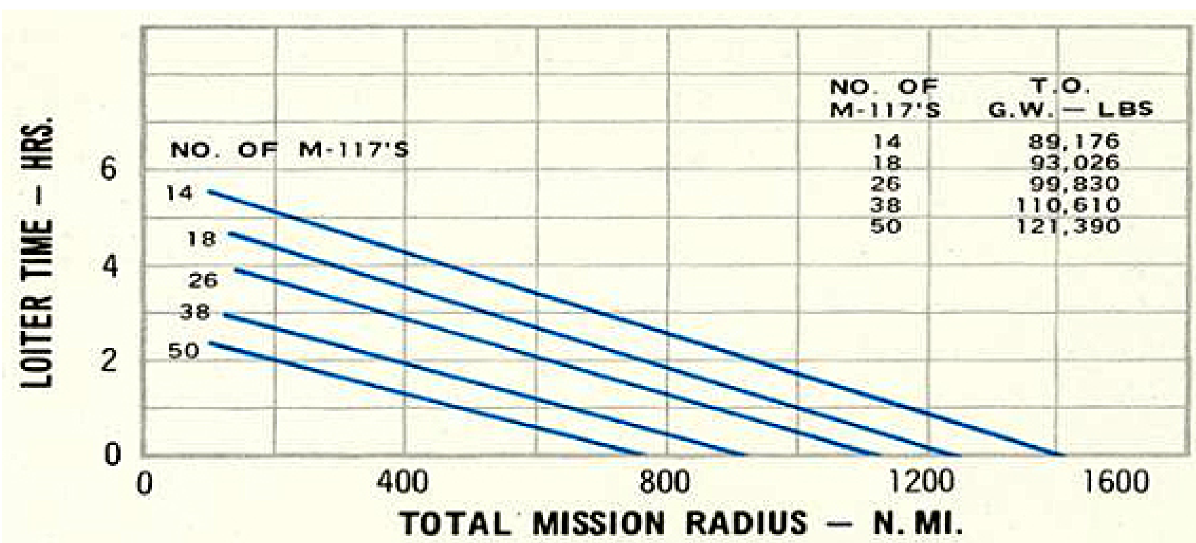


Figure 29: Tradeoff Between Loiter Time and Total Mission Radius [14]

The GD Proposal’s configuration is 14 M-117 general purpose bombs. Two are carried internally and six are loaded on each of two pivoting pylons stations (Figure 30). According to Figure 29, an aircraft configured as such has a loiter time of 5.1hours for a total radius mission of 200 N.Mi.

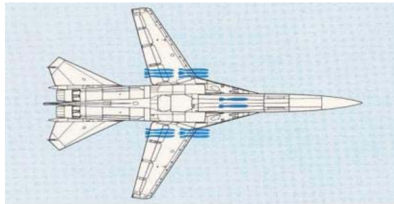


Figure 30: Loiter Configuration [14]

6.2.2.6 Intercept Mission

This mission is explained in section 5.4.4. Cruise at Mach 2.2 is performed to the intercept point where a 5 minute maximum power Mach 2.5 combat fuel allowance is observed. Return to base is accomplished at optimum Mach 2.2 cruise conditions with all missiles aboard (Figure 31).

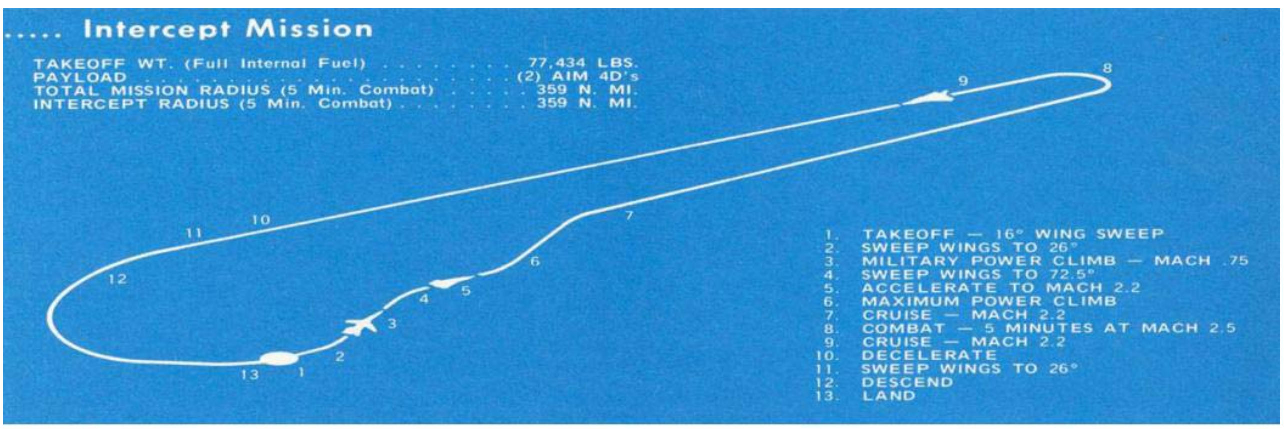


Figure 31: Intercept Mission Profile [14]

The criterion of performance in this kind of mission is the combat time at Mach 2.5 as a function of the total mission radius. This is given on Figure 32 for different numbers of AIM-4/D air-to-air missiles carried by the aircraft.

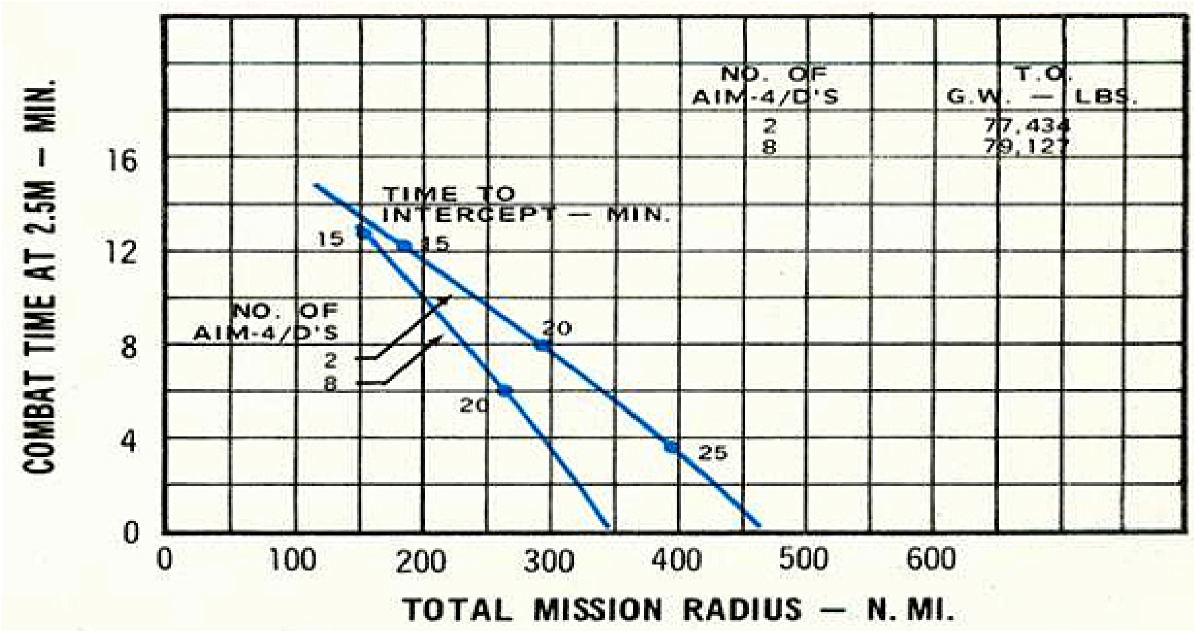


Figure 32: Tradeoff Between Combat Time at Mach 2.5 and Total Mission Radius [14]

In the GD proposal, the total mission radius is 359 nautical miles and the aircraft is configured with 2 AIM-4/D air-to-air missiles mounted in the weapons bay (Figure 33). Figure 32 shows that in these conditions, an aircraft is able to perform a 5 min combat at Mach 2.5.

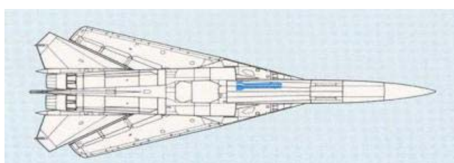


Figure 33: Intercept Configuration [14]

6.2.2.7 Ferry Mission

This mission has been described in section 5.4.5 and is shown by Figure 34.

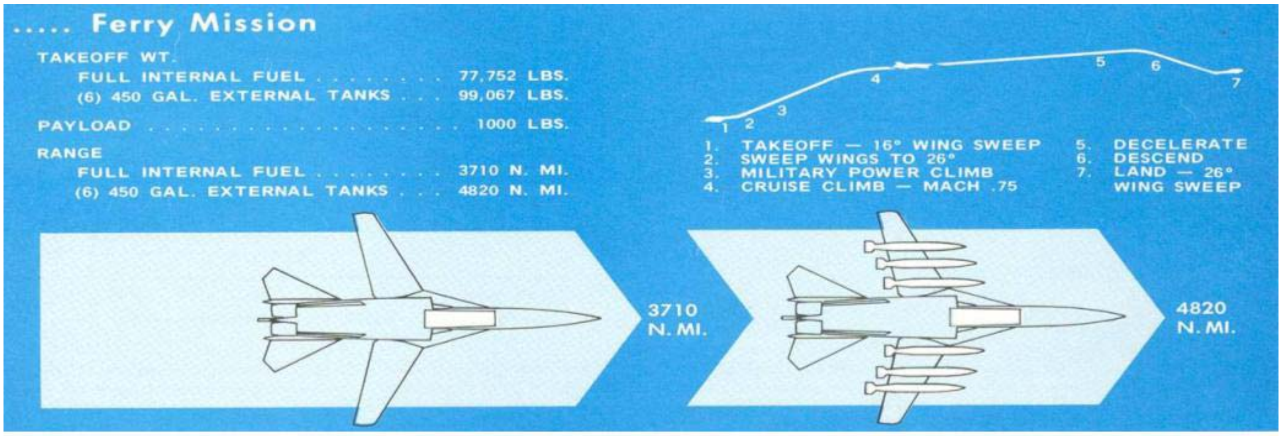


Figure 34: Ferry Mission Profile [14]

It is important to know the range of the aircraft depending on Mach number. This is given by Figure 35 for an aircraft carrying a 1000 lbs ferry kit (fuel tanks in the weapon bay).

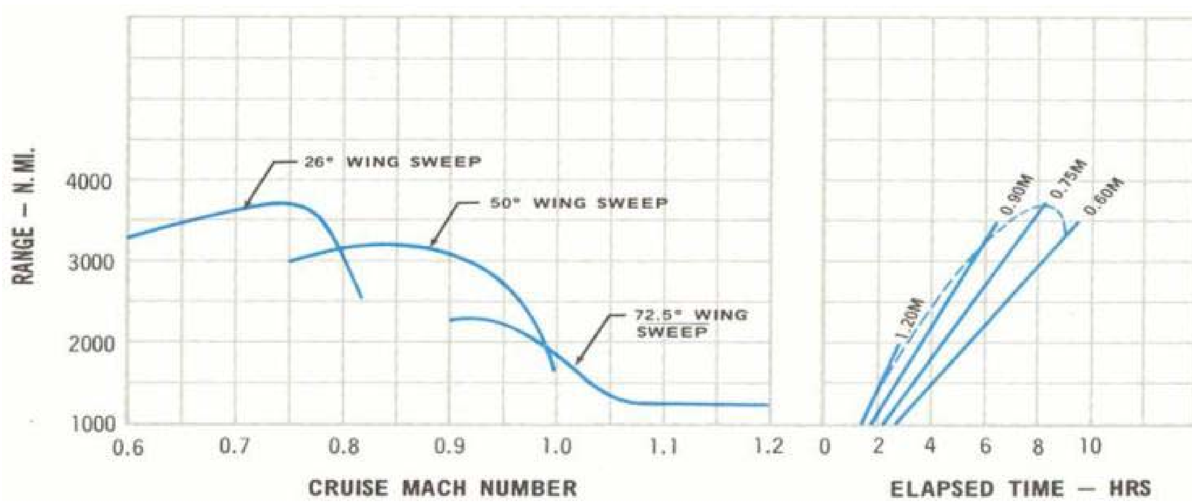


Figure 35: Range as a Function of Cruise Mach Number, Sweepback Angle, and Time [14]

Note a decrease in the range for high speeds and large sweepback angles. It is due to the higher drag resulting from these conditions. The maximum range is obtained for a Mach 0.75 cruise speed and a sweepback angle of 26 degrees. The ferry range is then 3710 nautical miles. With the addition of six 450 gallon external fuel tanks, ferry range is increased to 4820 nautical miles if the tanks are dropped when empty.

6.3 Description of Major Sub-systems

This section will describe the following major aircraft subsystems: Airframe and Materials, Wings and Sweep Mechanism, Propulsion, Fuel System, Electrical System, Hydraulic and Pneumatic System, Payload Weapons and External Stores, Landing Gear, Cockpit, Avionics, Control System, and Crew Escape Module.

6.3.1 Airframe and Materials

The requirements for the F-111 drove the need for a high-strength structure. The aircraft was constructed using mainly steel and aluminum alloys, with limited use of titanium. The fuselage has a semi-monocoque structure, assembled using large one-piece machined structural members for high strength-to-weight ratios. The F-111 was the first production aircraft to have a variable wing-sweep mechanism, and it will be described further in the next section. The Navy version was designed to have a folding nose radome to accommodate length restrictions associated with carrier operations. It had an overall length of 20.97m (68ft. 9.5in.) and was 19.74m (64ft. 9.2in.) with the radome folded. The slightly longer Air Force version has a total length of 22.40m (73ft. 6in.) with a height of 5.22m (17ft. 1.4in.). Figure 36 below shows the basic internal structure of the F-111.

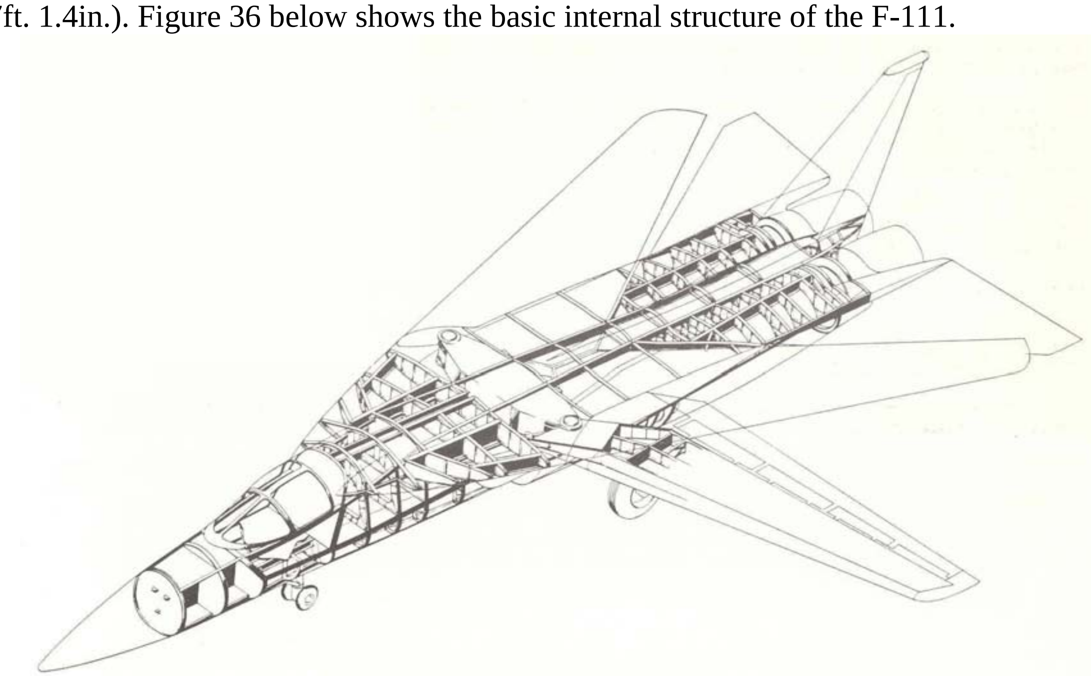


Figure 36: F-111 Structural arrangement [10]

The external panels mainly consisted of bonded honeycomb-sandwich panels. As shown in Figure 37, these panels consist of thin, high-density inner and outer facings bonded to a low-density aluminum honeycomb core. Typical to many aerospace applications, these panels are used to overcome the problem of increasing weight with increasing material thickness.

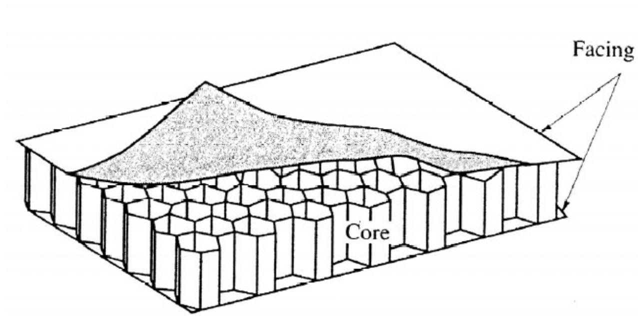


Figure 37: Honeycomb-sandwich panel [15]

By weight, the material use was about one third steel, and two thirds aluminum. Lockheed Martin Tactical Aircraft Systems (which acquired the General Dynamics, Fort Worth division in 1993) identified a list of 13 different materials used in the F-111. This list is presented as Table 11 in the appendix. Of the 13 materials, the most important was D6ac steel, since it was used in the most structure-critical components. General Dynamics classified 15 critical forgings and 11 critical parts (other than forgings), where failure in flight would likely be catastrophic and resulting in loss of aircraft. Of these parts, all but two were made using D6ac steel. In particular, much of the wing pivot fitting, wing pivot support assembly, and wing carry-through box was made from D6ac steel. D6ac is an ultra-high-strength steel with medium carbon content. However, due to manufacturing defects, the material exhibits a large variation in fracture toughness, with the lower limit being unacceptably low for the F-111. This was the cause of the initial failures of the F-111, and will be described in further detail in Section 10.2.

The remaining two critical parts were the upper and lower wing surfaces, and were manufactured using 2024-T851 aluminum. The high operating speed of the F-111 meant that the wings would experience correspondingly high operating temperatures, where the strength of the aluminum alloys would be reduced. Among the aluminum alloys used in the F-111, 2024-T851 aluminum exhibited lower strength at room temperature than the 7xxx-series alloys, but outperformed them at higher temperatures, so it was eventually selected.

6.3.2 Wings and Sweep mechanism

The F-111 has cantilever shoulder wings that have a sweep angle range of 16^o (spread) to 72.5^o (fully swept). The wings have a five-spar structure, with stressed and sculptured wing skin panels made from 2024-T851 aluminum. Each panel had a honeycomb-sandwich structure, and was made from a single piece of metal from the root to the tip, and from the leading to trailing edges.

Leading-edge slats and double-slotted trailing-edge flaps spanned the full wing, allowing the wing area and camber to change for loiter and take-off. For loiter, the double-slotted flaps extend with a 10^o deflection, while the slats extend and droop to 31^o, thereby increasing the camber and wing area for optimal loiter time. For take-off, both slats and flaps deflect to a maximum of 40^o for maximum lift. The wings also have air-brake/lift dumpers that operate as spoilers for lateral control at low speeds.

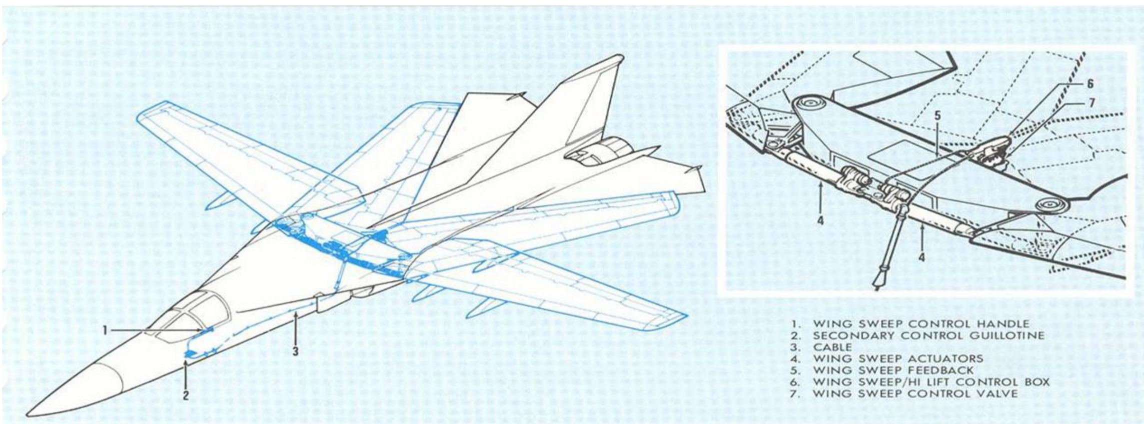


Figure 38: F-111 wings and sweep mechanism [12]

As shown in Figure 38, the sweep mechanism has a single pin pivot arrangement. Dual loading paths were provided to reduce stress levels. The wing carry-through box was assembled as a single unit and was designed such that it may be easily removed and mated to the fuselage to facilitate maintenance activities. It also doubles-up as part of the forward fuselage fuel tank. A dry-film lubricant was used to lubricate the bearing surfaces, and double-seals protect these surfaces from contamination by foreign particles. Also, a special grease compound protected the joint from moisture.

The wings are swept and spread via a hydraulic mechanical actuation system as shown in Figure 39. The system was actuated via a manual control from the cockpit. The two acme-threaded hydraulic actuators are interconnected to ensure symmetrical wing position. Each actuator is powered by a hydraulic motor, and is able to operate under 4g load conditions. Locking is achieved by the use of three spring-positioned, locking rollers, with “no back” rollers that lock when hydraulic pressure is removed. The two actuators are powered by separate hydraulic systems so that in the event of failure of either system, the remaining system can still provide wing actuation through the mechanical interconnect. The hydraulic system is described further in Section 6.3.6.

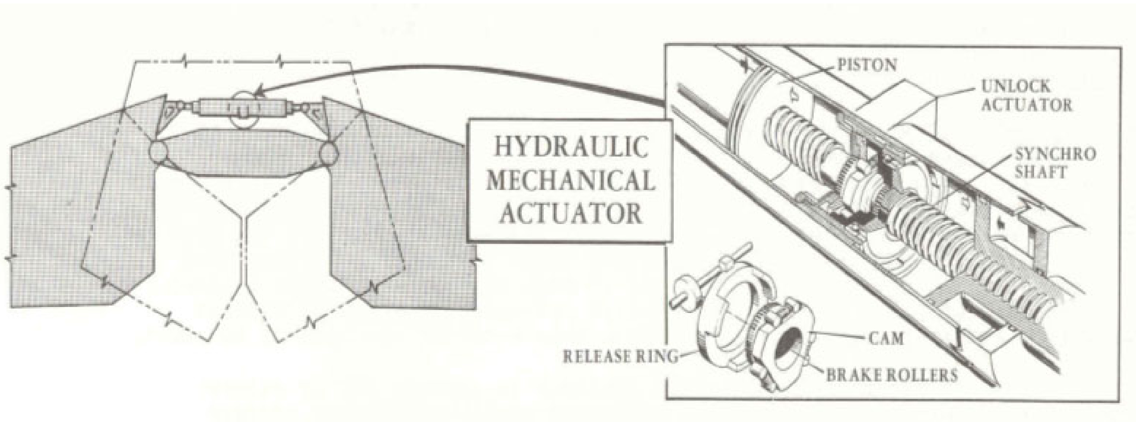


Figure 39: F-111 wing sweep actuation system [10]

6.3.3 Propulsion

6.3.3.1 Engine

Two Pratt and Whitney TF30 afterburning turbofan engines powered the F-111. The TF30 was the first afterburning turbofan ever developed, and was a key technological advance that made the development of the F-111 possible. Before the F-111, turbofans had been built, but only for subsonic bombers and transports. By combining afterburner and turbofan technology, a higher maximum thrust and superior fuel economy was achieved.

