F-111 Case Study

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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.

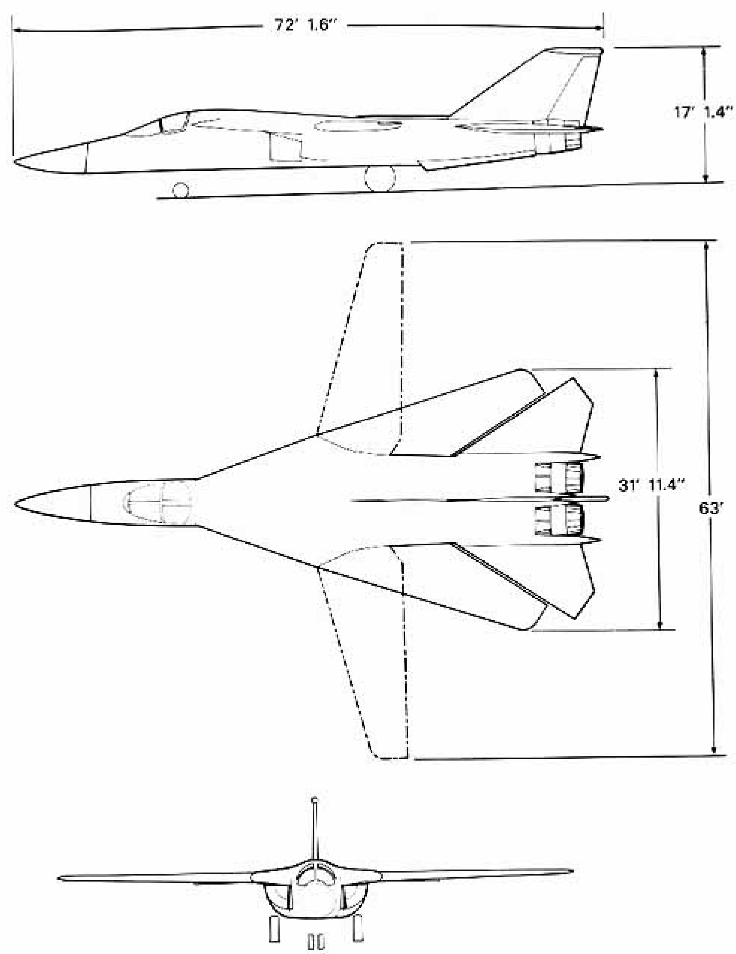

Figure 1: 3-view of the F-111A (from [3])

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].

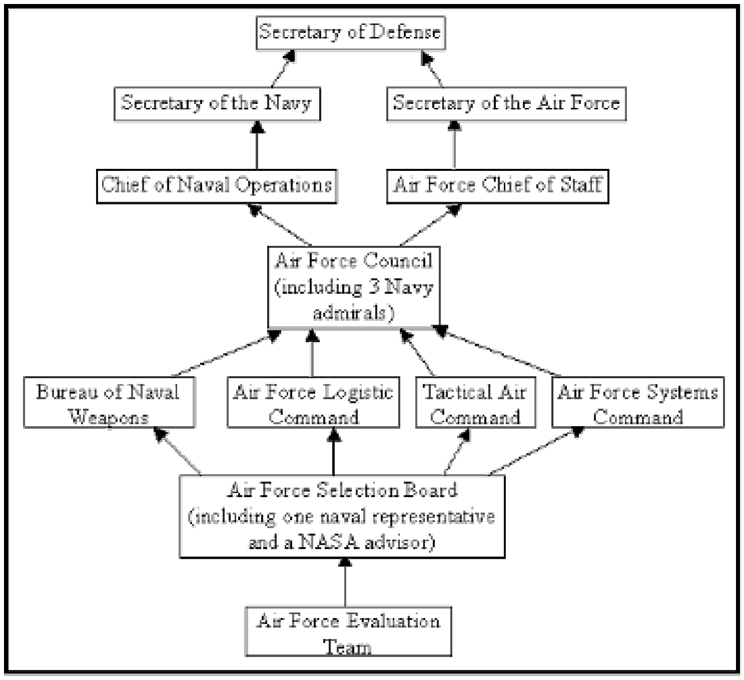

Figure 2: F-111 Source Selection Architecture [5]

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

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[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].