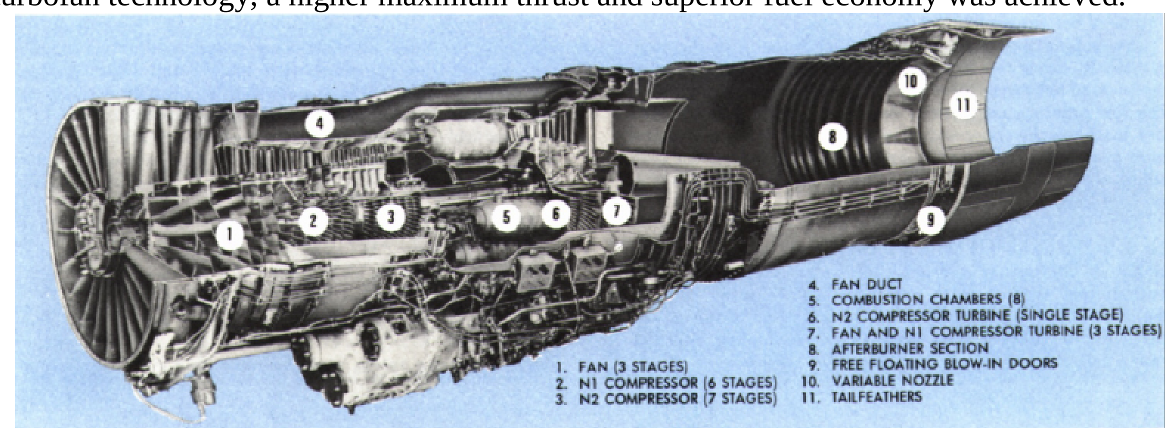


Figure 40: Pratt and Whitney TF30-P-3 engine [12]

Figure 40 shows a cutaway diagram of the TF30-P-3 afterburning turbofan. The 3 fan stages provide initial pressurization of the air entering the engine. The outer portion of fan air is pumped through the fan duct that surrounds the basic engine core, and subsequently joins the airflow from the turbine discharge. The inner portion of fan air goes through the basic engine, and is compressed through six stages of low pressure compression (N1), followed by 7 stages of high pressure compression (N2). This air is then diffused into the can-annular combustion chamber containing 8 combustion cans. Fuel is metered by a conventional hydro-mechanical control and supplied via four dual orifice fuel nozzles at the forward end of each combustion chamber. Ignition occurs via igniter plugs located in two of the combustion chambers. Following ignition, combustion is self-sustaining. The turbines are driven by the heated fuel-air mixture entering the turbine section. The high pressure compressor turbine is single-stage, while the low pressure compressor turbine has three-stages.

Leaving the turbine, the engine air joins the outer fan air in the afterburner section. Here, an afterburner fuel control injects fuel at several stages, providing thrust ranging from minimum to maximum afterburner. Aft of the afterburner section is a variable nozzle that is hydro-mechanically controlled. Six free floating blow-in doors open and close according to pressure differences between the air inside and outside. When open, outside air enters and supplements the engine exhaust to increase engine thrust. The free-floating tail feathers similarly vary in cross-section according to differential pressure.

Initially, the F-111 used the TF30-P-1 version of the engine, but it was later replaced by the TF30-P-3 in the production F-111A. Compared to the P-1, the P-3 had a redesigned stator inlet, compressor spools with changed blade angles, a sixth stage bleed to improve stall tolerance, a new afterburner fuel system, and a modified nozzle. Both versions have a static thrust of 10,700 lb st (47.6 kN) and 18,500 lb st (82.3kN) with afterburning, but the TF30-P-3 has lower supersonic specific fuel consumption at sea level. Both versions also have a specific fuel consumption of 2.50 lb/h/lb st. The air-intake system was a Hamilton Standard (now Hamiltion Sundstrand) hydro-mechanical system with movable shock-cone.

Subsequent versions of the TF30 were used in variants and upgrades of the F-111, as well as other aircraft, such as the Vought A-7A and the F-14. A summary of the different TF30 versions and aircraft that used them is provided in Table 4 below. Thrust and specific fuel consumption is provided where available.

Table 4: List of TF30 versions [1, 16]

Engine	Aircraft	Thrust, lb st (kg st)	SFC, lb/h/lb st
TF30-P-1	F-111 (pre-production)	18,500 (8,390)	2.50
TF30-P-3	F-111A	18,500 (8,390)	2.50
TF30-P-12	F-111B	20,250 (9,185)	3.04
TF30-P-7	FB-111	20,350 (9,231)	3.013
TF30-P-9	F-111D	19,600 (8,891)	2.61
TF30-P-412	F-14	20,900 (9,480)	--
TF30-P-100	F-111F	25,100 (11,340)	2.45
TF30-P-6 (non A/B)	Vought A-7A	11,350 (5,150)	0.620
TF30-P-8 (non A/B)	Vought A-7B Corsair II	12,200 (5,534)	0.630
TF30-P-408 (non A/B)	--	13,400 (6,080)	0.64

Further technical details of the TF30 engine as presented in *Jane's All The World's Aircraft, 1976-77* may be found in the appendix.

6.3.3.2 Engine-inlet

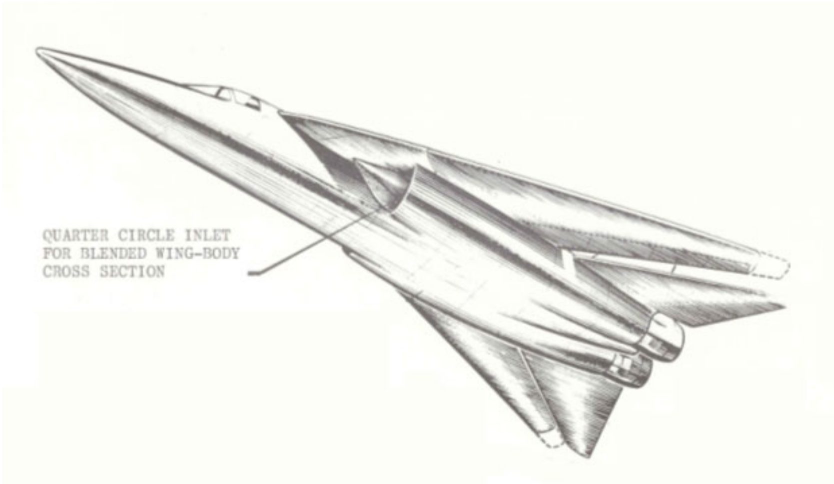
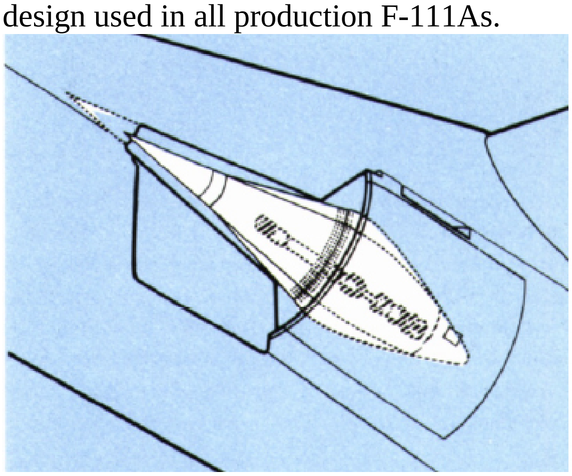


Figure 41: Location of F-111 engine-inlet [10]

The original engine-inlet was a quarter-circle design with a high-speed bypass system coupled with a movable inlet spike. As shown in Figure 41, the inlet was located aft of the leading edge of the wing and next to the fuselage, and a splitter plate was designed to direct turbulent airflow away from the inlet. The inlet spike varied the geometry of the air inlet to control the inlet shock wave pattern. However, the turbulence created by the airflow over the wing and fuselage was not properly anticipated during the design of the inlet. Early F-111s had major compatibility problems between the engine and the engine-inlet, and suffered from repeated compressor surges and stalls, particularly at higher speeds and angles of attack. Subsequent modifications by General Dynamics resulted in the Triple Plow I (TP I) inlet design used in all production F-111As.



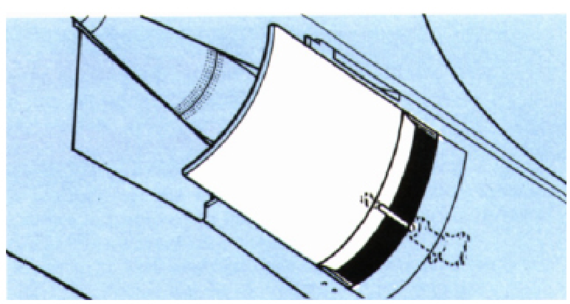


Figure 42: F-111 movable inlet spike (left) and variable cowl (right) [12]

The TP I design incorporated a translating cowl as shown in Figure 42. The translating cowl allows additional air to enter the inlet for better performance during ground operation and low speed flight. Additionally, the splitter plate was curved and extended outwards by 4 inches from the original design. A notched side-plate was also placed within the inlet, accompanied with a thickening of the inlet lip. As a result, the engine stall region was moved to Mach 2 in maneuvering flight and Mach 2.35 in level flight, and was deemed satisfactory, since further changes would require a structural change to the aircraft.

NASA, the Air Force, and General Dynamics pursued further improvement to the inlet to produce the Triple Plow II (TP II) design in late 1967, which moved the stall region beyond Mach 2.4 at high altitudes and angles of attack. The TP I and TP II are shown side by side in Figure 43. The TP II design had three blow-in doors, and the inlets and ducts were enlarged and moved outward (away from fuselage) by about 4 inches. Having no more need for the splitter plate, it was removed. Also, the inlet spike was extended by about 18 inches. Common to both designs, vortex generators were installed in the inlet aft of the translating cowl. These "teethy-looking" features can be seen in Figure 43. The vortex generators were placed in pairs of opposing angles of attack, creating contra-rotating vortices that prevent airflow separation from the duct walls, and cancel their rotational energy before reaching the compressor face. The TP II design was incorporated into the later F-111 models: the F-111D, E, F, Gs as well as the FB-111As.

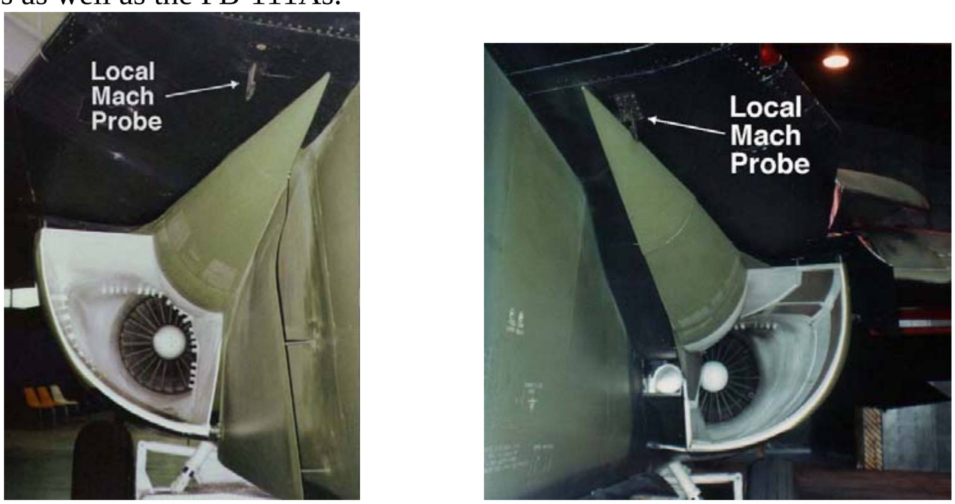
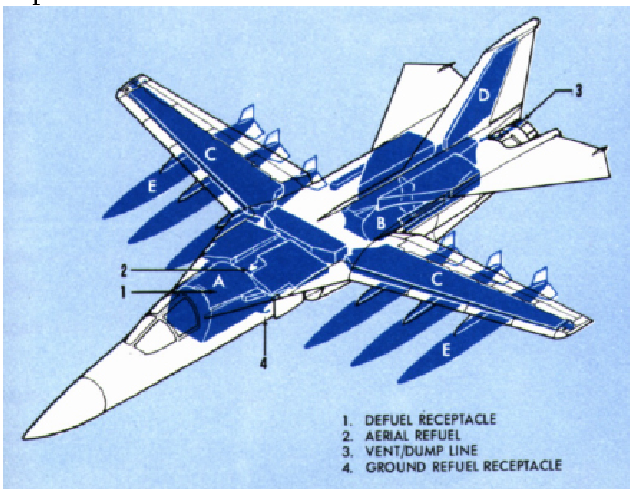


Figure 43: Triple Plow I (left) and Triple Plow II (right) engine inlets [17]

6.3.4 Fuel System

The F-111 has two fuselage tanks located forward and aft, a vent tank (in vertical stabilizer), as well as two wing tanks (one in each wing). The forward fuselage tank is further divided into bay F-1, bay F-2 and a reservoir tank, while the aft fuselage tank is divided into bay A-1 and bay A-2. Additionally, a total of six 600 gallon external tanks could be carried on the external wing pylons. The maximum internal fuel capacity is 5015.5 gallons, and maximum external capacity is 3607.4 gallons, giving a total capacity of 8622.9 gallons. Figure 44 below shows the layout of the fuel tanks, fuel receptacles and corresponding capacities of each tank.



TANK	CAPACITY (1)	
	GALLON	LB
A FWD TANK	2,808.3	18,254
BAY F-1	1,187.2	7,717
BAY F-2	1,234.6	8,025
RESERVOIR TANK	386.5	2,512
B AFT TANK	1,428.8	9,287
BAY A-1	1,054.3	6,853
BAY A-2	374.5	2,434
C WING TANK	778.4	5,060
RH WING TANK	389.2	2,530
LH WING TANK	389.2	2,530
D VENT TANK	....	....
AIRPLANE TOTAL	5,015.5	32,601
E EXTERNAL STORES (6) 600 GAL. NOM.	3,607.4	23,448
TOTAL: AIRPLANE & EXTERNAL STORES	8,622.9	56,049

Figure 44: F-111 Fuel System [12]

Fuel is only supplied to the engines from the fuselage tanks, so wing and external fuel is transferred to the fuselage tanks for consumption. Wing tank fuel is transferred by two pumps in each wing, while external tank fuel is transferred by pressurized air. There are four fuel supply modes: FWD, AFT, BOTH and AUTO. In FWD or AFT modes, fuel to both engines is supplied by the forward or aft tanks respectively. In BOTH and AUTO modes, the left engine consumes fuel from the forward tank, while the right engine consumes from the aft tank. Additionally, in the AUTO mode, a gauging system senses excessive imbalances between the forward and aft tanks. If it senses too much fuel in the forward tank, the aft tank pumps are turned off, and both engines consume from the forward tank until balance is restored. On the other hand, if there is too much fuel in the aft tank, excessive fuel is automatically pumped into the forward tank.

A pressure fuelling point is located in the port side of the fuselage, forward of the engine air intake. There is also a gravity fuel filler/in-flight refueling receptacle located aft of the cockpit in the top of the fuselage.

6.3.5 Electrical System

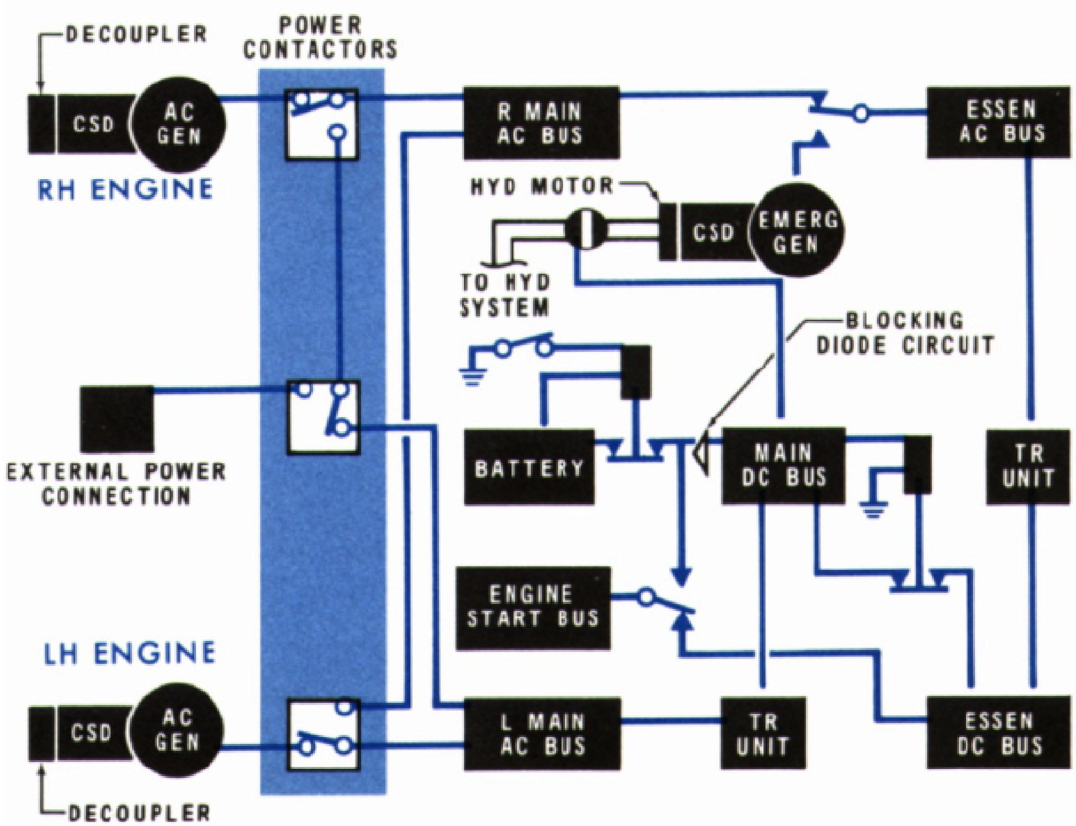


Figure 45: F-111 Electrical System [12]

Figure 45 above is a schematic of the electrical system in the F-111. The electrical system provides 400 cycle, 115/200 volt, 3 phase AC and 28 volt DC power. AC power is supplied by two 60KVA systems. Two oil-cooled generators are driven by engine-powered constant speed transmissions, and can be controlled by the pilot via an on-off switch for each generator. However, in the event of engine shutdown or generator-drive malfunction, the generator will automatically be switched off even when the control switch is on. Under normal operation, the two generators supply separate load buses, but if either generator is switched off, the two buses will be automatically connected. A single generator is sufficient to power the whole aircraft.

DC power is generated from the AC power system by two 28 volt, 150 amp transformer-rectifiers, which are supplied by a separate AC buses. Each transformer-rectifier feeds individual DC buses that are normally connected by a bus tie relay. As with the AC power generators, each DC bus is capable of powering the entire aircraft load, but there are no controls necessary for the DC power system. A nickel-cadmium battery charged by the DC system provides power for starter operation, minimum engine instruments, and minimum cockpit lighting when external power is not available.

In the event of the loss of primary generating systems, an emergency electrical power system provides power to all electrical systems essential for flight, which includes primary flight controls, external lighting and the anti-icing system. The emergency power is supplied by a 10KVA, 400 cycle, 115/200 volt, 3 phase, air-cooled generator driven by a hydraulic motor. When activated, shutoff valves are automatically opened to supply hydraulic power to the motor and cooling air to the generator. The generator is automatically connected to the buses that power the essential flight systems.

6.3.6 Hydraulic and Pneumatic System

Two independent, parallel, 3000 psi hydraulic systems, designated as "primary" and "utility", provides hydraulic power to the aircraft. Under normal conditions, the two systems concurrently supply power to flight controls and wing sweep; however, either system alone supplies enough power for these functions. The utility system also powers the landing gear, tail bumper, nose wheel steering, wheel brakes, speed brakes, flaps, air inlet control, aerial refueling, weapon trapeze, weapon bay doors, weapon bay gun, and emergency electrical generator. Figure 46 below is a schematic of the hydraulic system.

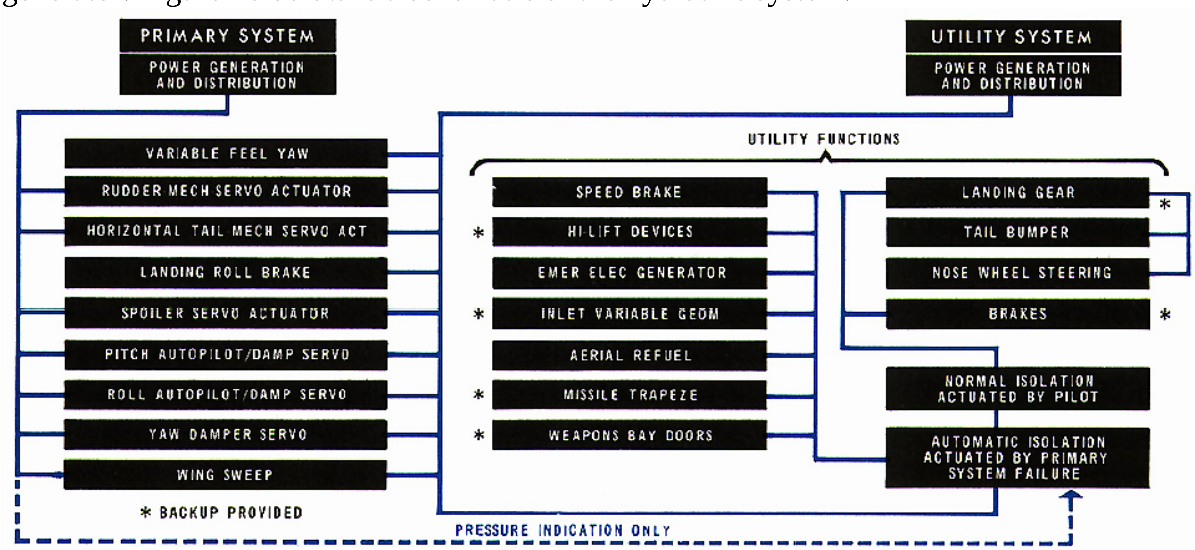


Figure 46: F-111 Hydraulic System [12]

Each system is supplied by two engine-driven, variable-delivery pumps. For redundancy considerations, one pump in each system is driven by the right engine, and the other is driven by the left engine. Each system has a piston-type reservoir that provides fluid storage, and is pressurized by stored nitrogen. The reservoirs are controlled by pressure regulators and relief valves. A pressure transmitter in each system also provides pressure information to the cockpit, and a caution light for each pump comes on in the event of low pressure. Also, in the event of hydraulic rupture or loss of primary system pressure, an automatic isolation valve prevents fluid loss to the utility system flight controls, wing sweep motors, and reservoir.

6.3.7 Payload, Weapons and External Stores

The Air Force version, the F-111A, has no fixed weapons or external stores configurations and instead utilizes a “plug and play” concept of inserting different weapons packages for the specific mission. It has a versatile weapons capability, and can carry an array of air-to-surface, air-to-ground, conventional and nuclear weapons, as well external fuel tanks. The internal weapons bay can house an M61 multi barrel 20mm gatling gun and one 750 lb class bomb or missile, or two bombs or missiles. External stores can be carried on four hardpoints under each wing. Of these four hardpoints, the two inboard pylons pivot as the wings sweep to remain parallel to the fuselage. The two outboard pylons are non-pivoting and are jettisonable prior to sweepback.

..... Weapons

1. JETTISONABLE, NON-PIVOT
2. JETTISONABLE, NON-PIVOT
3. NON-JETTISONABLE, PIVOTING
4. NON-JETTISONABLE, PIVOTING
WB WEAPONS BAY
5. NON-JETTISONABLE, PIVOTING
6. NON-JETTISONABLE, PIVOTING
7. JETTISONABLE, NON-PIVOT
8. JETTISONABLE, NON-PIVOT

		UP TO 72.5° WING SWEEP						UP TO 55° WING SWEEP						26° WING SWEEP									
		3	4	WB	5	6	TOT	3	4	WB	5	6	TOT	1	2	3	4	WB	5	6	7	8	TOT
MISSILES	AIM-9B	2	1	2	1	2	8	2	1	2	1	2	8			2	1	2	1	2			8
	AGM-12B	1	1	2	1	1	6	1	1	2	1	1	6		1	1	1	2	1	1	1		8
	SHRIKE	1	1		1	1	4	1	1		1	1	4			1	1		1	1			4
ROCKET LAUNCHERS	LAU-3A/A	3	1		1	3	8	3	3		3	3	12	3	3	3	3		3	3	3	3	24
	LAU-10/A	3	1		1	3	8	3	3		3	3	12	3	3	3	3		3	3	3	3	24
	LAU-18/A	3	1		1	3	8	3	3		3	3	12	3	3	3	3		3	3	3	3	24
GUNS	SUU-16A	1	1		1	1	4	1	1		1	1	4			1	1		1	1			4
	GUN MODULE			1			1			1			1					1					1
NUCLEAR WEAPONS	MK-43	1	1	1	1	1	5	1	1	1	1	1	5			1	1	1	1	1			5
	MK-57	1	1	2	1	1	6	1	1	2	1	1	6			1	1	2	1	1			6
	TX-61	1	1	2	1	1	6	1	1	2	1	1	6			1	1	2	1	1			6

1. JETTISONABLE, NON-PIVOT
2. JETTISONABLE, NON-PIVOT
3. NON-JETTISONABLE, PIVOTING
4. NON-JETTISONABLE, PIVOTING
WB WEAPONS BAY
5. NON-JETTISONABLE, PIVOTING
6. NON-JETTISONABLE, PIVOTING
7. JETTISONABLE, NON-PIVOT
8. JETTISONABLE, NON-PIVOT

		UP TO 72.5° WING SWEEP						UP TO 55° WING SWEEP						26° WING SWEEP									
		3	4	WB	5	6	TOT	3	4	WB	5	6	TOT	1	2	3	4	WB	5	6	7	8	TOT
CONVENTIONAL BOMBS	M-117	6	2	2	2	6	18	6	6	2	6	6	26	6	6	6	6	2	6	6	6	6	50
	MC-1	6	2	2	2	6	18	6	6	2	6	6	26	6	6	6	6	2	6	6	6	6	50
	BLU-1/B	2	1	1	1	2	7	2	2	1	2	2	9	2	2	2	2	1	2	2	2	2	17
	MLU-10/B	3	3	2	3	3	14	3	3	2	3	3	14	3	3	3	3	2	3	3	3	3	26
	BLU-14/B	3	3	2	3	3	14	3	3	2	3	3	14	3	3	3	3	2	3	3	3	3	26
DISPENSERS	CBU-1A/A													3	3						3	3	12
	CBU-2A/A													3	3						3	3	12
	CBU-3/A													3	3						3	3	12
	SUU-13/A	3	3		3	3	12	3	3		3	3	12	3	3	3	3		3	3	3	3	24
	CBU-6/A													3	3						3	3	12
	A/B 45Y-1	1	1		1	1	4	1	1		1	1	4	1	1	1	1		1	1	1	1	8
	TMU-28E	1	1		1	1	4	1	1		1	1	4	1	1	1	1		1	1	1	1	8
TRAINING	MN-1A	1	1	1	1	1	5	1	1	1	1	1	5			1	1	1	1	1			5
FUEL TANKS	450 GAL.	1	1		1	1	4	1	1		1	1	4		1	1	1		1	1	1		6

Figure 47: F-111A Weapons configuration chart [14]

6.3.8 Landing Gear

The landing gear is a hydraulically actuated forward retracting tri-cycle type. The main leg consists of a single wheel mounted on either side of a common trunnion, while the nose unit has twin wheels. A photograph of the main gear is shown in Figure 48.

Figure 48: F-111 Main Landing Gear [18]

During retraction, hydraulic actuators cause the nose unit to retract forward. For the main gear, the legs pivot downwards and aft as the wheels retract forward and up. The wheels then stow side-by-side in the fuselage between the engine air intake ducts.

The braking system utilizes disc brakes equipped with an anti-skid system. Dual hydraulic brake circuits provide the redundancy necessary to ensure safe operation. In addition, two pneumatically charged hydraulic accumulators provide hydraulic pressure for emergency braking or parking. Actuation of the auxiliary brake control handle applies accumulator pressure to brake for parking.

In order to minimize the danger of a failed downlock, the gear linkages are designed such that landing loads tend to extend the drag strut to the locked down position. Large, low-pressure tires are used to ensure operational capability from semi-prepared airfields.

The plane also has a hydraulically operated tail bumper that extends and retracts with the landing gear. This prevents the control surfaces, engines and aft portions of the aircraft from being damaged in the event that the tail accidentally contacts the ground. It also provides some protection against over-rotation during take-off and landing.

6.3.9 Cockpit and Avionics

6.3.9.1 Cockpit

The crew compartment of the F-111 was a pressurized and temperature controlled environment. This provided a comfortable workspace for the crewmembers. The whole organization of the cockpit has been greatly influenced by the choice of side-by-side seating. It was designed to promote the "team concept", allowing a better communication between the Aircraft Commander and the Pilot. This design choice also avoided the need of a separate airplane designed for crew training.

The compact arrangement of instruments minimized the need for duplication. The Aircraft Commander sat on the left in the "primary flight station" equipped with all the instruments necessary for flight control. The Weapons Systems Officer (WSO) sat on the right in the "primary avionics systems control station" equipped with weapons delivery controls, and also with instruments necessary to perform pilot functions. It resulted in two self-sufficient stations but offered a sufficient flexibility in the task distribution between the crewmembers.

Nuclear shielding curtains were included in the cockpit over the crew stations to reflect the flash if the F-111 was ever used for a nuclear delivery mission. Another interesting feature of the cockpit was individual ladders stored under each pilot station reducing ground support necessary for operations.

Figure 49 shows the arrangement of instruments in F-111A. The two striped handles on the center console are the ejection handles. The hood on the right is the WSO's attack radar display [12].

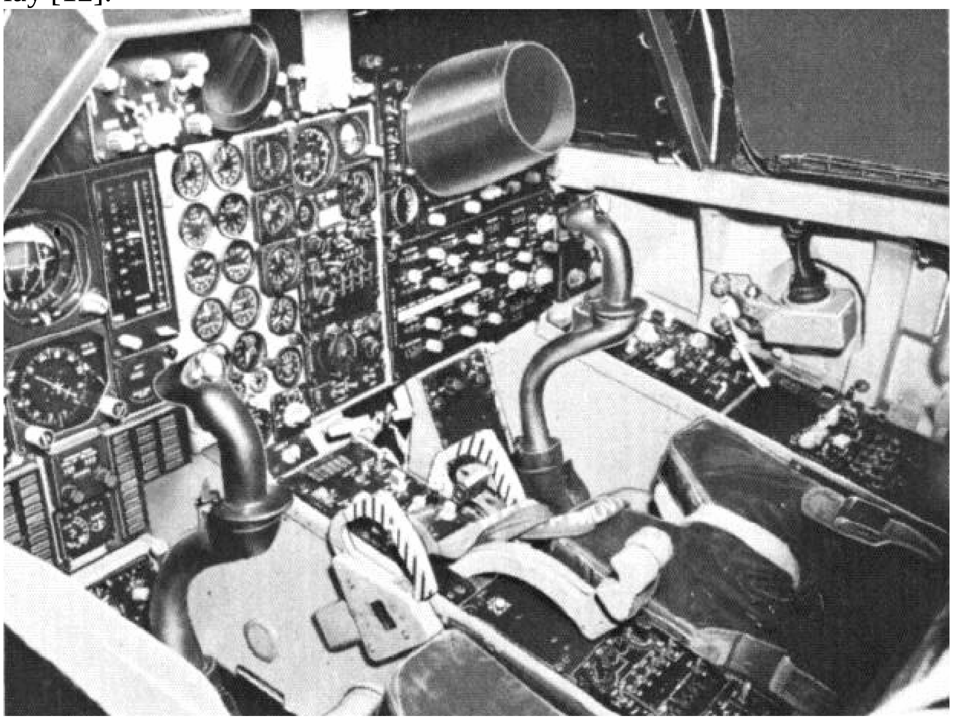


Figure 49: F-111 cockpit [12]

The bottom of the optical sight can be seen in the upper-left corner of Figure 49. The optical sight was part of the navigation and attack system and was an early head-up display. It was located in front of the pilot's left seat station only. The optical sight is shown below in Figure 50. The left side shows the display unit. The right side shows the one of the displays shown to the pilot. The pilot could select several displays of varying information.

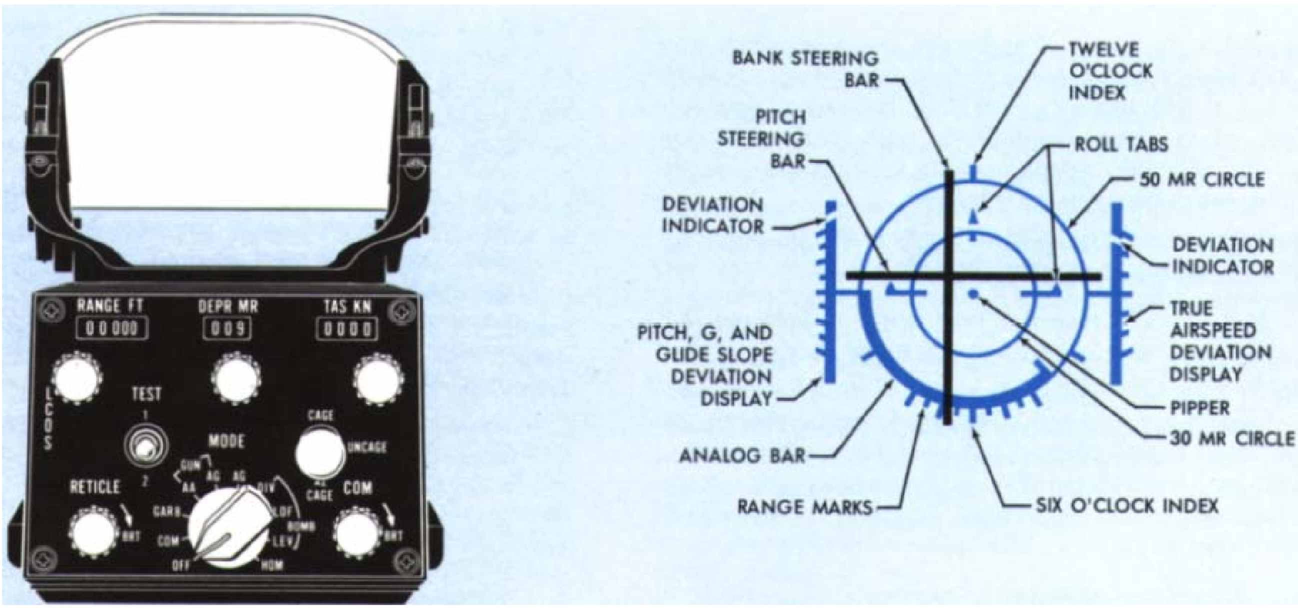


Figure 50: Optical sight (Heads-up display) [12]

One flaw of the design of the F-111 cockpit was in the sweep control handle. The wing sweep control was located on the left side of the left-seat pilot, just under the canopy. The control was shaped like a trombone handle or a pistol grip. There were three problems with the design of the handle: its location, shape, and direction for controlling sweep. It was important for the pilot to always know where the wings were, and at least one crash was caused by the pilots sweeping the wings the wrong way [17]. According to an early F-111A flight manual (reference 23), the sweep control was slid forward to sweep the wings back, and aft to sweep the wings forward. This seemingly reverse logic of the designers was based on airspeed. Pushing the controller forward meant the airplane would go faster when the wings swept back, and the designers thought that would be the best correlation for the pilot. The pilots came back to the designers during testing and said that it made no sense, and the controller direction was switched so that pulling it back swept the wings back instead of forward [46]. The next two problems were never fixed. One was that the shape and motion of the control had nothing to do with the shape and movement of the wings. If the control had been shaped like a wing and rotated, then the pilot would be able to tell by feel where the wings were. The final problem was that the control was difficult for the WSO to reach. If the pilot were killed, the WSO would have had no chance at flying the airplane and reaching the control around the pilot's slumped body. This was a concern for WSO's in the F-111 [46].

6.3.9.2 Avionics

The avionics system provided navigation, terrain-following, air and ground attack capability and management, threat detection, and automatic flight controls. The avionics package was called Mk I Avionics. Later variants of the F-111 carried Mk II and MK IIB avionics, which will not be discussed in detail here. Most aircraft components in or related to the avionics package were listed in the table below:

Table 5: Mk I Avionics Components and Related Components and Manufacturers [1]

Component	Manufacturer
Terrain Following Radar (Air Force only)	Texas Instruments
Doppler Radar (Navy only)	Hughes
Attack Radars (Air Force only)	General Electric
Flight Control Systems	
Navigation and attack system	Litton Industries
Inertial Reference Unit	
Astrocompass	
Air Data Computers	Bendix Corp, Navigation and Control
Low-Alt radar altimeter	Honeywell
Radar homing and warning system	Textron
Electrical Generating Systems	Westinghouse Electric Corp
Mk II/IIB Avionics	Autonetics Division of North American

6.3.9.3 Terrain Following Radar

The terrain-following radar (TFR) was the most significant component of the avionics system providing one of the most important and unique capabilities of the F-111. TFR allowed the F-111 to fly high speed at a constant altitude above varying terrain. Typical altitudes in use were in the 200-1000 ft range, with higher altitudes used in steep, mountainous terrain [20]. By flying in the nap of the earth the F-111 could penetrate deep into enemy territory by a combination of staying below the radar horizon and hiding behind terrain features. TFR allowed the F-111 to perform its mission day or night and in all weather conditions except heavy rain.

In terrain following flight, the TFR constantly monitored the terrain in front of, and to the sides of the aircraft. The TFR's analog computers constantly recalculated which object in front of the aircraft to use to calculate a trajectory. When approaching an obstacle, the TFR commanded the airplane to pull-up at the minimum distance calculated. The computers shaped the flight path so that the airplane was flying level again as it crested the peak, keeping altitude and thus detectability to a minimum. The TFR could be set for a soft, medium, or hard ride depending on how tight the pilot wanted to hug the terrain. Most pilots flew with a medium setting. The TFR also could command horizontal flight to fly around tall and skinny obstacles such as communications towers. The system monitored obstacles to the left and right of the airplane's path for when the pilot changed course and to be able to accurately measure the height above ground while in a bank. A center mounted cockpit display showed a side view of the topography directly in front and the calculated path planned by the computers [21].

The TFR was relied on to safely guide the aircraft at night and through clouds, where the crew could not monitor the system and detect faults. For redundancy, the system had two independent systems. The active system performed self-checks every 0.7 seconds, and switched to the other system if a fault was detected. If this failed the system goes into its failsafe mode in which it commands a 2-g pull-up and warns the crew of a malfunction via a warning light [21]. Each of the two systems had a scanner. In normal operations, one scanner scanned vertically along the flight path for vertical path planning. The other scanner scanned horizontally for steerage information with a 30 degree azimuth range [23]. If the primary vertical scanner failed, the secondary scanner would begin to scan vertically [23].

The TFR could be operated in manual or automatic mode. In manual mode, the TFR displayed terrain information to the pilot. In automatic mode, the TFR displayed this information and flew the aircraft [21]. As mentioned above, pilots could select a soft, medium, or hard ride. This determined how sharp the aircraft would pull-up or down in following the terrain, which in-turn, determined the g-load experienced by the pilots. A hard ride limited the g-load to +3.0 and 0 absolute and was uncomfortable for the crew [23]. The preferred medium ride produced typical g-loads of ¾ to 1 ½ [22]. The altitude setting for TFR flight could be dialed in to any height from 1,000 to 200 ft AGL. Switching to automatic TFR flight from a higher altitude put the aircraft into a steep dive and then pulled out of the just at the dialed in TFR setting [21].

The system was all-weather capable, and could fly day or night. Rain and other forms of precipitation could interfere with radar operation and would result in the fail-safe mode if the TFR cannot distinguish the ground from the rain [23]. If the system got a bad signal due to a radar or electrical problem the aircraft automatically climbs [1].

6.3.9.4 Navigation and Attack System

The navigation and attack system consisted of inertial measurement units and an analog computer/ display unit. The inertial measurement unit gyros where located on a stabilized platform in the nose of the aircraft [12]. The navigational computer received inertial data from the gyros. The navigational computer computed and displayed latitude and longitude, ground speed, ground track, wind speed, wind direction, stabilized magnetic heading, pitch and roll attitude, and steerage information to a target or waypoint. The computer stored target information, and up to three alternate target destinations. It sent ground track steerage signals to the autopilot. Inertial measured position could be updated via a fix taken by the attack radar [23]. The computer worked with the attack radar for bombing calculations and weapons delivery. Several pilot-selectable weapons delivery modes were available for various types of weapons [23]. The radar bombing system was day or night all weather capable [24]. The navigation and attack system could bomb a target offset from a radar-visible feature [23]. This feature was used in South East Asia for radar beacon offset bombing. The attack radar provided ground target identification and air-to-air search and range tracking. In air mode, the attack radar had an 85% probability of detecting a one square meter target at 15 nautical miles [12]. The system scans ±45 degrees in azimuth and ±30 degrees in elevation, and will lock on a target within 10 nautical miles [12]. The attack radar could also be used to navigate around and between thunderstorms [23]. The navigation and attack system had continuous in-flight monitoring. Sensed errors were displayed to the pilot via warning lights. If there was an error in the inertial measurement unit, the navigational computer used the last stored wind speed, air data, and backup compass measurements to calculate navigational information [23].

6.3.10 Stability and Control

6.3.10.1 Pilot Controls and Control Surfaces (Primary Flight Controls)

Pilot controls in the F-111 were the conventional center-stick and rudder pedal arrangement. Sticks and pedals in the pilot and co-pilot seats were the same and perform the same function. The stick gave lateral (roll) and longitudinal (pitch) command. The pedals gave directional (yaw) command. The stick had low-friction break-out forces for better flying qualities [23]. Pilot controls were mechanically linked to control surface servo actuators [23]. Dual hydraulics moved control surfaces and provide redundancy (see Section 6.3.6 on hydraulics). The electrical and hydraulic systems provide emergency backup power to the control system.

There were no ailerons on the F-111. Flaps and slats increased lift for take-off, landing, and low-speed flight. Wing spoilers were used for lateral controls at low speeds [23]. Horizontal stabilizers moved independently for lateral control and collectively for longitudinal control [23]. The horizontal tail surfaces were connected to the airframe by a pivot and move as a whole. The single vertical tail has an independently movable rudder [23].

6.3.10.2 Flight Control System (Automatic Flight Controls)

The flight control system provides autopilot modes and stability and command augmentation. Autopilot includes heading, altitude, and mach number hold. The autopilot could receive signals from the TFR to flying in terrain-following flight. Stability augmentation was provided in all three axes. Command augmentation was provided in the pitch and roll axes [23]. Stability augmentation gained through roll, pitch, and yaw damping which were independently selectable [23].

6.3.10.3 Longitudinal Control

Longitudinal control came from a direct mechanical linkage from the control stick to horizontal tail surface servo actuators [23]. Purely fore-aft movement of the stick causes the tail surfaces to pivot symmetrically [23]. An artificial force-feel spring gives the pilot 10.8 lbs of forces per inch of longitudinal displacement [23].

6.3.10.4 Lateral Control

Lateral Control came from a direct mechanical linkage to horizontal tail servo actuators and an electrical linkage to spoilers [23]. Lateral movement of the stick caused the horizontal tail surfaces to pivot asymmetrically and the spoilers to actuate appropriately. Spoilers work by causing roll by reducing (spoiling) the lift on one wing, where more conventional ailerons cause roll by increasing the lift on one wing. Spoilers prevent roll-reversal problems caused by ailerons. Spoiler authority (the amount the spoiler contributed to roll) was at a maximum with the wings forward, allowing the spoilers to deflect up to 45 degrees. With greater aft wing-sweep, less spoiler deflection was allowed, down to zero degrees deflection at 45 degrees of sweep. Spoiler authority was also scheduled out as wing sweep increases from a maximum deflection of 45 degrees to zero. At wing sweep angles aft of 45 degrees (where 16 degrees was fully unswept, and 72.5 degrees was fully swept), spoiler command was zeroed so that they were not used [23]. For added safety with wings aft of 47 degrees of wing sweep, hydraulic power was cut off to the spoilers. If a spoiler accidentally deployed, the induced roll caused the pilot to input lateral stick to roll the other way causing both spoilers to be up, which causes a spoiler monitor to cut off hydraulic power to both spoilers causing them to go flat. There was a spoiler monitor reset button for this situation. There was a spoiler authority schedule based on wing sweep.

Differential tail surfaces were effective at all sweep angles. For a coupled lateral and longitudinal command the differential lateral command and the collective longitudinal command were summed mechanically [23]. “Full” lateral stick to the force detent gives full spoiler deflection and ¼ differential stabilizer [23]. For extra roll authority in emergencies, stick can be forced past detent to the stops [23].

The F-111 lateral control scheme was similar to that of other aircraft. Delta wing airplanes using ailerons on the trailing edge of the wing were similar to an F-111 using tail surfaces with its wings swept. The F-4 used spoilers and ailerons. The F-18 uses differential tail in addition to ailerons.

6.3.10.5 Directional Control

Directional control comes from a direct mechanical linkage from the pedals to the rudder servo actuators [23]. This was a conventional system. Yaw damping was mechanically added in series.

6.3.10.6 Stability and Command Augmentation

Longitudinal command augmentation maintains constant stick force per g-load [23]. At higher speed, less surface deflection results from the same stick command. The control system compares commanded and measured pitch rate and g-load and mechanically reduces or increases surface deflection to match the command [23]. An estimated stick force per g-load chart was below:

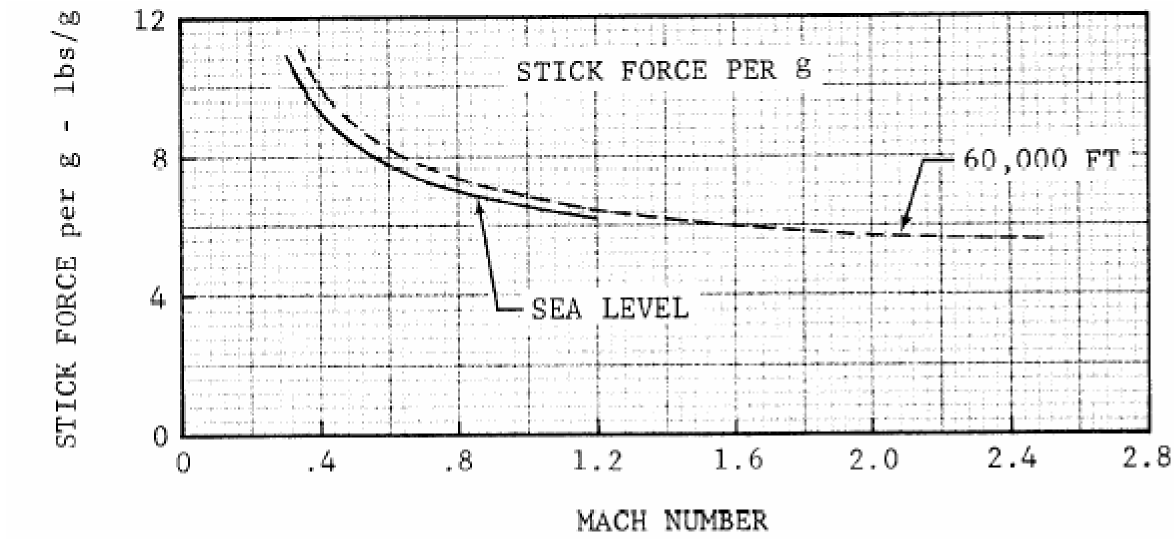


Figure 51: Stick Force per G-Load [23]

Lateral command augmentation provides for constant roll rate per lateral stick deflection by comparing actual roll rate to commanded roll rate. The error was used as in the longitudinal case to increase or reduce control surface deflections [23]. There was no directional command augmentation.

Stability augmentation comes from roll, pitch, and yaw damping [23]. When selected on, these dampers improve the dynamic stability of the aircraft. The aircraft has a restricted flight envelope with the dampers off [23]. The yaw damper also provides automatic turn coordination [23].

6.3.10.7 Stability Effects of Wing Sweep

The aircraft was stable for all sweep angles. Several factors combine to cause this. Longitudinal static stability is achieved when the center of gravity is forward of the aerodynamic center. As the wings were swept back in the F-111, the aerodynamic center and the center of gravity moved back. The amount the aerodynamic center moved depended only on the sweep angle, while the change in center of gravity depended on the sweep angle and the amount of fuel in its wings. The fuel in the wings was burned off first, so less weight went aft by the time the wings were swept back in a flight. The F-111 had outboard positioned wing pivots based on a NASA study in 1961 showed that such a configuration reduced changes in longitudinal stability for variable sweep aircraft. The outboard position meant that less of the wing changed position with sweep. At high speeds, the body of the aircraft significantly contributed to the total lift. In general, aft movement of the aerodynamic center makes an aircraft more stable, and aft movement of the center of gravity makes an aircraft less stable. So the combination of aft movement of the aerodynamic center and the contribution of the body to lift countered the destabilizing effects of the aft movement of the center of gravity with sweep. Any small remaining effects from a wing sweep were hidden from the pilot by the stability augmentation system [25]. There were no stability transients during sweep.