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* 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.

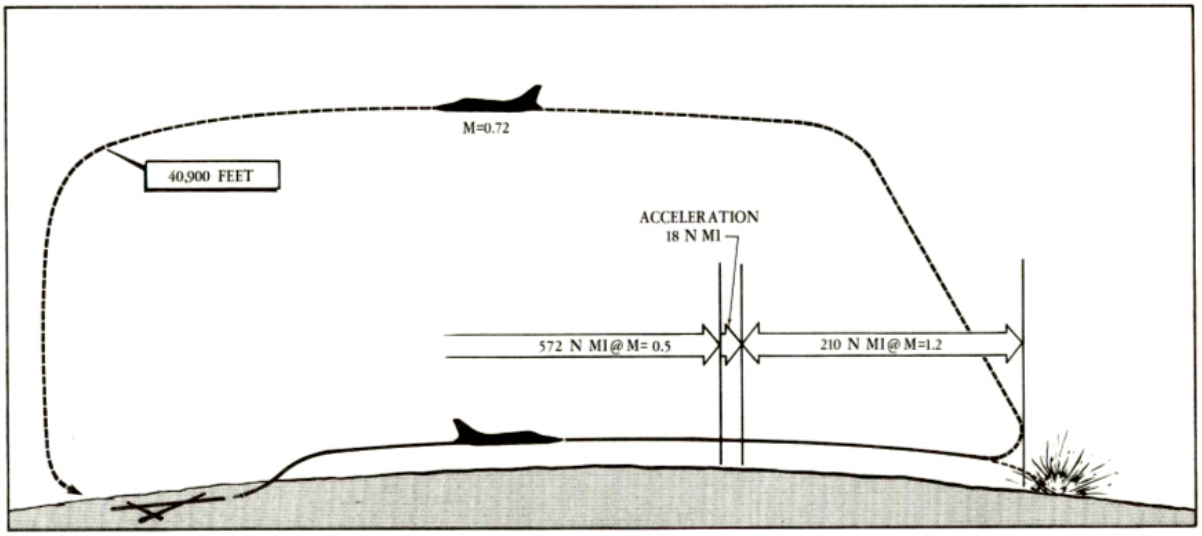


Figure 6: Sketch of a Lo-Lo-Hi mission, from [10]

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.

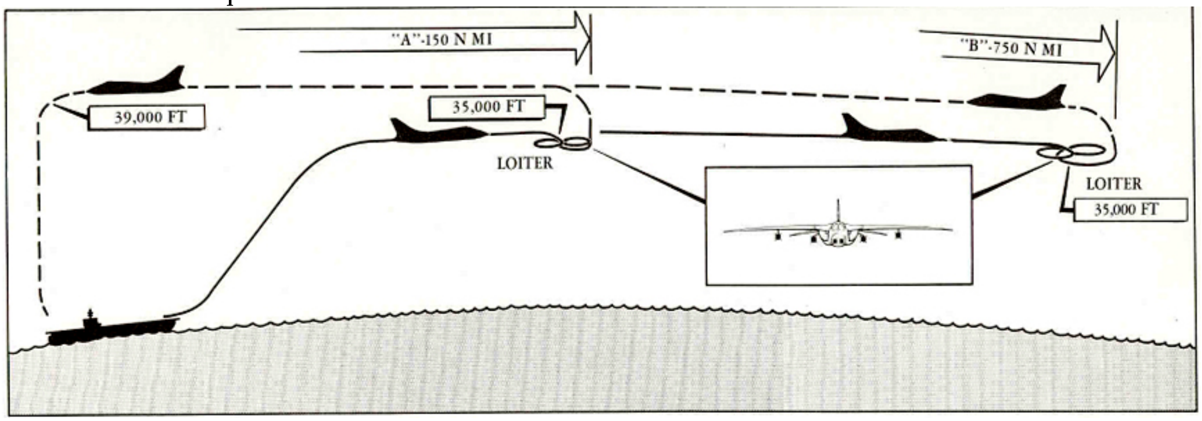


Figure 7: Sketch of a loiter mission extracted from [10]

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.