Normal operation up to 0.8 Mach call for a 26° sweep, and a 45° or greater sweep for supersonic flight [23]. At 26°, the non-pivoting outer wing pylons line up with the airflow. Higher sweep angles increase stall speed and angle of attack. At subsonic speeds and 45° or greater sweep, spoiler lock-out significantly reduces roll control authority [23]. Also at high sweep angles, roll angles greater than 60° resulted in excessive sideslip [23]. Other flying qualities were good for all sweep angles.

There was a directional transient that caused Dutch Roll (short period lateral oscillations) and mild buffeting in the transonic regime [23]. Stall angle-of-attack (AOA) was 20° with flaps and slats extended. AOA above 8-10° can cause buffeting at high speeds.

Wing-sweep contributed to stability at low-level high-speed flight. Highly swept or delta wings have a shallower lift slope than straight wings. This means that as angle-of-attack varies, the lift on the aircraft varies less, and buffeting will be reduced. Pilots noted that the F-111 gave a very smooth ride at low levels where other aircraft would have heavy buffeting [26]. This was important for the F-111's terrain following mission. Flying long-range with heavy buffeting is very taxing on crew. The smooth ride of the F-111 reduced crew fatigue keeping them alert for their often very dangerous missions [26].

6.3.10.8 Horizontal Tail

In addition to providing lateral control in an unconventional manner, the horizontal tail surfaces were against convention as lifting surfaces. This gives a better lift-to-drag ratio, weight savings, and improved maneuverability [14]. The horizontal tail surfaces also had anhedral for high speed directional stability.

6.3.11 Crew Escape Module

The crew escape module was the emergency egress system for the F-111. The module was very different from more typical ejection seats in most fighter aircraft. It was designed for crew survival in ejections throughout the entire flight envelope including low-level high Mach and high altitude, high Mach flight. It was designed to work down to zero altitude at 0 kts and on or under water [12]. There was no provision for modifying the ejection from an inverted airplane. The crew module's predecessor was the B-58 escape capsules, which slammed a cover over each crewmember and ejected them in individual containers. The F-111 was the first aircraft to enclose the crew in a single module.

The module was composed of the pressurized aircraft cockpit, the forward portion of the wing glove, an emergency oxygen system, a rocket, recovery parachutes, and impact and flotation bags [27]. Survival gear was contained behind crew headrests [27]. The module protected the crew from water or other hazardous environments and required no personal parachute or individual survival gear [27]. The module had sensors that would separate the module from the aircraft in the event of water landing. This way, a sinking airplane would not suck the crew underwater. The phases of ejection were explained below.

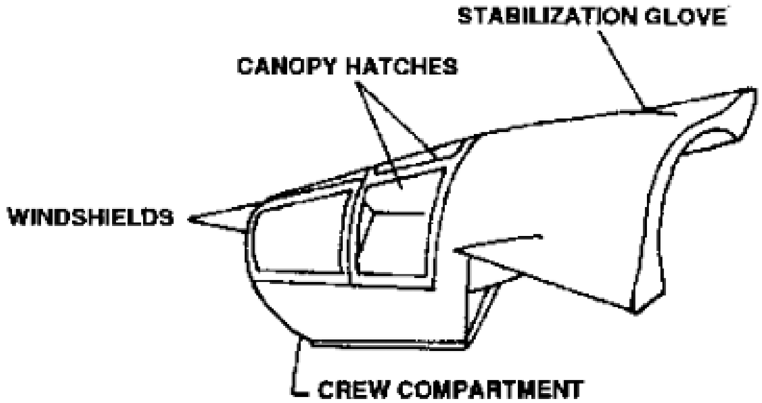


Figure 52: Crew Escape Module [Coynes]

6.3.11.1 Escape Module Separation

Either crewmember could initiate the ejection sequence by squeezing a D-shaped ejection handle and pulling up. Explosive charges cut through the metal holding the crew module to the rest of the aircraft and guillotines severed electrical connections, control wires, and antennas [27]. The 40,000 lb rocket motor fired to propel the module up and away from the aircraft [21].

6.3.11.2 Stabilization

Immediately upon module separation the module was entering an air stream that could be very low airspeeds or over Mach 2. Several devices were employed for stabilization of the module. The wing glove / stabilizer prevented pitch down [27]. Spring actuated stabilization flaps prevented pitch up in a transonic ejection [27]. Spring actuated pitch flaps trimmed out the module [27]. A small stabilization / braking parachute also deployed. As the rocket motor burned out, chaff was released as an extra precaution against lingering missiles searching for a target [11].

The recovery chute deployed reefed to reduce shock loads. Once the lines were stretched and there was some load on the chute, the reef was cut to allow the chute to fully deploy [27]. Impact bags were inflated on the bottom of the module.

6.3.11.3 Landing

On landing, blow-out plugs on the impact bags to absorbed some of the shock of landing. In a water landing, flotation bags could be inflated to keep the module floating and up right. The module was watertight. If the aircraft landed in water without an ejection, the crew could separate from the aircraft to avoid being pulled under [27].

An illustrated ejection sequence is shown in the figure below:

Figure 53: Ejection Sequence [F-111 Escape Module, Phillips]

The crew escape module was used several times in operations, both in combat and non-combat situations. There was no good data of crew deaths due to failed ejection due to the nature of the F-111 mission (see section 3.4.1). Despite this, there were many instances where the crew of a doomed F-111 was saved by the crew module. Additionally, there were no known or confirmed instances where the crew was found dead in an ejected module [17].

6.4 Sub-system Interfaces

Table 6 on the next page is an N^2 diagram depicting the functional interactions between the major subsystems. Each cell depicts an output from the subsystem on the leftmost column as an input to the subsystem on the top row.

Note that the various subsystems are highly coupled and interdependent. In particular, the cockpit and avionics, which represent interactions with the pilots, is the most heavily interdependent with the rest of the subsystems. The hydraulic and pneumatic system, together with the electrical system, provide actuation and power to all the other subsystems, and form an integral part of the aircraft. These two systems, in turn, derive all power from the engine, emphasizing the importance of the powerplant in the overall design of the aircraft. Furthermore, the engine is highly coupled with the hydraulic system: the engine generates power for the hydraulic system, while the hydraulic system controls airflow into the engine by varying inlet geometry.

Table 6: N^2 Diagram for F-111 major subsystems

From \ To	Airframe	Wings and Sweep Mechanism	Propulsion	Fuel System	Electrical System	Hydr. and Pneumatic System	Payload	Landing Gear	Cockpit and Avionics	Flight Control System	Crew Escape Module
Airframe			Engine mounting	Space for fuselage tanks	Provides space	Provides space		Stowage during flight	Provides space	Provides space	Provides space
Wings and Sweep Mechanism	Lift			Provides space for wing tanks		Wing sweep feedback	Hardpoints for pylon stations		Wing sweep data		Part of forward wing for stability
Propulsion	Thrust	Thrust			Power generation	Power generation			Data sent		
Fuel System			Fuel to engine						Fuel level data		
Electrical System	Anti-icing		Ignition	Power to pumps					Power for electronics	Power to controls	
Hydr. and Pneumatic System	Weapon bay doors	Wing sweep actuation	Vary inlet geometry		Emergency electrical generation		Weapon trapeze	Extension, retraction, brakes, steering		Actuation of control surfaces	
Payload				External tanks							
Landing Gear	Landing, braking and parking								Gear status		
Cockpit and Avionics		Wing sweep control	Throttle control	Fuel supply mode control, fuel dump	Generator on/off switch		Payload release control, Fire-power control	Gear up/down control		Pilot input, Auto-pilot and TFR	
Flight Control System	Commands to tail and rudder	Commands to spoilers, slat and flaps									
Crew Escape Module									Provides space		

6.5 Weight

Weight data for the F-111 in various resources is conflicting and incomplete. Various resources have different numbers for aircraft weights. The one consistency in weight data was that later publications reported higher weight showing that the weight of the F-111 increased over time. This is a common occurrence in most aircraft as improvements are made (especially in engines) and envelopes are expanded as the aircraft is proven over time. Among various resources, the empty weight of the F-111A varied from 46,000 lb to 47,500 lb.

Early in the TFX program the Navy and the Air Force were at odds over gross weight. For the Air Force, low-level supersonic range and buffeting drove up gross weight. For the Navy, carrier suitability drove down weight (and size). The Navy wanted an airplane that was 55,000 lb max and the Air Force wanted 75,000 lb minimum [5]. The final maximum take-off weights proposed by General Dynamics in its 1962 winning proposal were [14]:

F-111A	69,000 lb
F-111B	63,000 lb

During development, the F-111 gross weight grew so much that it had to enter a Super Weight Improvement Program (SWIP). SWIP re-design began in January of 1964 [28]. In the first month of the program, 42 weight saving changes were proposed. The design made it into the last developmental aircraft, number 12 for the F-111A [1]. Weight was reduced by 4,000 lb through SWIP [1].

Despite SWIP improvements, the weight of the aircraft continued to grow. By November 1964 the first development aircraft gross weights were [29]:

F-111A	77,306 lb
F-111B	71,380 lb

A pie chart breakdown of weight of the F-111A from proposal is shown in Figure 54.

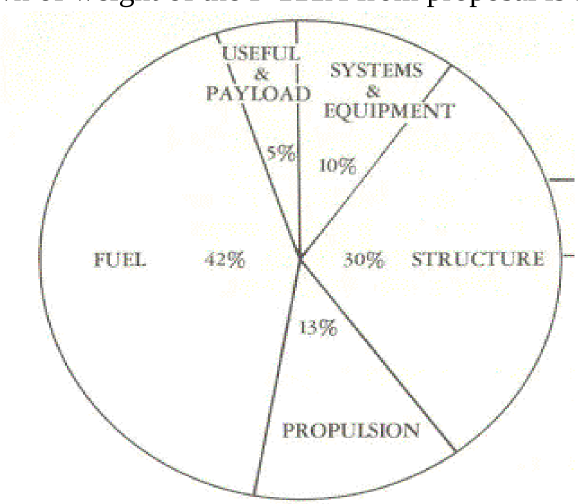


Figure 54: Proposed Weight Breakdown [14]

The Navy's pull-out from the F-111 program likely impacted the growth of the F-111A. F-111A weights as reported in 1987 [30]:

Empty Weight:	46,172 lb
Combat Weight:	63,051 lb
Gross Weight:	82,819 lb
Max T.O. weight:	98,850 lb

Available weights for F-111 variants are below:

Table 7: F-111 Weights [30]

	F-111A	F-111B	F-111F	EF-111A
Empty	46,172	46,000	47,450	55,275
Combat	63,051	68,365	62,350	70,000
Gross	82,819	72,421	95,333	72,750
Max T.O.	98,850	77,566	100,000	89,000

6.6 Development Cost Breakdown

6.6.1 The Reason for a Joint Program: a "One billion dollar saving"

Although it is known that cost reduction was the driving force to develop a common aircraft for both the Air Force and the Navy, the effectiveness of the idea is generally contested a posteriori. However, data on the subject is blurred and scattered and dependent on the kind of accounting used.

The concept behind the joint development of the aircraft was a net saving of $1 billion in 1960 dollars. In 2003's dollars, this amount is worth about six times as much. This huge saving was so important that the project was rapidly called the "one billion dollar program". With reference to Figure 55 displaying the result of studies conducted under Project 34 in 1961 (see Section 5.3 for the description of this project): the cost of a joint project, with 1700 aircraft, had been projected to be $5 billion (curve labeled "Project 34 Recommended Combined Program"), while two separate projects would have cost more than $6 billion ("Navy only" and "Air Force only"). The upper curve labeled "F-111A+F-111B 1964" gives an idea of what the real cost was in 1964. Costs include acquisition as well as R&D. Thus in 1964 it was already clear that cost overruns would be a major characteristic of the program. The next figures were hand-written by George A. Spangenberg who was the Evaluation Division Director of NAVAIR until 1973. In the TFX controversy, he cautioned that engineering a plane appropriate for both Air Force and Navy carrier use would be extremely difficult and fought against the "compromises" that in his opinion were making the Navy plane unsuitable for use. Although the following numbers seems *a posteriori* to be relevant, one should keep in mind that Spangenberg was "on the Navy side" and therefore against the Navy version of the F-111. It has also been decided to keep these figures because of their "historical" value.

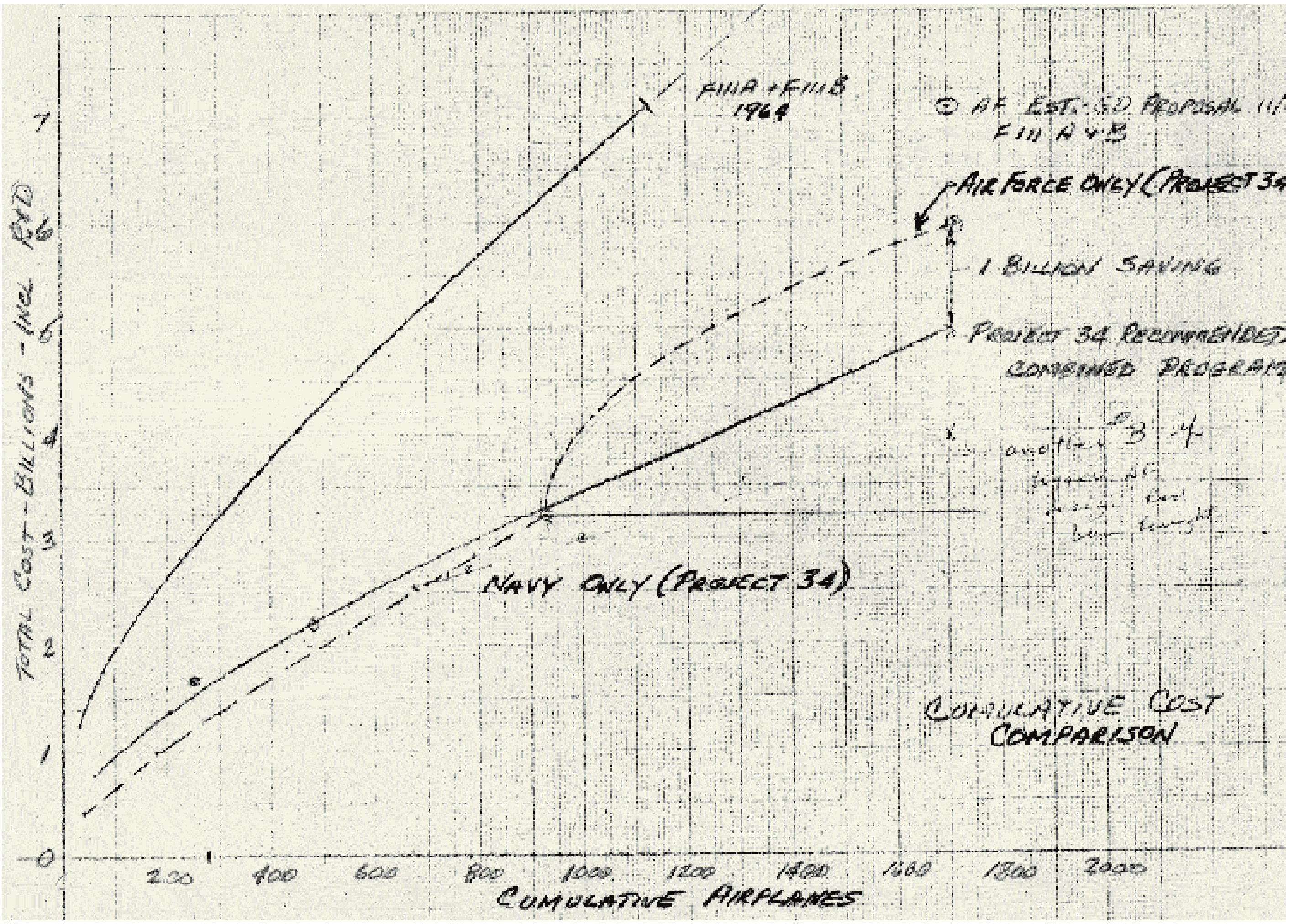


Figure 55: Total cost of the TFX project (from [9])

6.6.2 Unit Costs: An Indicator of Cost Overrun

Figure 56 below was taken from a Memorandum dated February 8, 1965 and shows Unit Cost data previsions of the F-111 in 1961 as a function of number of aircraft produced (research and development cost not included). Basically, the more aircraft purchased, the less cost per unit. The compromise design was supposed to be overall more expensive than the AF design, but cheaper than Navy design. The much larger and heavier Air Force design was initially more expensive than the Navy design but reduces rapidly so that its last buy is but 60% as expensive at the same point in production.

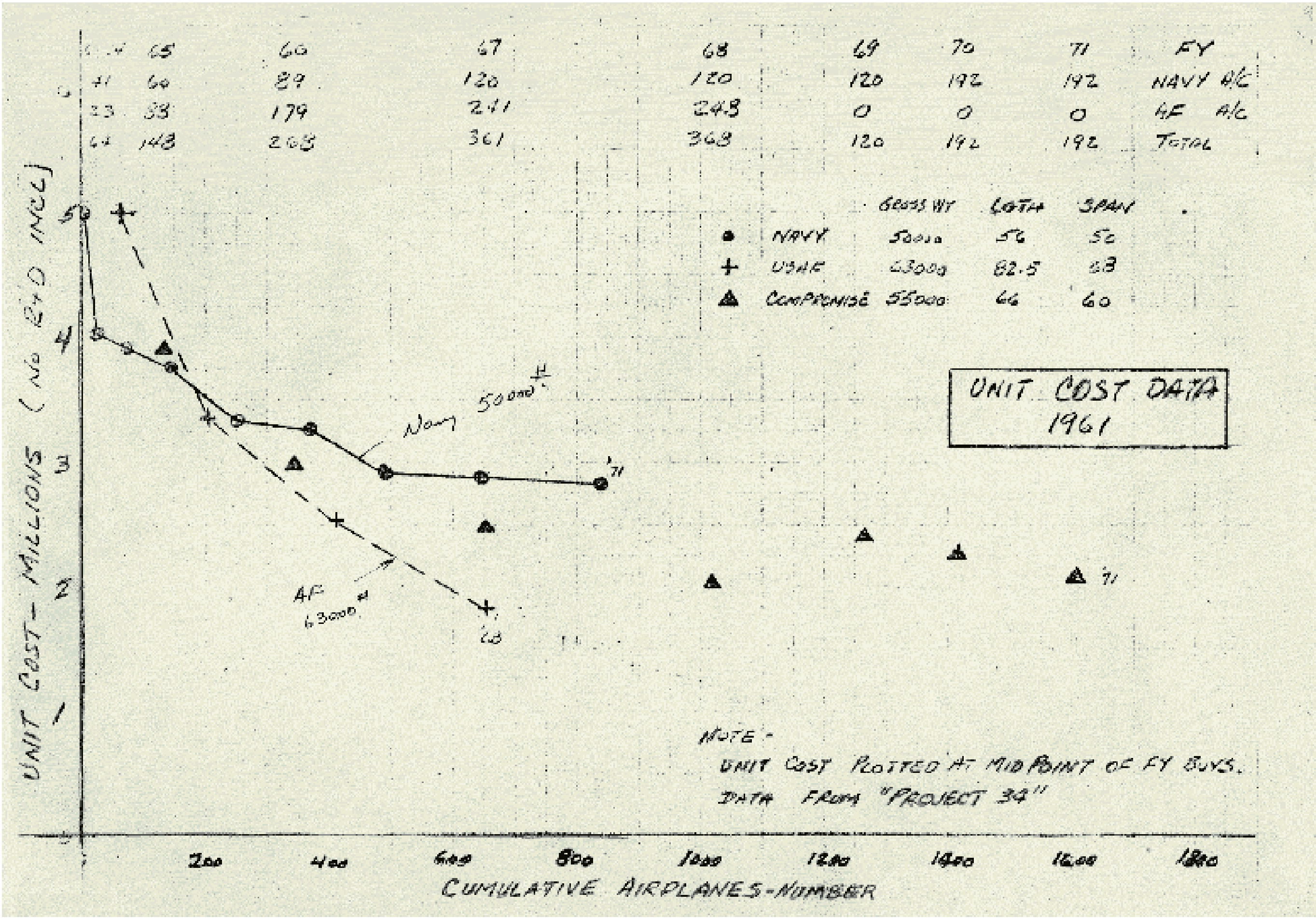


Figure 56: Unit cost predictions, 1961 (from [9])

Comparing this chart with the data published in 1964, it is quite obvious that the predictions of 1961 were quite fanciful, as we see in Figure 57.

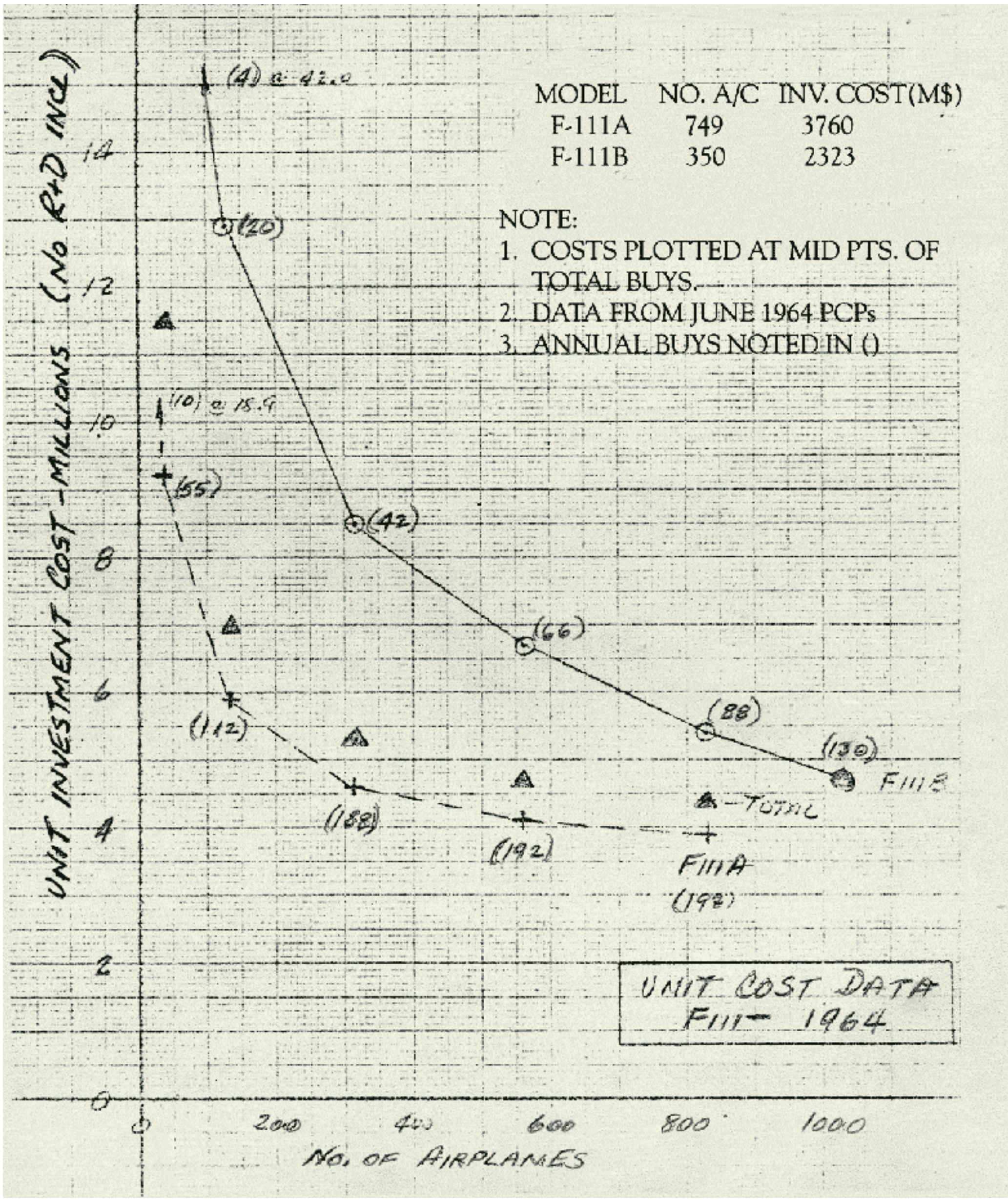


Figure 57: Unit Cost predictions, 1964 (from [9])

Figure 57 shows the estimates of acquisition and the evolution of the Unit Cost as a function of the number of airplanes. Note that instead of the $4 million max. per unit predicted in 1961 the price had dramatically risen to $10 million (1964 dollars), which was more than twice that expected three years before. There is no longer a crossing point where the F-111A became cheaper than the F-111B. The F-111B has more electronic equipment, but it is procured later, relatively, that the F-111A.

In the next figure the comparison is drawn between the unit costs as they were predicted in 1961 versus 1964. Estimations used 1964 dollars vs. 1961 dollars but the difference between the unit costs cannot be only explained by this only factor. It can be seen that the flattened-out costs were at least double those on which the original Project 34 recommendation was made, a main factor of cost overrun, mainly due to change of requirements. At this time, a cumulative cost plot can be plotted as seen in Figure 55. It is seen that that cost is about 2 Billion above the original estimate, although the number of aircraft has decreased by 35% from 1726 to 1122 from 1961 to 1964.

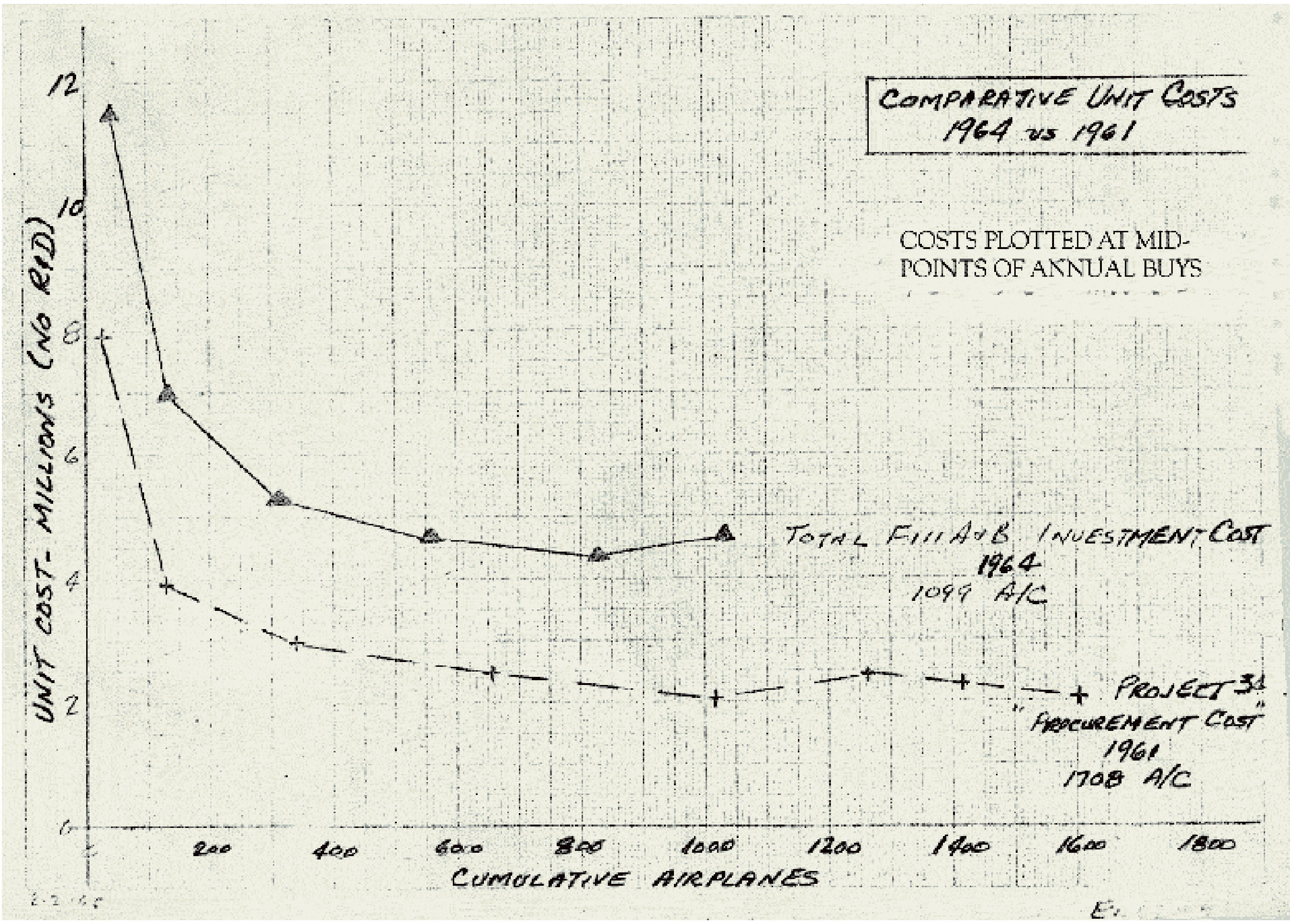


Figure 58 Comparative Unit costs 1964 vs 1961 (from [9])

Overall, the F-111 project turned out to be about twice as expensive as originally intended [28]. According to many sources this was primarily because of the Navy's withdrawal from the program, which resulted in only one service using an aircraft that was designed to play a multi-service role. But from the evolution of costs during the development phase it is clear that cost overrun was initiated before 1968, mainly for change in requirements from both USAF and Navy. The F-111 was over-designed for its purposes, and ended up costing too much. Because of the highly change in the unit cost, predictions made in the early 60s were totally unreliable. Therefore GD had to balance its overrun due to change of requirements and cancellations by increasing the Unit Cost for each aircraft.

6.7 History of Program Cost

6.7.1 The Proposal

The first data on program cost were published by GD in its Sept. 1961 proposal. In order to show that their costs were realistic and that they would remain under control as the program progressed, they gave a detailed description of their management methods, and recalled their results from the preceding 5 years, during which they had negotiated over $2 billion dollars worth of contracts that had been performed within 0.6% of estimated cost. GD estimated the cost as shown in Figure 59: they first computed an estimate based on firm commitments for materials or subcontracts. Then, they evaluated in-plant labor and overhead based on realistic projections of employment level, labor rates, and man-hours developed from prior experience in similar programs. Figure 59 shows the division of costs for the TFX. The first observation one can make is that they did not try to estimate overall program costs related to changing requirements although it has been seen previously (see Section 6.6.2) than these changes of requirements have driven a large amount of cost overrun in the 1961-1964 period, as it is shown in section 6.7.2.

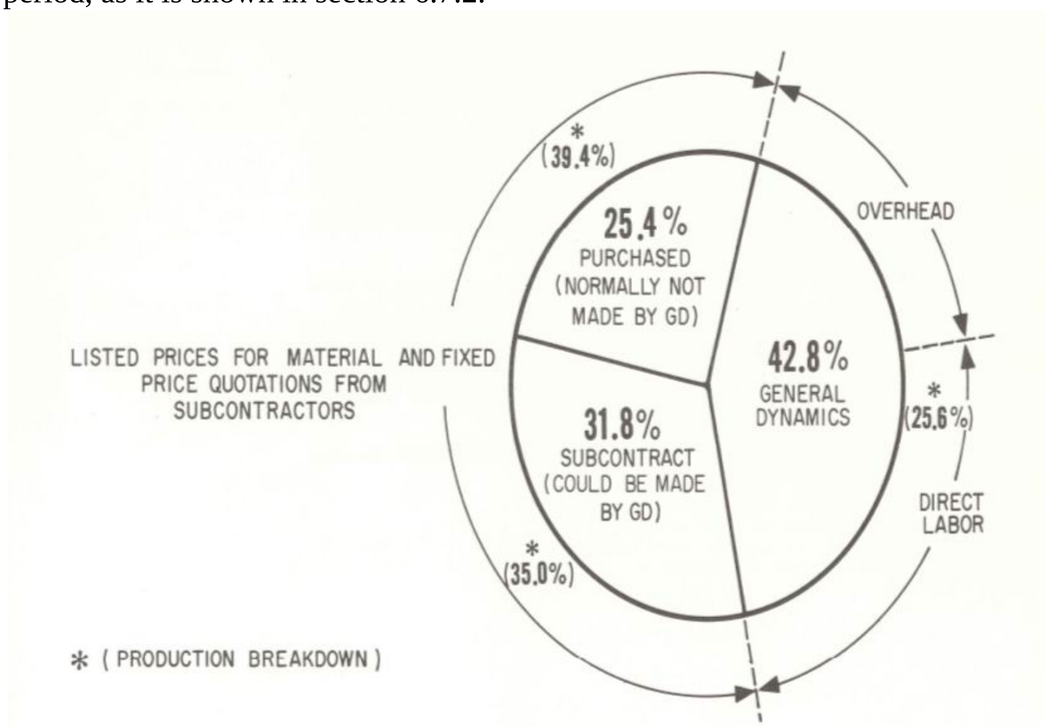


Figure 59: Cost breakdown, from [10]

6.7.2 Program Costs Over the Development Timeline

Cost was a significant issue the F-111 Program: every request had to be fully justified. Congress issued several reports: in the mid-60's a first study evaluated that at mid-program 30% to 60% of the total cost had been spent, a quite encouraging estimation. Nevertheless as seen previously the key points are that ever-increasing costs occurred in the F-111 development program as well as rapid changes in estimations. They were mostly due to frequent modifications of requirements from both services. Because the F-111 was a very political program, strong controversies were generated and many congressional reports were issued regarding the development cost without a partial objectivity. Once the overrun was clearly identified it was too late to step back in the program, and the only way to save money on the program was to reduce the number of units produced.

7.0 Systems Engineering and Program Management

7.1 Requirements Management

During the F-111's development, the Department of Defense went through a radical shift in management techniques. Secretary of Defense McNamara spearheaded the "systems analysis" effort with the ultimate goal of improving the efficiency and warfighting capabilities of the U.S. military. Unfortunately for the F-111, the program found itself caught in the middle of the paradigm shift and as a result had many negative aspects of both the old ways and the new.

7.1.1 Military Requirements Approach of the 1950's

Defense programs can pose some of the most difficult budgeting and management problems. National security is often regarded as priceless therefore making it quite challenging to quantify the actual worth of national defense [31]. As a result, the military would create a "wish list" of programs and funding that it judged would provide security for the nation. Since this "wish list" did not account for cost constraints, it always went far beyond the financial means of the nation.

During the Eisenhower administration the financial limits came in the form of explicit budget ceilings for each service. Once given an amount, the service could each spend as desired, without regard to the other services or even to a national strategy. Such spending tended to produce redundant weapons systems or systems that did not add much value to the overall military posture. Furthermore, unrestricted budget caps encouraged the services to spend on glamorous programs, such as high performance planes or ships, while neglecting the more mundane tasks. Similarly, the services often engaged in the practice of "gold-plating," that is, spending high amounts of money to add extra features to weapons, often providing diminishing returns.

Since military spending was capped, each service had to compete for its share of the budget. This became a quite murky political process that would ultimately decide on some compromise between all the services' wishlists. The entire process of wish lists, budget ceilings, and negotiation became known as the "military requirements approach" toward requirements [31].

The resultant inter-service competition, along with the competition from the Soviet Union, also led to a management philosophy known as the "weapons system approach" [31]. "Weapons system" called for a project to be a complete package from its inception. All aspects of the program, from development, procurement, training, and support, were all to be accounted for and decided early in the program.

7.1.2 McNamara's Systems Analysis

When Robert S. McNamara took office as Secretary of Defense in 1961, he set out to completely revamp the defense acquisition process. His new paradigm, known as "systems analysis" essentially sought to apply the scientific method to the military [31]. Rather than begin with a budget limit and try to fit as many wishlist programs in to it, McNamara chose to identify the threats facing the nation, select a force structure from a set of alternative capabilities to counter those threats, and then to find the least expensive way to achieve those capabilities [31]. Consequently weapons system requirements were derived from the most cost effective way to achieve a certain force structure.

This high level analysis of needs and cost-effectiveness tended to concentrate decision making authority over weapons programs in the Office of the Secretary of Defense in a way unseen in the Eisenhower administration. Naturally, this caused a significant resistance among the services which constituted a major flaw in systems analysis. In its focus on quantitative values, systems analysis often ignored political and other "soft" factors that could not easily be quantified.

7.1.3 The F-111 in Changing Procurement Paradigms

Conceived in the 1950's, the F-111 was born in the military requirements approach. The United States faced the threat of a quick nuclear strike by the Soviet Union. Countering that threat required a quick, survivable capability to deliver a nuclear weapon. In this nuclear strike mission, lower and faster flight would produce a more survivable aircraft. The F-105 could already perform the low altitude nuclear mission at high subsonic speeds at sea level, so the only way to improve survivability would be to go supersonic. Notice no consideration of cost or value added by the extra cost of low altitude supersonic flight.

Focusing on the specific mission of nuclear strike, the Air Force requirements referred little to air-to-air combat. Instead, it was assumed that the capabilities for such a "secondary" mission would emerge naturally from an aircraft that was supposed to be fast anyway [6]. No requirement specified any maneuverability capabilities.

When the Navy's fleet defense missions were added to the TFX program, the two sets of requirements were simply concatenated. In fact, the two sets were never actually combined into a single requirements document, remaining separated into SOR-183 and the Memo of September 1. Furthermore, the two sets of requirements were never prioritized, leaving an ambiguously defined aircraft. The requirements met the classic military requirements approach calling for a "gold plated" aircraft that could outperform its predecessors.

When McNamara's team took over at the Pentagon in 1961, the two sets of requirements had already been defined, but were intended to produce separate aircraft. McNamara had other plans, though, and in his drive for efficiency, he decided to combine the two programs into the first joint development. A joint program certainly did not fall on either service's "wish list," but McNamara judged it as the most cost-effective way to provide for national defense. But unlike the Eisenhower Pentagon, McNamara controlled the decision instead of the Services. One reason Boeing lost the competition was because it catered to the Services' desires, essentially designing two separate airplanes. General Dynamics chose a design with much more commonality, along the lines of the desires of McNamara.

Unfortunately, the actual requirements for the F-111 escaped rigorous systems analysis. The reasons are unclear; some in McNamara's team argued that at the time of the F-111 decision the Systems Analysis Office was not fully established as an independent entity [31]. Others disputed this, contending that the F-111 was McNamara's hobbyhorse that the SAO would not upset. In any case, the F-111's requirements were never challenged with rational systems analysis.

7.2 Program Management

One aspect of program management that survived the transition from military requirements to systems analysis was the "fast-track" development cycle. Under this strategy, the aircraft was both developed and produced concurrently without a lengthy research and development process. The weapons system approach of the 1950's emphasized complete planning for an entire lifecycle from the beginning [31]. The intention was to avoid the long delays and eliminate the added costs of transitioning from prototypes to production tooling. Given McNamara's interest in keeping costs down, the "fast-track" strategy fit well with the cost effectiveness priority. Fast-track development assumed the initial design had few flaws in order to be truly cost-effective, however. As the problems with the engine inlet and the engines themselves showed, it was a poor assumption.

7.2.1 Air Force and Navy Management

The F-111, as the first joint aircraft development program, prominently accentuated the differences between the services' program management. The most basic cause of friction between the Navy and Air Force was the fact that the F-111 program was led by the Air Force, while the Navy played a supporting role [6]. In an era of such intense inter-service rivalry, the Navy quickly became disinterested in the program. It had been slighted before when its Missiler program was cancelled; now it was subordinate to the Air Force in the only aircraft development program it had.

Physical location and officer ranks also played a part in the friction [6]. The Air Force's development office was based at Wright-Patterson Air Force Base in Ohio, whereas the Navy's office was based in Washington, D.C. The two offices communicated via mail, causing significant delays in decision-making, especially pertaining to small issues that should be handled quickly. In many cases, issues that should have been resolved quickly in a short meeting were left ignored until it was too late while letters passed back and forth between the two offices.

When the Services did cooperate in person, differences in number of personnel and rank between the services mattered. Whereas the Air Force had a general in charge of its F-111 program, the Navy only sent a captain. Furthermore, the Navy only had a fraction of the personnel in the F-111 office. Whether this lack of high level personnel commitment led to or resulted from the Navy's ambivalence to the F-111 is unclear but certainly affected how the program progressed.

The services also had significant differences in how they selected a contractor in the first place. The Air Force primarily looked for a contractor that had the capability to produce an acceptable aircraft. The Navy, on the other hand, had much more in-house technical capabilities, and wanted to see a solid design before contractor selection [31].

7.2.2 Pentagon Management

Under McNamara's leadership, the Pentagon was much more heavily involved in the decision-making than in previous programs, but also very sporadically [6]. As already mentioned, McNamara himself made the contractor selection. But between contractor selection and the first flight, McNamara only monitored its progress through memorandums. Following the first flight, though, the Secretary became more involve again, even holding weekly meetings to deal with issues as they came up if they were brought to attention. The most important issue brought to the Secretary was weight. The F-111 grew significantly in weight, prompting a series of high level meetings known as the "Icarus meetings."

Other problems, though, were not brought up, and in fact were sometimes ignored. The most striking example is the inlet problems, which were recognized on the ground just before the first flight in December 1964. In a memo from Air Force Secretary Eugene Zuckert to McNamara discussing performance problems written five months after the first flight, no mention of the now commonly recognized inlet problems appeared. Instead, Zuckert assumed that the several unnamed deficiencies would be remedied naturally as the development progressed. It was not until July, 1965, after commitment to production was made, did McNamara learn of the inlet problems.

7.2.3 Contractor Management

General Dynamics, and the prime subcontractor Grumman, divided up tasks primarily by function. General Dynamics was responsible for the entire program, but focused on the Air Force and joint aspects of the F-111. Grumman handled the purely Navy components, such as the F-111B's landing gear, tailhook, and horizontal stabilizer. A graphical display of Grumman's responsibility is shown in Figure 60.

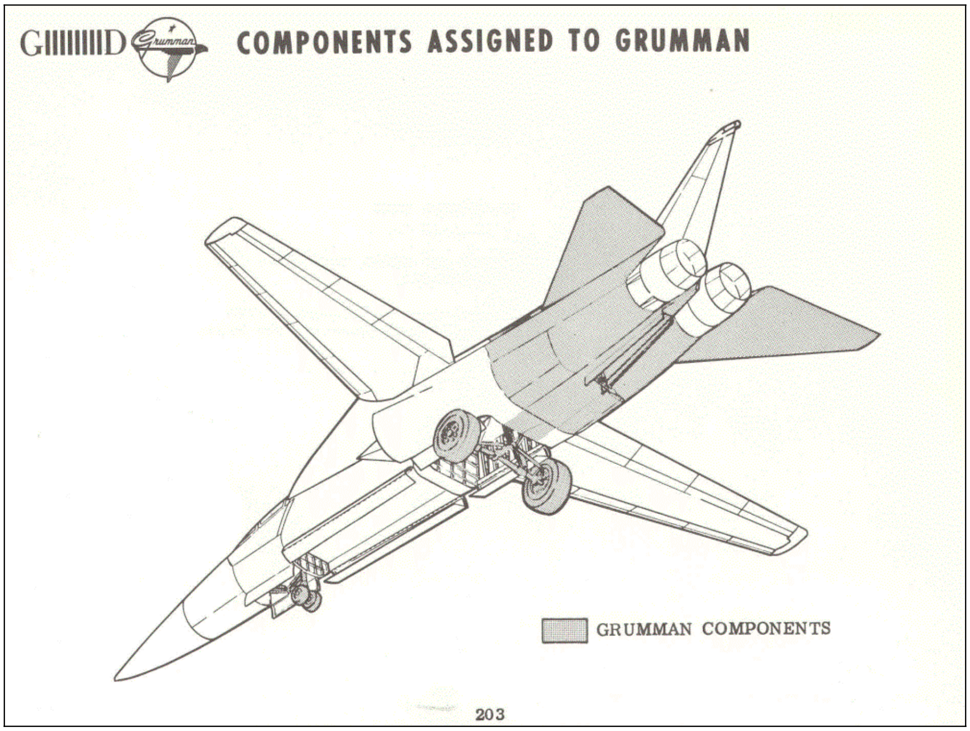
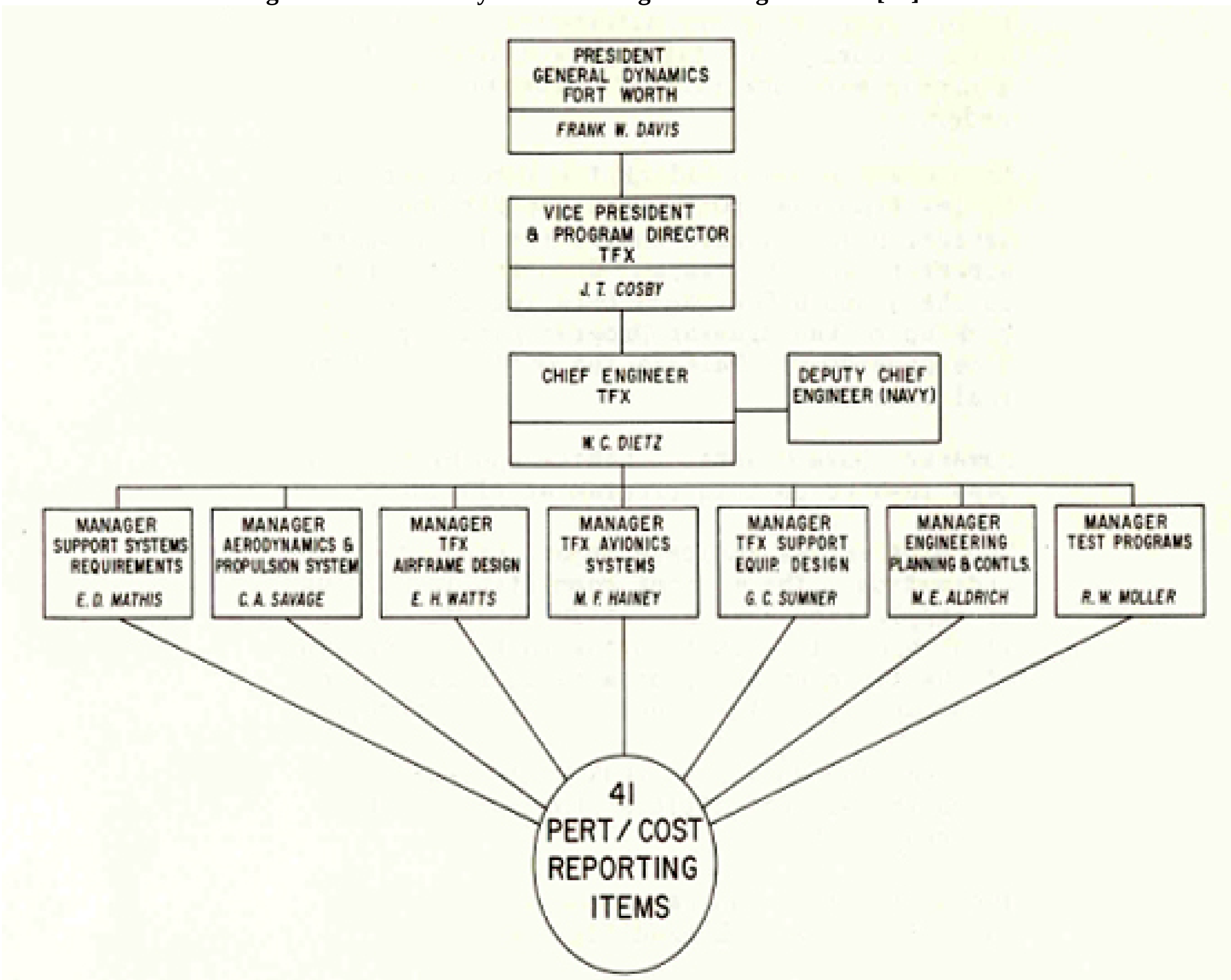


Figure 60: Grumman Components [10]

Internally, General Dynamics divided their work as was typical at that time. Requirements, Aerodynamics and Propulsion, Airframe, Avionics, Support Equipment, and Testing groups all fell under different managers, as shown in Figure 61. All of the components of the integrated product reported to the Chief Engineer, but no evidence points to the existence of integrated teams below the manager level.

Figure 61: General Dynamics Management Organization [10]



One interesting feature General Dynamics incorporated was a new system for managing reliability requirements [11]. Using new computer technology, the system was to help the Reliability Director utilize the large amount of information involved. As a result, reliability issues could be caught during periodic assessments of reliability and addressed before they could cause expensive problems further downstream. No information turned up on how well this system worked, but it obviously failed to prevent the wing box failures. The reliability tracking system appears similar to more recent risk management techniques of quantifying mean times to failure as they flow down a system.

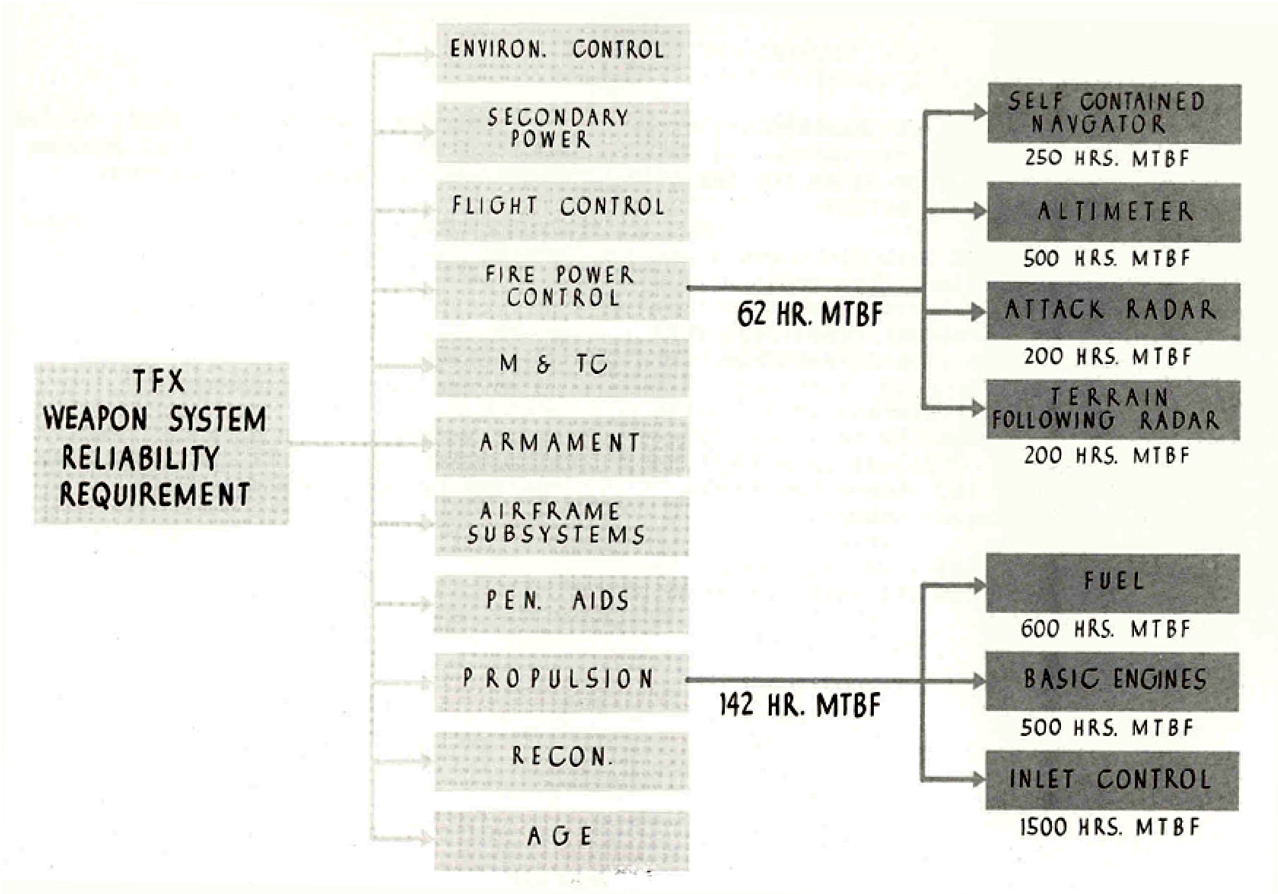


Figure 62: Quantitative Reliability Management [10]

Both research and development as well as production occurred at General Dynamics's Fort Worth, Texas facility [10]. Production rates were planned to be 39 aircraft per month, but could be increased several times over if necessary. General Dynamics's Fort Worth plant, built in World War II for rapid production of B-24's, is shown in Figure 63 as set up for F-111 production.

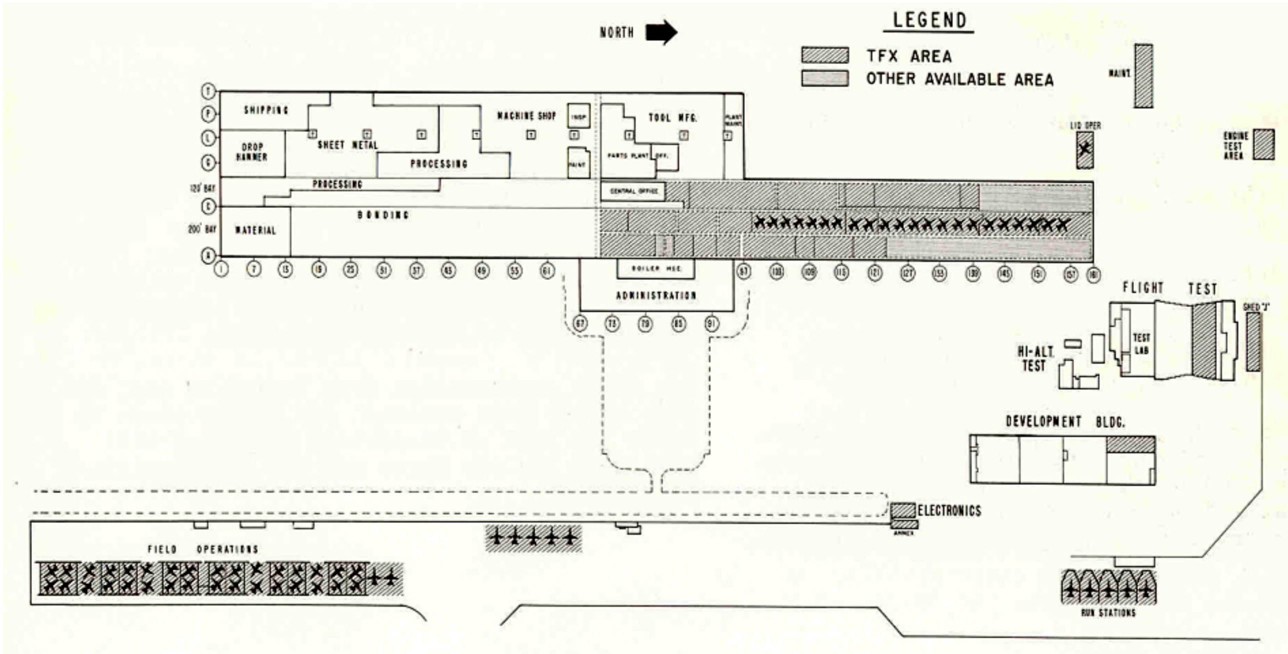


Figure 63: General Dynamics Forth Worth Production Facility [10]

The F-111 had 17 subcontractors who were supported by about 6000 suppliers in 44 states [32]. Although there were not specific political figures connected with the F-111, it certainly did not hurt the program to have constituents in so many states.

7.3 Key Program Decisions

At this point, it should be apparent that the F-111 was a rather complex aircraft that was developed in a complicated context. It is thus useful to provide a summary of the key decisions made during the course of the F-111 program. Each key decision was motivated by a higher-level need, and had subsequent implications on decisions made further down the development timeline.

The most important decision that shaped the F-111 program was the decision for a joint aircraft program shared by the Air Force and the Navy. As discussed in Section 2.0, the motivation behind this stemmed primarily from the desire to save costs by eliminating the duplication of design, manufacturing, and maintenance across the services. The joint program forced the Air Force and Navy to work together, when neither service was willing or prepared to do so. As a result, Air Force and Navy requirements were simply concatenated and poorly integrated. Commonality was also a major concern and it drove much of the design. As shown by the requirements flowdown and description of major subsystems, this resulted in an aircraft that tried to accomplish too much. In addition, the joint program suffered from continually escalating costs and turned out to be about twice as expensive as originally projected.

Another key program decision was the decision to develop an aircraft that could fly supersonic below enemy radar. The Air Force wanted an aircraft that could penetrate deep into Soviet territory to deliver nuclear weapons and it was believed that developing an aircraft with a sea-level supersonic dash capability was the best way to achieve this. In retrospect, it is arguable whether this was the best way to achieve the desired nuclear strike capability, but nonetheless, the Air Force had thought it to be so. This key decision resulted in the requirement for the Mach 1.2 capability at sea level, and as discussed in chapter 4, this requirement was the most important driver in the design of the aircraft, affecting almost all of the major subsystems. The high structural strength required to withstand Mach 1.2 at sea level also caused the aircraft to be overly heavy. A weight reduction program was undertaken but it achieved limited success.

The decision to award the contract to General Dynamics also represented a key event in the program timeline. As explained in Section 3.4, the Source Selection unanimously recommended the Boeing design, but Secretary McNamara chose the General Dynamics design because it presented lower development risk and greater commonality between the Air Force and Navy versions. It can be noted that the emphasis on a joint program and its perceived cost-effectiveness had trickled down to affect this decision.

At the design stage, two key decisions are worthy of note. One key design decision is the use of afterburning turbofan engines. The TF30 engines were the first afterburning turbofans ever produced, and it represented a key technological advance in military aviation. Without the development of this engine, it would not have been possible for some of the requirements, such as range and top speed, to be fulfilled. On the downside, the introduction of this new technology brought with it related problems. The initial engine and inlet compatibility problems resulted in performance issues that were eventually solved, but with inevitable costs.

Another key design decision was the use of swing wings. Although swing wings had been in development for a period of time preceding the F-111 program, the F-111 was the first production aircraft to feature them. Again, this was a major technological advance that made it possible to achieve some of the requirements, such as the supersonic dash capability with short take-off and landing distance.

Finally, a decision that had significant implications for the program was the withdrawal of the Navy from the program in 1968. The Navy’s decision was a controversial one and was allegedly based on weight constraints and unsuitability for carrier operations. There have been speculations that the Navy had planned to withdraw since the beginning, although documented interviews with personnel involved in the program revealed that the Navy pull-out was never expected. In any case, the Air Force was left with an aircraft with unnecessary features related to Navy requirements, such as the side-by-side seating, escape module, and variable geometry wings for optimized loiter time. These features not only represented unnecessary weight, but it also meant that much development time, cost and effort related to combining requirements was utterly wasted. Apart from tangible repercussions, the Navy withdrawal also reflected the failure of the joint program concept, which had been the single-most important design driver since the beginning.

8.0 Lifecycle considerations

Because cost of aerospace products is high and especially military aircraft, customers typically expect to fly the plane for some time. Broadly speaking there are 8 steps in the lifecycle of an aircraft program:

1. Development
2. Manufacturing
3. Verification
4. Training
5. Deployment
6. Operation
7. Support
8. Disposal

In the case of the F-111, the lifetime was dictated by the structural life of the aircraft. GD engineers agreed on 10,000 hours, although it will be seen later in Section 8.0 that many in the fleet have significantly surpassed this lifetime. First instance, the Australian F-111's have served for over 20,000 hours. Therefore it is reasonable to assume that F-111 had been planned for retirement in the 80's, since F-111 was supposed to be the only tactical fighter in the 70's.

8.1 Design for maintainability

Maintainability of the F-111A is described in the "General Dynamics F-111A Information Booklet LTP12-18" of June 28th , 1968 [12]. The main objective of the maintenance philosophy was to minimize the need of Aerospace Ground Equipment (AGE). Maintainers then used built-in test capability along with AGE. Tests stations were functionally-oriented to allow the testing of components with similar characteristics. This helped to suppress the need of redundant AGE. Test stations consisted in standard racks with front covers serving as work space when installed. Maintenance that required deeper work was performed at depots.

The entire aircraft had been designed to facilitate fault isolation. Built-in self-test circuits allowed the technicians to isolate a fault in a removable unit. Independent system checkouts could also be performed from test switches located in the cockpit. In case of further investigations, a suitcase-type tester was directly plugged in equipment switches to isolate the fault.

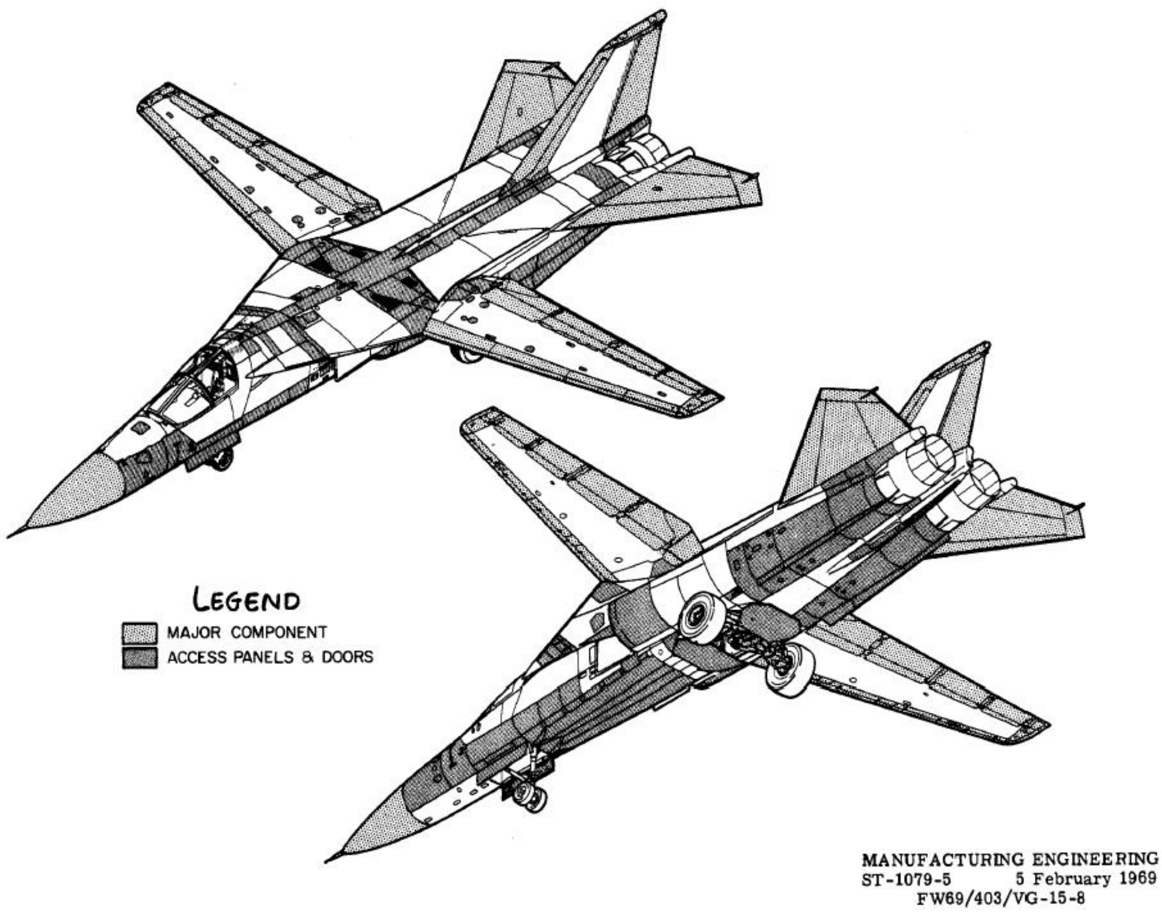


Figure 64: Access panels and major components [33]

In the design of the F-111, high stress had been put on good equipment accessibility. This aimed at allowing the best possible maintenance from ground level with a minimum of technicians. In this purpose, nonstructural doors had been added to permit easy access to electronic subsystems and equipment test points (Figure 64). Wiring and connections were designed as integral parts of equipment racks to reduce connector malfunctions. Mechanical pieces had been specially shaped to fit only with the right connectors, and no special tool was necessary to break disconnects [12]. The engine had also been specifically designed to provide an easy maintenance and developed a certain number of interesting features: power packages were identical for the two engines, the mounting had been simplified and clamshell-type clamps were used for power package disconnect joint instead of close tolerance pins. For engine accessories inaccessible in first attempt, an engine rollout feature facilitated the access to these parts without removing totally the engine [12].

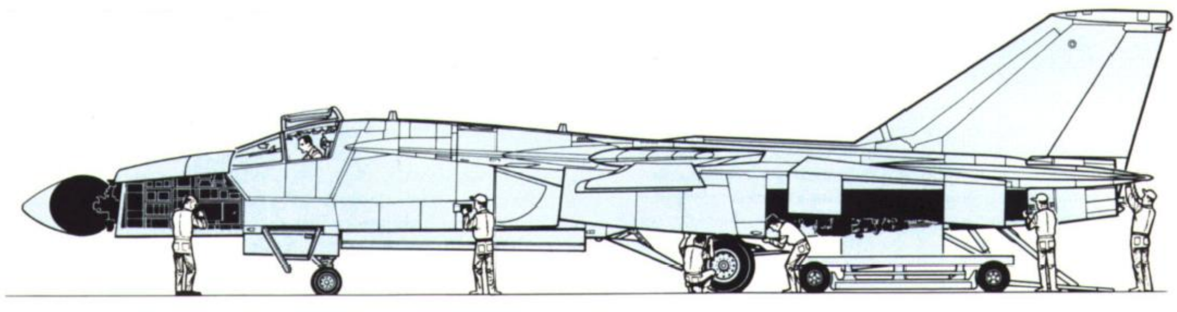


Figure 65: F-111A's maintenance [12]

Figure 65 shows the maintenance process with technicians testingthe aircraft's subsystems form the cockpit switches or externally thanks to the nonstructural doors. A more detailed distribution of access doors is given by Figure 64.

As given by GD LTP12-18, at the completion of operational testing, the maintenance performance of the F-111A matched well with the initial requirements.
The Maintainability Design Requirements were [12]:

- 35 maintenance man-hours per flight hour
- 75% operational ready-rate
- 30 flight hours per month per aircraft
- 30 minute quick-turnaround time
- 5 minute reaction time
- 5 day alert capability
- 15 minute maximum fault isolation time
- 15 minute operational checkout

Based on flight test experiments, the performance of the aircraft in terms of maintainability due to the features previously described were as follows [12]:

- test airplane turnaround in 35 minutes
- 85 to 100% effective fault isolation by self-tests, in 15 minutes or less
- access to forward electronics bay: 2 minutes per door
- unlatch the nose: 3 minutes
- removal and replacement of wheel and brake assembly: 30 minutes
- average oxygen servicing: 12 to 15 minutes
- average hydraulic servicing: 7 minutes

Finally, increased maintenance experience allowed the Air Force to get below the 35 maintenance man-hours per flight hour requirement, as shown in Figure 66.

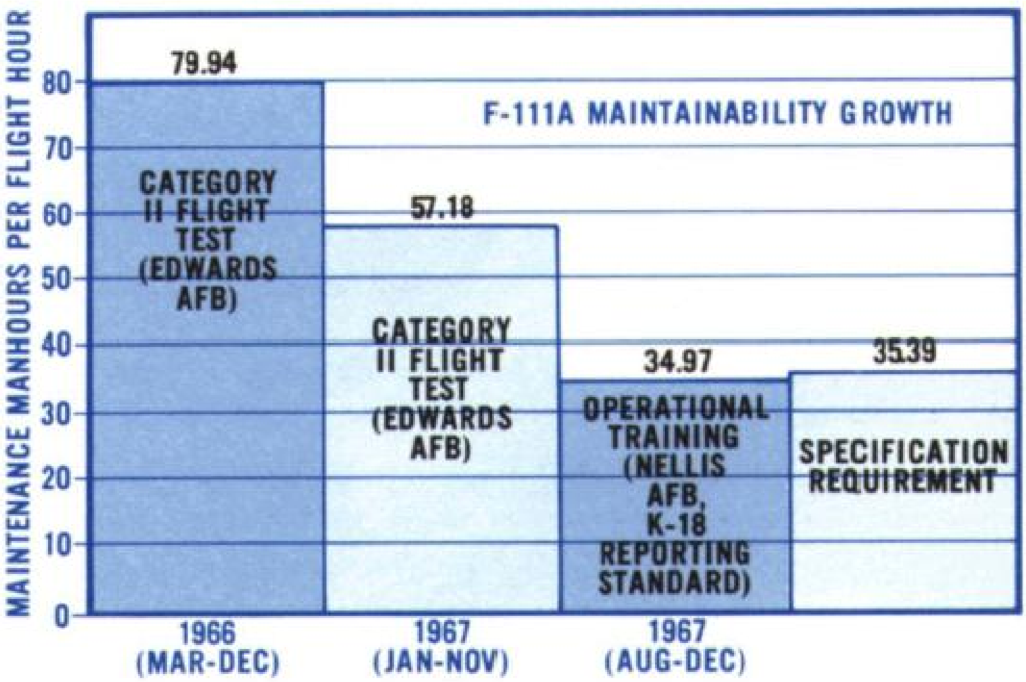


Figure 66: Maintainability growth due to increased maintenance experience [12]

8.2 Testing and Validation

The immediate need of operational capability in Vietnam yielded a reduced test period for F-111. The first F-111A rolled out the General Dynamics plant in Fort Worth, Texas, on October 15, 1964. It was 22 months after the program beginning and two weeks ahead of schedule. The first test flight happened two months later, on December 21, 1964 from Carswell Air Force Base, Texas. The F-111A was powered by YTF30-P-1 turbofans but the escape module was not yet available and so it had two conventional ejector seats. Because of problems with flaps, the flight had to be shortened to 22 minutes, yet it was considered as generally satisfactory. The second flight took place on January 6, 1965 and on this occasion, the wings were swept for the first time from 16 (full aft) to 72 degrees (full forward) and the aircraft achieved Mach 1.3. On February 25,1965, the second F-111A took off. The ninth F-111A crashed on January 19, 1967 because of an incorrect wing setting [19].

The actual escape module (Section 6.3.11) was installed on the 12th F-111A after an independent test to check its ability to protect the crew in the case of an ejection. It was criticized for its excessively hard landing and several crew members were injured during landing in ejector module [19]. On October 19, 1967 the 14th plane experienced a total hydraulic failure and became uncontrollable. The two pilots were then required to eject in the escape module at 28,000 ft and 280 knots airspeed, and were not injured in the process.

The Pratt & Whitney TF30-P-1 which was supposed to equip the F-111As flew for the first time on July 20, 1965. It then equipped the first 30 production F-111A but encountered numerous compressor stalls at high speeds and high angles of attack. This necessitated new variable-geometry inlet ducts as described in Section 6.3.3.2 [19].

Bombing accuracy of the aircraft's radar was tested in the spring of 1967 during a series of tests known as Combat Bullseye I. This series of test validated the very good performances of the plane [19].

8.3 Manufacturing

The F-111 was manufactured in Fort Worth, more precisely in GDFW / USAF Plant No.4, next to Lake Worth in Texas that later served to produce the F-16 and JSF. Figure 67 is an aerial shot taken in 1969. The facility of Fort Worth, Texas was established in 1943 as a joint venture between the DOD and Consolidated Vultee, where the latter produced B-36, B-32 and B-24 aircrafts throughout the decade. Consolidated Vultee changed its name to Convair in the late 1950s, and the facility produced F-102, F-106 and B-58s. GD finally bought the facility in the 60s for the in-house design, development and assembly of the F-111.

Figure 67: Aerial shot of GDFW 1969 (from [35])

In the photograph are many of the F-111's in what was then called the "hold mode" after the wing carry-thru box failure (see section10.2). F-111C's were produced for the RAAF at this time and are stored in the right of the photo, most of them in the "X" area being prepared for storage, some are stored at the Flight line (see Figure 68).

Figure 68: Flight line in 1969 (from [35])

The main factory building in the aerial shot was 1 mile long and 3 floors high. As its peak of production GD employed around 28,000 people in 3 shifts – 7 days. An F-111 was produced nearly every day. Pictures showing the F-111 production line at GDFW in 1968 are presented in Figure 69 and Figure 70. The latter describes the fitting of a wing to an F-111A and presents the details of the sweep wing mechanism. From the pictures one has a good idea of the organization of the production line. The F-111s were aligned in the main building as it was determined by the plant layout. The first and main part of the assembly building was used for production and tool manufacturing, the next part of the production line was a place where the primary, mating and miscellaneous components were assembled (fuselage, crew module, engine, landing gear, fuel tanks). The last part of the building was dedicated to the final assembly and aircraft completion stations. Because of the different versions of the F-111, the area was divided in many lines, one for each type of F-111 (see Figure 69). For instance, in January 1969, F-111, F-111D and FB-111A were assembled in this area.

Figure 69: Production line of F-111(from [35])

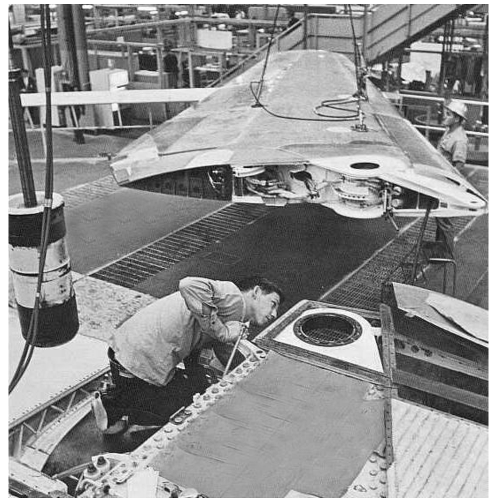


Figure 70: fitting of a wing (from [35])

As it has been said previously there was no prototype in the F-111A program. This decision of no-prototyping and immediate manufacturing was an agreement between GD and the DOD. It was merely motivated by an expected save of time and money. Regarding verification and validation processes, they were fallouts of the contract specifications that involved traditional methods such as Inspection, Analysis and Testing primarily.

Although no quantitative information is so far available concerning the recurring costs, i.e. production and support costs, production costs went over target during the F-111 program, but it varied quite a bit by model. The support costs also varied by model, the worst by far being the F-111D which was caused by the required avionics package which GD was not in favor of installing but overruled by direction.

8.4 Disposal

As seen in the timeline in Section 3.1, the last F-111A was transferred in 1996 to the Aircraft Maintenance And Regeneration Center, or AMARC. AMARC is on the edge of Davis-Monthan AFB in Arizonan desert, and has an enormous number and types of US aircrafts in indefinite storage (Figure 71 and Figure 72). The choice of this place is crucial because the dry desert air prevents significant corrosion to the airframes and enables to use them when spare parts are required.

Figure 71: F-111A stored in Arizona (from [17])

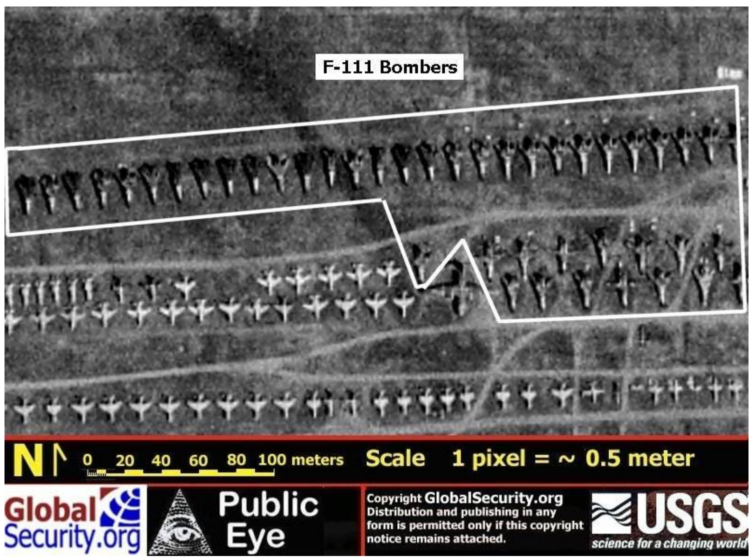


Figure 72: Satellite view of AMARC, showing the F-111 location (from [37])

The retirement of the RAAF version of the F-111 has not been fully decided. On Nov. 7, 2003 the RAAF advised that by 2010 the F-111 could be withdrawn from service, 6 years before the date that was previously envisaged. F-111 represents roughly half of its firepower, and will be replace by the Joint Strike Fighter (JSF) aircraft and upgrades of the F/A-18.

8.5 Derivatives

Several derivatives had been designed, corresponding to incremental improvements for the A-F models, or to achieve different missions in the case of the FB, EF and RF models. More details are available in [19]. All the models are listed in Table 1 with the main differences between them. The following paragraphs provide a good idea of the technical differences between them, although section 10.1 focuses on sales and deliveries.

A-F models…

The **F-111A** has so far been extensively described, and high-level metrics are reported in section 0.

The **F-111B** (see Figure 73) was developed for the Navy but was cancelled before its actual production when the Navy decided to leave the program (March 1968). The main reason was that it was found to be too heavy for carrier-borne operations during the tests (although according to Jim Phillips the tests of carrier-landings were impressive). Performances were also under the requirements, especially in terms of range. A larger wing was developed for the F-111B, with a span of 70 feet in the fully extended (16° sweep) setting -- 7 feet more than the F-111A. Grumman F-14 Tomcat was designed in 1968 to replace the controversial F-111B.

Figure 73: F-111B (from[34])

The **F-111C** was the RAAF version of the F-111A, although it had some design differences. It had the longer wing of the B version, stronger landing gear and a higher gross weigth. The avionics were slightly better and F-111C was the only F-111 able of firing Harpoon missiles. Ordered by the Australian government in 1966, the first F-111C was to be delivered on Sept. 6, 1968, but it was delayed until 1973 because of structural problems. A current upgrade should keep them flying until the year 2006.

The **F-111D** version was developed from the A with more sophisticated electronics. The F-111D featured an improved Mark II avionics package, more powerful TF TF30-P-9 engines, and an environmental control system. It was ordered on May 10, 1967. The first F-111D flew on May 15, 1970. Development problems with the F-111D's advanced avionics caused so many delays that the Air Force decided to acquire the simpler F-111E as an interim version. 96 F-111Ds were delivered between June 30, 1970 and February 20, 1973.

The **F-111E** was an intermediate version with modified air intakes to improve the engine's performance at speeds above Mach 2.2. They were ordered in 1968. The deliveries to the Air Force took place from 1969 to May 28, 1971 for a total of 94 planes.

The **F-111F** had improved turbofan engines give F-111F models 35 percent more thrust than previous F-111A and E engines. The avionics systems of the F model combine features of the F-111D and E. The F-111F was ordered on July 1, 1970. The first F-111F entered service in January 1972. The last F-111F was delivered to the USAF in September of 1976.

Different missions…

FB-111A (see Figure 74): In December 1966 General Dynamics was awarded a contract to develop a strategic version of the F-111 fighter-bomber. The FB-111A was planned to replace the B-58 and to have the mission flexibility the B-58 lacked. It was a two-engine jet bomber with afterburner. The first production FB-111A aircraft flew on July 13, 1968. The last FB-111A was delivered on June 30, 1971. With the ending of the Cold War, many SAC FB-111As were no longer needed, so they were converted to the tactical mode by taking out the large heavy long range radar and tracking tools, and replacing them with the shorter range ones, as installed in the F-111F. This conversion, being slightly different from any of the others, was redesignated F-111G. Without the threat of the Warsaw Pact, the USAF did not require the numbers of aircraft as before, so many F-111Gs were supplied to the RAAF.

Figure 74: FB-111A in action (from [36])

FB-111H: This version had a longer fuselage and new engines, GE F101, with 20% more power than the original TF30 power-plants. The program was cancelled on the grounds of cost.

EF-111A: This model was a transformation by Grumman of the F-111A with radar jamming equipment for electronic warfare.

RF-111A, C & D: These versions were a response to a need for reconnaissance missions.

9.0
10.0 Operating Experience

10.1 Sales/Deliveries

After the contract competition described in section 3.4, the initial development contract was awarded to the General Dynamics team in November 1962. The initial contract called for 18 F-111A and five F-111B pre-production development aircraft. The first of these began production in the fall if 1963 and the first roll-out was October 15, 1964. The development F-111A first flight was 10 days ahead of schedule on December 21, 1964 [1]. The first operational F-111A was delivered in October 1967, while testing was ongoing. A total of 141 production F-111As were delivered; the last on August 30, 1969 ([1] and Section 2.2).

The first of five development versions of the Navy F-111B first flew May 18, 1965 [1]. First flight of a production F-111B took place on June 29, 1968. Limited aircraft carrier suitability testing was successfully completed in July 1968. Twenty-four production aircraft were initially ordered, but only one was produced. Congress canceled the Navy program in the summer1968. Six F-111Bs were produced in total, including the five development aircraft, before the program was cancelled [1].

The F-111C was produced for the RAAF where they are still in service. Sixty-six aircraft were ordered. Deliveries were supposed to begin on September 6, 1968, but structural problems delayed delivery until 1973. In 2003, proposals were on the table to retire the airplane from service early in 2006. This was proposed because of the rising maintenance costs of the aging fleet. It was reported in September 2003 that Australia will be rejecting these proposals, and instead will be extending service of the F-111 until 2020 [38]. Modernization of South-East Asian Air Forces is one reason for keeping the aircraft. Another reason is that the introduction of new tankers and other support aircraft coming in 2005 to enhance the capability of Australia's F-18s will not be able to replace the F-111's capability, at least according to one Senator [38]. The JSF may not come in on time.

The F-111D was ordered on May 10, 1967 but the upgraded advanced avionics of the variant caused severe delays. Completed F-111Ds sat waiting for the avionics to be completed. The first flight was on May 15th, 1970. Ninety-six aircraft were produced, with the last being delivered on February 20, 1973.

The F-111E was ordered in 1968 as a follow-on to the A model and as an interim to the delayed D model. Ninety-four were ordered [1]. Ninety-four were delivered between 1969 and May 28, 1971.

Fifty-Eight F-111Fs were ordered. The F-111F was ordered on July 1, 1970, and entered service in January, 1972. The last was delivered in September 1976 and was the last of the F-111s to be delivered.

FB-111A was produced to replace the B-58. Secretary McNamara announced a requirement for 210 on December 10, 1965. The initial contract called for 64 to be produced in spring 1967. On March 20, 1969 McNamara announced that only 76 out of 210 aircraft would be contracted [1]. First flight of a prototype went in July 1967. Two prototypes total were produced and were converted development F-111As [1]. The first production flight went on July 13, 1968. The last was delivered June 30, 1971.

10.2 Initial Problems

The F-111 experienced two major initial problems. The first problem was experienced during initial flight tests of the F-111A, and involved repeated engine surges and stalls due to incompatibility between the engine and the engine inlet. Information on this problem has already been presented in Section 6.3.3.2. The second problem was structural, and will be further presented here.

The first documented in-flight failure involved an F-111 deployed in Vietnam in early 1968. The F-111A in this accident crashed due to a sudden catastrophic failure in the tailplane system, and it was later discovered that the failure was caused by a fatigue fracture of a welded joint in the power unit of the left tailplane [21]. A similar accident occurred shortly after in May 1968 near Nellis Air Force Base, but despite the severity of these accidents, information regarding these accidents is limited.

In December 1969, the most well-known accident occurred at the Nellis Air Force Base range, and involved an F-111A that had accumulated just over 100 flight hours. During a pull-up from a rocket-firing pass, the left wing of the aircraft separated from the main body, causing the aircraft to crash. The accident was attributed to a fatigue crack in the wing pivot fitting that reached a critical length of a mere 23.6mm. Investigations revealed that the crack originated from an initial flaw present in the D6ac steel from manufacture. Following the accident, the fleet was grounded and a Recovery Program was implemented, which involved subjecting each aircraft to improved Non-Destructive Inspections (NDI), as well as a Cold-Proof Load Test (CPLT).

During the Recovery Program, it was found that the NDI techniques used during manufacture were inadequate. The pulse echo ultrasound used had not been designed to pick up flaws with an orientation similar to the one that caused the December 1969 crash. This problem was subsequently rectified by the use of a delta-scan ultrasonic that could identify such flaws regardless of orientation. Also, the magnaflux technique used was not powerful enough, and was replaced by a modified process involving magnetic rubber particle inspection. This technique has since become standard, and can find cracks as small as 0.020 inches (0.5mm), as well as identify scratches, tool marks and corrosion pits.

The CPLT used during the Recovery Program was devised to counter the problem of varying toughness in D6ac steel. D6ac steel had a toughness that varied according to the quench rate, with the lower limit being below the acceptable level. Hence, the critical crack size could be very small and it was difficult to inspect the aircraft critical components, such as the Wing-Carry-Through-Box and empennage, for such small cracks. The CPLT subjected the Wing-Carry-Through-Box and empennage of each aircraft to two load conditions, -2.4g and +7.33g at 56^{o} of wing sweep, at a temperature of –40°C. The reasoning behind the test was that the toughness and critical crack size of D6ac steel were significantly lower at such low temperatures, so if failure did not occur under the test conditions, it should not occur in service as well. The CPLT has been relatively successful in preventing further in-flight failures. Since the implementation of the CPLT in 1969, eleven more failures have been induced on-the-ground (as opposed to in-flight).

10.3 Operational Deployment and Combat

The first operational F-111s delivered were F-111As delivered in July 1967 [19]. The test program was incomplete, but the Air Force was pressured to prove the airplane's operational effectiveness to counter its negative publicity [21]. Combat Bullseye I testing in 1967 proved the high accuracy and reliability of the attack and navigation system in bombing [32]. Boosted by the success of Combat Bullseye testing, the Air Force handed some F-111s over to Col. Dethman, CO of 448th Tactical Fighter Squadron (TFS) at Nellis AFB in Nevada. Col. Dethman ran an intense program named Harvest Reaper to identify deficiencies in the airplane in preparation for combat. During October, 1967 under the "Harvest Reaper" program, each airplane flew almost 60 hours, double the 30 monthly hours desired by the Air Force [21]. Also in 1967, Operation Combat Trident was launched to train pilots for combat. Twenty-two pilots were trained by seven instructors in a program that ended in March of 1968. Just nine days after completion of the training program, six F-111As were sent to an Air Force base in Thailand to begin combat operations in Vietnam. F-111As were the only F-111 variant to participate in Vietnam.

10.3.1 Vietnam

10.3.1.1 Operation Combat Lancer

According to Bill Gunston, the Joint Chiefs made a political decision to send the F-111 into combat to "prove the concept of deep interdiction by individual unescorted aircraft, with no backup from tankers, ECM or any other aircraft." The first mission in Vietnam was flown on March 25th, 1968. In the next month, 55 missions were flown, all at night, with 52 reported successful, and 3 aircraft lost. During this first deployment to Vietnam, no F-111s received any battle damage, and no radar threat receiver warning ever went off, indicating that enemy radars never acquired the airplanes [21]. The first F-111 was lost on March 28th, 1968, only a three days after the F-111s began combat operations. The second was lost two days later. The third loss on April 22nd led to the suspension and eventual termination of Combat Lancer. The first of these losses was never explained. The second loss was due to a structural weld failure in a tail control actuator. The third loss was likely either a similar structural failure or pilot error. Anecdotal evidence from other pilots suggests that the crew of the third loss may have been flying unsafely in manual TFR mode to fly as low as 50 ft above ground level. Section 10.4 summarizes F-111 combat losses.

The losses in Combat Lancer led to more controversy and criticism from the press and in Congress. This was despite high loss rates of other aircraft in Vietnam and a similar loss record (six airplanes lost in and out of combat in the first 5,000 flight hours) to other supersonic aircraft. Two more F-111s crashed due to structural problems in training flights in the United States in 1968. These crashes and other ground test structural failures led to a fleet grounding of the airplane in 1969 as explained in section 10.2. The structural problems eventually led to an extensive structural testing program of all existing aircraft.

10.3.1.2 Constant Guard V

The grounding was lifted in 1970 and the F-111 went back to Vietnam in 1972 in Operation Constant Guard V. Two squadrons of 24 airplanes each fought in Vietnam for five months. The squadrons attempted to set a record for deployment to combat speed. Unfortunately, this caused logistical problems at their destination in Thailand when they arrived ahead of schedule. As originally scheduled, the F-111 squadrons' arrivals would time up well with the departures of several F-4 squadrons from Takhli Airbase. When the F-111s showed up early, there was an overcrowding problem for 36 hours until the F-4s could leave [20].

On September 27th, 1972, four hours after the first airplanes reached Takhli, six F-111s were deployed with fresh crews on combat missions in North Vietnam [21]. The attempt at a record deployment may have doomed the mission that night. Of the six aircraft scheduled for attacks, three never made it in the air because of equipment failures found on the ground. One aborted once airborne due to an ECM equipment failure. Despite the appearances aborts, the F-111 actually proved to have exceptional operational reliability. Of the two aircraft that went on their missions, one was lost and the one that came back could not aquire its primary target and had to bomb an alternate (Botton, 2003). The first night of operations in Constant Guard V was spectacularly unsuccessful for the F-111. The cause of the crash is still unknown and the site was found in 1998 in Laos [17].

After the first night, F-111 missions were suspended until October 4th while crews underwent training and the concept of F-111 use was re-evaluated. During this period two changes were made to tactics. Previously, crews were to hold a TFR level of 1,000 ft AGL. This was changed to 1,000 ft above the highest terrain within five miles of the intended route for the mission, until dropping to 500 ft in the target area. Additionally, the crews would fly low-level over known terrain in Thailand to check out the TFR at the start of every mission [20]. In actual practice, pilots typically flew 500 to 1,000 ft in the mountains and dropped down to 200 ft closer to the target in smoother terrain [22]. At the resumption of combat operations, the first missions were flown against low threat targets. The number of missions flown and the threat level of the targets were gradually built up to the intended levels of about 24 missions per night. F-111s flew 215 missions through the end of October. The standard mission for the F-111 was a single ship penetration, high-speed at a low level, and flown at night.

The F-111 flew missions in the most heavily defended areas of Northern North Vietnam until President Nixon halted bombing north of the 20th parallel on October 23rd, 1972 [20]. During those bombing runs, F-111s encountered anti-aircraft artillery (AAA), small arms fire, and surface-to-air missiles (SAMs). Enemy MiGs were not a factor during Constant Guard V operations. One of the advantages the F-111 was thought to have was that in flying at 500 ft AGL and at high speed, the airplane would be gone before the enemy could detect it. The CHECO report explained that this advantage was proven with enemy trends in anti-aircraft artillery. In the first few weeks of operations, AAA typically came just after weapons release and detonated above and behind the aircraft. The enemy gradually worked its way down to the 500 ft altitude figured out to aim ahead of the sound. Pilots adjusted by changing to a 200 or 300 ft altitude. The enemy also attempted to use AAA to force the aircraft up to an altitude where missile batteries could acquire the aircraft. No damage was ever received from AAA fire. Enemy SAM batteries acquired F-111s flying as low as 500 ft. Until October 22^{nd}, SAM sites had targeted F-111s 70 times, with 16 SAMs being fired on 8 occasions [20].

After bombing was halted above the 20^{th} parallel, F-111 missions were shifted to Laos. From the end of October through the middle of November F-111s flew about 20 missions a night. Most were interdiction missions hitting truck parks and other logistical facilities. In mid-November some of the F-111 missions shifted to troop support. Radar beacon offset bombing was a new capability for the F-111 and was outside the role originally envisioned for the airplane. In this type of mission, ground troops carried a radar beacon and could call in a target based on an offset distance and bearing from their position. F-111s were sometimes diverted in-flight from preplanned missions to attack time-sensitive targets found by troops on the ground. F-111s flew over 450 missions in Laos in November and over 500 missions in December [20].

10.3.1.3 Linebacker II

Linebacker II was the next operation in which the F-111s were involved. Linebacker II operated from December 18^{th}-29^{th} of 1972 and consisted of B-52s bombing targets in North Vietnam, mostly near Hanoi and Haiphong. It was the largest bombing campaign of the war. F-111s played a vital role in suppression of enemy air defenses by attacking MiG airfields, SAM sites, and logistic facilities. Common missions for the F-111 were to attack airfields or SAM sites to pave the way for the B-52s to bomb major targets. The CHECO report notes that although there was no hard evidence of the F-111's effectiveness against SAM sites, there was a sharp reduction in the number of SAM launches against B-52s; it was enough that the Strategic Air Command running the B-52s "specifically requested F-111 pre-strikes." A comparison showing the advantage of an F-111 radar based attack system over A-7s and F-4s using LORAN (a radio beacon navigational system) was seen in an attack against an airfield in North Vietnam. According to the CHECO report: "a single F-111 sortie succeeded in temporarily placing the Yen Bai airfield in a non-operational status after 44 A-7/F-4s striking under LORAN conditions had been unable to inflict serious damage."

Following Linebacker II, the F-111 continued striking targets in Southern Vietnam and Laos. In January, the F-111 flew 126 missions in North Vietnam and 698 in Laos [20]. The last mission in South East Asia was flown on February 22, 1973. In all, 4,030 F-111 missions were flown in South East Asia in its second deployment to Vietnam. Over 3,980 of these were flown in low-level terrain following mode [21]. Only six aircraft were lost during this period, a rate comparable to the A-6 and F-105F in night, terrain following missions.

10.3.1.4 Evaluation of Effectiveness in Vietnam

F-111s usually flew with a load of 12 Mk-82, high-drag, 500 lb bombs on missions into North Vietnam. This load allowed the airplane to fly at low level and drop at low level without worrying about getting caught in the bomb fragmentation pattern. 4 Mk-84, low-drag, 2,000 lb bombs could be carried, and were used at first in 1972. The low-drag weapons required a 4-g pull-up on delivery to clear the fragmentation pattern [22]. The release and climb to over 1,000 ft altitude put the airplane in a vulnerable position after dropping, and only Mk-82s were used after the first two F-111s were lost. Mk-84s could be used to created high damage against bridges and storage facilities where the Mk-82 were proven to be ineffective [20]. The restriction against using Mk-84s limited the potential effectiveness of the F-111.

Many F-111 interdiction missions, especially in Laos, were against targets with low radar reflectivity and that low-threat in terms of air defense. F-111s flew at mid-altitude (18,000 ft) and carried 24 Mk-82s against these targets to increase their effectiveness against these targets [20].

The F-111 flew a small number of missions relative to the whole air campaign in Vietnam. The nature of its single-ship mission limited the impact of any one attack. Nevertheless, the Air Force recognized the value the airplane supplied in terms of destruction, harassment, and presence. The F-111 gave the Air Force around-the-clock strike ability, adding psychological impact to the damage caused. The fact that the airplane could come from anywhere at anytime without was a constant threat to the enemy. The F-111 was effectively used to keep pressure on the enemy in areas where significant damage had already been done, and to suppress SAM sites for B-52s [20]. The F-111 required less support than other aircraft. They rarely required tanking, and did not need fighter support or electronic warfare aircraft. They flew solo missions and ran independent of all other operations except when attacking a radar beacon offset target. The F-111 radar attack system allowed it to bomb accurately at night and in bad weather. F-4s and other aircraft bombed visually, and could not attack in bad weather, and needed a coordinated effort with flares to be able to bomb in dangerous night missions [22]. In Vietnam the F-111 proved its effectiveness in performing its intended mission of deep penetration of a heavily defended route to accurately attack a tactical target.

10.3.2 Libya: Operation El Dorado Canyon

In 1986, near the end of March, the U.S. Navy carrier groups were assembling off the coast of Libya in the Mediterranean Sea. Libya fired missiles at U.S. aircraft off its coast. The missiles caused no damage. The U.S. Navy responded by destroying the missile site and the replacement radar unit in two strikes and by attacking and destroying several Libyan naval ships that got too close to the American formations. On April 5th a bomb exploded in a West Berlin discotheque popular injuring 200 people, including 63 U.S. soldiers, and killing one soldier and one civilian. On the night of April 15th and 16th, U.S. Navy and Air Force planes attacked five targets in Libya. While the airplanes were still flying, President Reagan addressed the nation explaining the attacks based on “irrefutable proof” that Libya had ordered the terrorist bombing.

The only U.S. aircraft that could perform a precision night attack were the Navy A-6 and the Air Force F-111. President Reagan and his advisors selected five targets to be hit in the raid. Four of the targets were directly related to President Gadhafi's ability to create terrorism and the fifth was an airbase attacked to suppress any defensive response. There were not enough A-6's on board the carriers to carry out the mission, so Air Force F-111s were sent from bases in the United Kingdom.

The Navy and the Air Force geographically divided the targets for planning and coordination purposes. The Air Force took three targets in the area around Tripoli. The Air Force sent 24 F-111Fs, 5 EF-111s, and 28 KC-10 and KC-135 tankers. The mission was complicated by the fact that the French refused to allow the F-111s to fly over, and they had to go around adding 6-7 hours of time and fuel to the mission. All five targets were destroyed, but the French embassy in Tripoli and several other buildings near a target were accidentally hit as well [40]. The attack lasted 12 minutes. One aircraft was lost, an F-111F, likely from a SAM or AAA fire. Other than the possible shoot-down, not other resistance was put forth. The mission demonstrated the F-111s capability to perform a precision nighttime attack from long range.

10.3.3 Operation Desert Storm

On August 2, 1990 Iraq invaded Kuwait after oil pricing negotiations broke down. Efforts of the U.N. Security Council to bring a peaceful resolution to the conflict failed. Operation Desert Storm and the first Gulf War began on January 16th. U.N. forces led by the U.S. bombed continuously throughout the conflict. The Gulf War was noted for the use of precision strike weapons to hit military targets and avoid collateral damage as much as possible. The war ended February 27, 1991 after only 43 days.

The F-111F was one of eight main air-to-ground airplanes used by the U.S. The EF-111 was also used for its electronic warfare capability. 65,000 combat sorties were flown between all aircraft in the war. Of the eight U.S. air-to-ground airplane types, 16 were lost and 39 were damaged. After day two of Desert Storm, all aircraft were restricted to medium to high altitudes to minimize aircraft combat casualties from ground-based air defenses [40].

Sixty-six F-111Fs were deployed for Desert Storm along with several EF-111s. One EF-111A was lost in the war and three F-111Fs were damaged. The lost EF-111A flew in to terrain and is believed to have been evading a SAM when it happened. The damaged aircraft were F-111Fs that were hit by AAA. EF-111s provided electronic jamming to suppress Iraqi air defenses and "were vital ingredients in the successful execution of the air campaign," according to the Government Accounting Office evaluation of the Desert Storm air campaign for Congress. F-111Fs shared the ground attack role with other U.S. aircraft including F-117s and A-10s. The majority of targets bombed by F-111Fs were offensive counter-air installations, communication lines, and command and control facilities. F-111Fs also bombed a wide range of other target types and operated all over the combat zone including the most heavily defended areas around Baghdad. Like the F-117, the F-111Fs bombed only at night and primarily dropped laser guided bombs. The F-111F flew at least as many missions as the F-117, A-10, A-6 and others [40]. Besides tactical fixed targets, F-111Fs also attacked Iraqi armor. F-111Fs may have destroyed more tanks and trucks than any other airplane. Pilots called it "Tank Planking," and tended to hit one tank per bomb [26]. F-111Fs were also used, along with a 5000 lb "bunker buster" bomb designed for it, to stop an oil leak at a refinery on the Mediterranean.

Despite being one of the older aircraft involved in the bombing campaign, the F-111F proved to be at least as effective or even more effective than newer aircraft. To evaluate the success rates of aircraft, the GAO report determines the ratio of "Fully Successful" (FS) to "Not Fully Successful" (NFS) target assessments. FS means that a battle damage assessment determined an aircraft's target to be destroyed. NFS means that additional strike were necessary. As shown in the table below, the F-111F had the best ratio of 3.2:1. FS or NFS was given to aircraft that were involved in attacking that target [40].

Table 8: Comparison of Success Rates of Gulf War I Bombing Campaign Aircraft [40]

Platform	FS	NFS	FS:NFS ratio
A-6E	37	34	1.1:1
A-10	[a]	[a]	[a]
B-52	25	35	0.7:1
F-111F	41	13	3.2:1
F-117	122	87	1.4:1
F-15E	28	29	1.0:1
F-16	67	45	1.5:1
F/A-18	36	47	0.8:1
GR-1	21	17	1.2:1
TLAM	18	16	1.1:1
Total[b]	**190**	**167**	**1.1:1**

[a]No data available.

[b]Individual platform data do not sum to the total because individual targets were often attacked by multiple platforms.

The F-117 was the most heralded aircraft in Desert Storm and many claims to its effectiveness were made. The GAO report not only refutes or puts into doubt many of these claims, but also shows that the F-111F is a very comparable aircraft. The table below is a comparison of the F-117 and F-111F in striking common targets with laser guided bombs. A strike is defined as one attack on one target by an aircraft where more than one bomb can be dropped. More than one strike can occur in one flight of the aircraft. The F-117 and F-111F made a similar number of strikes, but the F-111F had a higher percentage of hits. The F-111F also dropped a higher number of bombs, over two per strike. The success of the F-111F relative to the F-117 could be attributed to better accuracy with laser-guided bombs, or to the fact that it could deliver more bombs in a single strike. The ability to release more bombs per strike could be seen a distinct advantage of the F-111F over the F-117. The facts were that the F-117 could carry two 2,000 lb bombs and the F-111F could carry four faster and farther.

Table 9: F-117 and F-111F Strike Results on 49 Common Targets [40]

Aircraft	Laser-guided bombs dropped	Number of strikes	Total dropped	Average bombs dropped per strike	Strikes where target was reported hit	
					Number	Percent
F-111F	GBU-10, -12, -15, -24A/B, -28	422	893	2.1	357	85
F-117	GBU-10, -12, -27	456	517	1.1	363	80

10.4 Summary of Combat Losses

When an F-111 was lost in combat, it was usually not known what caused the crash. This is largely due to the nature of the mission. F-111 crew typically flew solo missions, flew in radio silence, and did mission planning on their own. They usually weren't checking in with anyone, and no one knew where they were supposed to be in general. There were no other aircraft with them to witness a crash, and even the general vicinity of a crash was unknown. The nature of high-speed flight at low level means that there is little time to react to failures or to correct pilot error. That most of these missions were done at might only makes matters worse. Thirteen F-111s were lost in combat and 18 crews were killed.

Table 10: Summary of F-111 Combat Losses [17]

Operation	Date	Tail Number	Model	Cause	Crew Status
Combat Lancer	28Mar68	66-0022	A	Unknown	Presumed KIA
Combat Lancer	22Apr68	66-0024	A	Unknown, possibly pilot error or structural failure	Presumed KIA
Combat Lancer	28Nov68	66-0017	A	Structural Failure, tail actuator	Ejected and recovered safely
Constant Guard V	28Sep72	67-0078	A	Unknown, possible shoot down	Presumed KIA
Constant Guard V	16Oct72	67-0066	A	Unknown, likely hit by SAM	Presumed KIA
Constant Guard V	7Nov72	67-0063	A	Unknown	Presumed KIA
Constant Guard V	21Nov72	67-0092	A	Unknown	Presumed KIA
Linebacker II	18Dec72	67-0099	A	Unknown	Presumed KIA
Linebacker II	22Dec72	67-0068	A	Shot down	POW then released
After Linebacker II	14Mar73	67-0072	A	Main landing gear pin failed on take-off	Egressed safely
After Linebacker II	16Jun73	67-0111	A	Mid-air collision	Ejected and safely recovered
El Dorado Canyon	15Apr86	70-2389	F	Probable shoot-down	KIA
Desert Storm	13Feb91	66-0023	EF	Probable CFIT while avoiding SAM	KIA

11.0 Conclusions

Value delivered to stakeholders

F-111 plagued by controversy brought on by politicians and the media. The best way to objectively measure the success or the failure of a product is to look at the value delivered to key stakeholders, and relate this value to the requirements and expectations. Compared to the joint program goals, F-111 was a failure. In 1968 the Navy left the program, and the overall estimated cost of the program doubled. In achieving technical and operational goals, the F-111 was a success.

From an Air Force point of view, the aircraft achieved the high performance goals dictated by the requirements. It fulfilled its primary mission of long-range low-level tactical interdiction. It was able to fly at supersonic speed on the deck; it had slightly less than the required radius of action; it was able to take off and land on short airstrips; it had twice the required payload. The lifetime of the F-111 was double the expected value and the aircraft is still flying for Australia. The only mission it did not fulfill was the air-to-air combat role due to its lack of maneuverability.

From the Navy point of view, F-111 was an error from the beginning. The Navy seems to have never really been involved in the program, and it ended by the cancellation of the F-111B, although tests showed a good capability for carrier-based operations despite the heavy structure of the aircraft. The Navy benefited from the F-111 program, and used much of the technology and lessons learned from the F-111 in its F-14.

In operations, the F-111 proved to be highly successful. Its ability to perform a deep interdiction mission at low level into heavily defended areas at night was proven in South East Asia. The F-111 had a significant impact despite its limited used relative to other Vietnam War airplanes. The F-111 was instrumental to the successful raid on Libya in 1986. It was again instrumental in the first Gulf War in 1991. Data from the first Gulf War show that the F-111 was more effective in many ways than other aircraft including the F-117. The F-111 proved to be a self-sufficient aircraft in combat, flying solo missions where other aircraft required EW, fighter, and tanker support.

Regarding the position of the manufacturer, GD learned a lot from the F-111 program. It was a laboratory where a lot of new technologies were tested and great progress had been achieved in terms of design experience and systems engineering management. The next aircraft of GD, the F-16, can therefore be seen as the results of the lessons learned on the F-111 program. For this particular aircraft, GD decided to integrate fever new technologies, and overall keep the plane simple. The F-16 was a highly coproduced airplane. The idea behind this is quite simple: to sell the aircraft to many countries, contrasting to the F-111 program for which cooperation was never intended in the development period, although it was eventually sold to the RAAF. Grumman benefited similarly. Grumman began development of the F-14 with the Navy even before the Navy pulled out of the F-111 program. Grumman applied many of the lessons learned in the F-111 program to the F-14.

Lessons learned for future design

F-111 can be seen as a good sketch of what can happen when technical requirements do not match what the aircraft is really intended to be. The aircraft was intended to be a fighter and a bomber, but the technical requirements made it an attack aircraft. In this sense it was a schizophrenic airplane that would have been better designated with a "B" or "A" instead of "F." Misnaming an airplane is not unique to the F-111. This happened before with the F-105 and after with the F-117.

Regarding future design (F-14/F-15), the main lesson was the "Fly before you buy" slogan of DOD secretary and successor to McNamara, Melvin Laird. These aircraft, as well as the F-16, also incorporated lessons learned from Vietnam about the value of maneuverability for air-to-air combat. While it had been previously assumed that fighter capability would fall out of the high speed for the F-111, its successors had fighter requirements from the beginning.

F-111D was possibly first digital airplane and the first aircraft to use terrain following and auto TF, features that would be adopted in the next generation of fighters. F-111 had a swing wing and was the first afterburning turbofans in a military jet. It was also the first and last attempt to use of crew module (B-58 used individual escape module). From an engineering point of view F-111 was also a laboratory, and experiences learned in that laboratory influenced future design, whether these experiences were successful or not.

12.0 References

- [1] *Jane's All the World's Aircraft 1971-72***.** ed. John W.R. Taylor. Jane's Yearbooks, Franklin Watts Inc., New York, 1971.
- [2] Gunston, Bill. *The Encyclopedia of Modern Warplanes.* Barnes & Nobles Books, New York, 1995.
- [3] http://www.hq.nasa.gov
- [4] Gaddis, John Lewis. *Strategies of Containment.* New York: Oxford University Press; 1982
- [5] Art, Robert J. *The TFX Decision.* Boston: Little, Brown and Company, 1968.
- [6] Coulam, R.F. *Illusions of Choice: The F-111 and the Problem of Weapons Acquisition Reform.* Princeton, NJ :Princeton University Press., 1977.
- [7] http://www.strategic-air-command.com
- [8] http://www.globalaircraft.org
- [9] Memorandum by G. A. Spangenberg, dated February 8, 1965
- [10] General Dynamics TFX Proposal, 09/17/1962
- [11] Phillips, Jim. Interview 9/11/03
- [12] General Dynamics, *F-111A Information Booklet LTP12-18*, 28 June, 1968
- [13] F-111F Flight Manual. T.O. 1F-111F1, 18 May, 1979.
- [14] Philips Jim, Proposal Document
- [15] Whitehead S., McDonald M. and Bartholomeusz R. A. *Loading, Degradation and Repair of F-111 Bonded Honeycomb Sandwich Panels – Preliminary Study*, DSTO Aeronautical and Maritime Research Laboratory, Australia, Report DSTO-TR-1041, 2000
- [16] *Jane's All the World's Aircraft 1976-77***.** ed. John W.R. Taylor. Jane's Yearbooks, Franklin Watts Inc., New York, 1976
- [17] http://www.F-111.net

- [18] http://www.aircraftresourcecenter.com
- [19] Baugher, J. *http://home.att.net/~jbaugher1/f111_1.html*
- [20] Checo Report, *The F-111 in South East Asia*, September 1972-January 1973
- [21] Gunston, Bill. *The Great Book of Modern Warplanes.* Salamander Books Ltd, 1987.
- [22] Fetter, Jerry Lt. Col. USAF [Ret], interview on 11/9/03
- [23] F-111A Flight Manual (Utility). T.O. 1F-111(Y)A-1
- [24] http://www.fas.org/
- [25] Gwynne, Don. Email Sent: October 30, 2003 5:59 PM To: Philips, James M
- [26] Worrell, Ken. Lt. Col. USAF [Ret.], interview on 11/9/03
- [27] Coyne, Kevin. 21 Feb, 1974. http://www.f-111.net/ejection.htm
- [28] Philips, Jim. *F-111 chronology*
- [29] Spangenberg, George A. http://gasoralhistory.home.att.net/
- [30] Angelucci, Enzo. *The American Fighter*. Haynes Publishing Group: Sparkford, Nr. Yeovil, Somerset, 1987
- [31] Murdock, Clark A. *Defense Policy Formation.* Albany: State University of New York Press, 1974.
- [32] Cooper, Charles. *Combat Lancer The F-111A's Introduction to War*. Air Force Museum Friend's Journal. Volume 24 Number 2.
- [33] F-111/FB-111 Structural Breakdown, 1969
- [34] http://prototypes.free.fr
- [35] Semken, Graeme. http://users.chariot.net.au/~theburfs/aardvark.html
- [36] http://www.kepu.com.cn/gb/index.html
- [37] http://globalsecurity.org

- [38] Allard, Tom. *New tanks may be on way, but the F-111's here to stay*, Defense Reporter, Sydney Morning Herald, September 16, 2003.

- [39] David de Botton. *F-111A in South East Asia*. F-111.net (webmaster)

- [40] Anno, Stephen E., Col. and Lt. Col. William E. Einspahr. *Command and Control and Communications Lessons Learned: Iranian Rescue, Falklands Conflict, Grenada Invasion, Libya Raid.* Air War College Research Report, No.AU-AWC-88-043, Air University, United States Air Force.

- [41] Operation Desert Storm: Evaluation of the Air Campaign. Government Accounting Office. June 1997. GAO/NSIAD-97-134

- [42] Ball, D.L. and Doerfler, M.T., *Metallic Material Data for F-111 Durability and damage Tolerance Analysis*, LMTAS Report FZS-12-626, 1996

- [43] Coulam, R. F. *The Importance of the Beginning: Defense Doctrine and the Development of the F-111 Fighter-Bomber.* Public Policy, 23 (1), 1975.

- [44] Goodwin, B. Z. *The TFX Hearings: A Study in Controversy Creation*. Massachusetts Institute of Technology Thesis, Mgt, 1970 MS

- [45] Mills T., Clark G., Loader C, Sharp P. K. and Schmidt R, *Review of F-111 Structural Materials*, DSTO Aeronautical and Maritime Research Laboratory, Australia, Report DSTO-TR-1118, 2001

- [46] King, Dain, Lt. Col. USAF [Ret.], interview on 11/3/03

- [47] http://www.wpafb.af.mil/museum/ (USAF Museum)

Appendix A:

List of Materials used in the F-111

Table 11 is a list of 13 metallic materials used in the manufacture of the F-111. D6ac Ultra-High-Strength steel can be considered the most important, and was used in the production of the 11 out of 13 critical components of the aircraft. The other 2 critical components were the upper and lower wing surfaces, and was manufactured using 2024-T851 aluminum.

Table 11: List of F-111 metallic materials [42]

Material Designation and heat treatment	Material
4330V	Steel
4340 200-220† HT	Steel
D6ac 220-240 HT	Steel
D6ac 260-280 HT	Steel
PH13-8Mo H1000	Stainless Steel
15-5 PH H925	Stainless Steel
PH15-7Mo Th1050	Stainless Steel
17-4PH H900	Stainless Steel
2014-T6	Aluminum
2024-T62	Aluminum
2024-T851	Aluminum
2024-T852	Aluminum
2124-T851	Aluminum
7075-T6	Aluminum
7075-T651	Aluminum
7079-T651	Aluminum
6Al-4V STA	Titanium

Technical details of the Pratt and Whitney TF30 engine

The manufacturer and civil designation of the Pratt and Whitney TF30 engine is JTF10A. Technical details, as taken from [16] has been included here as a useful reference. Please refer to Table 4 presented in Section 6.3.3.1 for information on thrust and specific fuel consumption.

Type: Two-shaft axial-flow turbofan

Intake: Direct pitot annular type with 23 fixed inlet guide vanes (19 on P-8 and P-408). Hollow vanes pass anti-icing air.

Fan: Three stages (two on P-8 and P-408). Rotor and stator and casings all of titanium. Three rotor stages have 28)with part-span shrouds), 36 and 36 blades, all dovetailed; stator stages have 44, 44 and 48 blades, all rivet-retained. Pressure ratio 2.14:1. Mass flow typically 112 kg (247lb)/sec (P-100 118 kg; 260 lb/sec).

LP compressor: Six stages (seven on P-8 and P-408), constructed integrally with fan to form nine-stage spool. Wholly of titanium construction, except stator blades of steel.

HP compressor: Seven stages, constructed mainly of nickel-based alloy.

Combustion chamber: Can-annular, with steel casing and eight Hastelloy X flame cans each held at the front by four dual-orifice burners. Spark igniters in chambers 4 and 5.

Fuel system: HP system (above 69 bars; 1,000 lb/sq in), with conventional hydro-mechanical control. Main elements comprise fuel pump, filter, heater, fuel control, P & D valve and nozzles. Separate afterburner system for A/B engines. No water injection.

Fuel grade: JP-4, JP-5.

HP turbine: Single stage, with film-cooled nozzle guide vanes (stators) and air-cooled rotor of cobalt-based alloy (P-100 vanes and blades of directionally solidified alloy). Max gas temperature, early models 1,137^{o}C, P-100 1,316 ^{o}C.

LP turbine: Three-stages of nickel-based alloys. Rotor stages have 88, 86 and 72 fir-tree root blades. Gas temperature after turbine, typically 550 ^{o}C.

Jet pipe (non A/B engine): Simple steel pipe where fan airflow and core gas mix before passing through fixed nozzle.

Afterburner: Diffuser leads to combustion section comprising double-wall outer duct and inner liner carrying five-zone combustion system. Ignition by auxiliary squirt in A/B diffuser, coupled with main squirt in No. 4 burner can which produces hot-streak of fuel through the turbine (P-100 engine, fully modulated light-up by 4-joule electrical ignition system). Max gas temperature 1,490 ^{o}C.

Nozzle (A/B engines): Primary nozzle has variable area, with six hinged segments actuated by engine-fuel rams (P-100, 18 iris segments translated along curved profile by six long-stroke rams). Ejector nozzle has six blow-in doors with free tail-feathers.

Accessory drives: Main gearbox under compressor, driven by bevel shaft from HP spool. Contains major elements of lubrication and breather systems. Drive pads at front and rear for main and A/B fuel pumps, main oil pump, N_2 tachometer, starter, fluid power pumps and power take-off.

Lubrication system: Self-contained dry-sump hot-tank system. Accessory gearbox housing forms 15 litre (4 US gal; 3.3 Imp gal) tank. Oil circulated at 3.10 bars (45 lb/sq in) through pump, filter, coolers (air/oil on airframe, fuel/oil on engine and A/B fuel/oil cooler) and three main bearing components; returned by scavenge pumps and de-aerator.

Oil grade: MIL-L-7808

Mounting: Two-planar. Front peripheral pair of flanges absorb vertical, side and thrust loads; rear pair of peripheral flanges (in line with No. 6 bearing behind LP turbine) absorb vertical and side loads.

Starting: Air-turbine starter on left forward drive pad of accessory gearbox.

APPENDIX B:

F-111 Case Study Interview Questions
Distinguished interviewee: F. A. (Mike) Curtis
Date: 08-25-2003

Personal Background:
I was born in Washington, DC, and moved with my family to western Massachusetts where I spent my grade school and high school days. Starting in 1940, I spent 3 years in Haverford College. I then joined the Army. After the war, I went to Western Poly for two years where I completed my Engineering degree. In 1948 I went to Cal Tech where I received an MS in Aero in 1949. My first job a Fort Worth was on the B-58 where I worked for 10 years. I then moved on to the F-111 for 15 years which is described below. I then spent 15 years on the F-16 program. Special assignments included work on the B-57 and some space related projects.

Interviewers: Jim Phillips and Dr. Keith Richey

What was your role in the F-111 development?

In pre-design, I was the head of the Stability and Flight Control and Navigation Section. The program was proposed out of Engineering with no real program involvement. Bill Dietz was the proposal leader. When we won the contract, J. B (Bing) Cosby was put in as the Program Director. In 1965, I was the F-111K proposal leader. We started out the program after we won with supposed tighter connection to the program director, but we re-functionalized back to a stronger engineering led effort in June/July 1967. We had a strong Project Office that Bill Dietz led. I took over the F-111A & Common effort in that Project Office.

What were some of the "Systems Engineering Principles" used by the Contractor? By the Government?

Early on there was a new specification that was micro-managed to the point that we were constrained to mediocrity. Systems leads were WBS Managers that made for effective management because their charter was to coordinate and work across all departments in particular the factory as well as the subcontractors. Part of their responsibility was to review specifications, drawings Material specifications, test activities, etc. They also had the responsibility of having the team look at alternatives if test results revealed issues.

What was the impact of the joint service requirement in the beginning? How did it impact Systems Engineering?

The F-111B drove the majority of the design requirements. We won because of the common design for the two services that was required by Mr. McNamara. Grumman proposed a specialized aircraft while we were trying to meet common F-111 requirements. The Navy had more experienced airplane people in their office.

The Navy required side by side seating on our common aircraft design and abandoned it on the Grumman specialized design.
The fineness ratio was made especially tough by the USAF requirement of Mach 1.2 on the deck. Strong engineering leaders: they listened and then made a decision. Consensus

decision making was not used. A major issue later was the fact that the USAF forced Mark II Avionics on the airplane which was predicted by us to be unworkable, and it proved to be a maintenance nightmare.
The Navy canceled in 1970.

Describe the political climate in the source selection and in the early development.
You will get a better answer from Bob Widmer.

What was the impact of the F-111B cancellation? Did you see it coming?
It was too late too influence the design to take out the Navy requirements that had costly impacts to a specialized USAF design. I did not see the cancellation coming.

What were the "long poles" in the early design? How were they addressed?
Mach 1.2 at sea level Inlet design and structural strength were emphasized.

What were the main managerial issues in the development? How were they dealt with?
Contractor: Organization changes, example Lewis came in from F-4. Communication problems with Program Office – Cosby and Engineering
Lack of detailed Lessons Learned.
Customer: Specification, some really silly requirements, example wing sweep control direction decision. Lack of feedback from the bases.

What technical issues came up in development that you did not expect? What was their impact on the program?
How were the solutions to the technical/programmatic/managerial problems identified?
Mostly though joint industry/government teams.

What was your memory of the best times in the development program?
Delivering the Australian aircraft in 1973.

What is your memory of the worst time in the development?
The Nellis crash due to the wing pivot fitting failure where the crew was killed.

What was your post-development role in the F-111?
Getting aircraft delivered.
Navigation pod development and integration
Getting aircraft ready for Viet Nam

If you had to do the F-111 job over, what would you do differently?
Strive to understand and manage the political issues better.
Work the D avionics problem better.
Work the SAC desire to have a big aircraft better.
Work the Navy situation better.

How do you think the so-called “modern systems engineering” principles could have been applied to the F-111.

Work requirements more aggressively with the customer.
Work the systems architecture smarter.
Some improvement in system and subsystem design.
Some improvements in verification and test.
Some improvement in systems integration.
Work life cycle support better.
This would have made tremendous differences in improvements in reliability and Maintainability especially of early aircraft.
Improve communication and better reputation especially of the F-111F

Have you noticed issues similar to those on F-111 occurring on other aircraft programs?

What do you think the lessons learned from the F-111 are for the JSF?

Stress the Navy/Air Force and Marine commonality.

Looking at the Sage Friedman matrix for Systems Engineering, let’s go over a few of your thoughts on each item with respect to the F-111.

Out of this came the F-111 family of aircraft and the F-14 which was built for a specialized role.

What do you think is the primary “take away” message for AF acquisition students as they review the F-111 history of the development and systems engineering?

The common requirements were impossible to fully achieve or Government management was too inflexible to compromise.