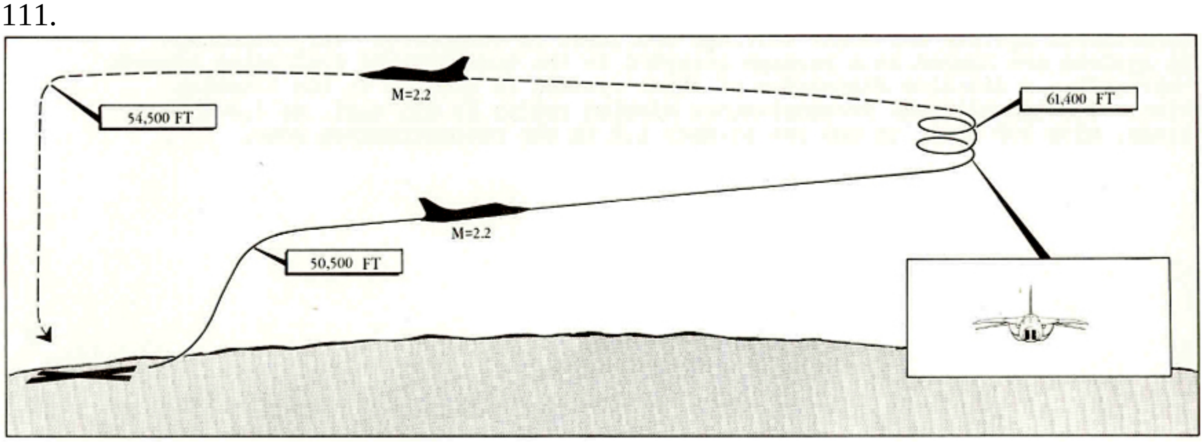
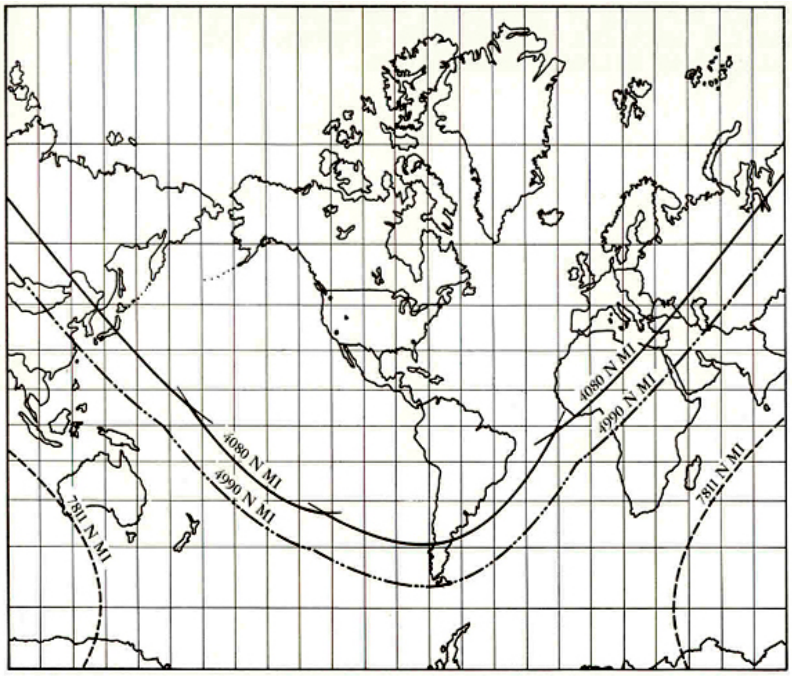


Figure 8: Sketch of an interception mission from [10]

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.

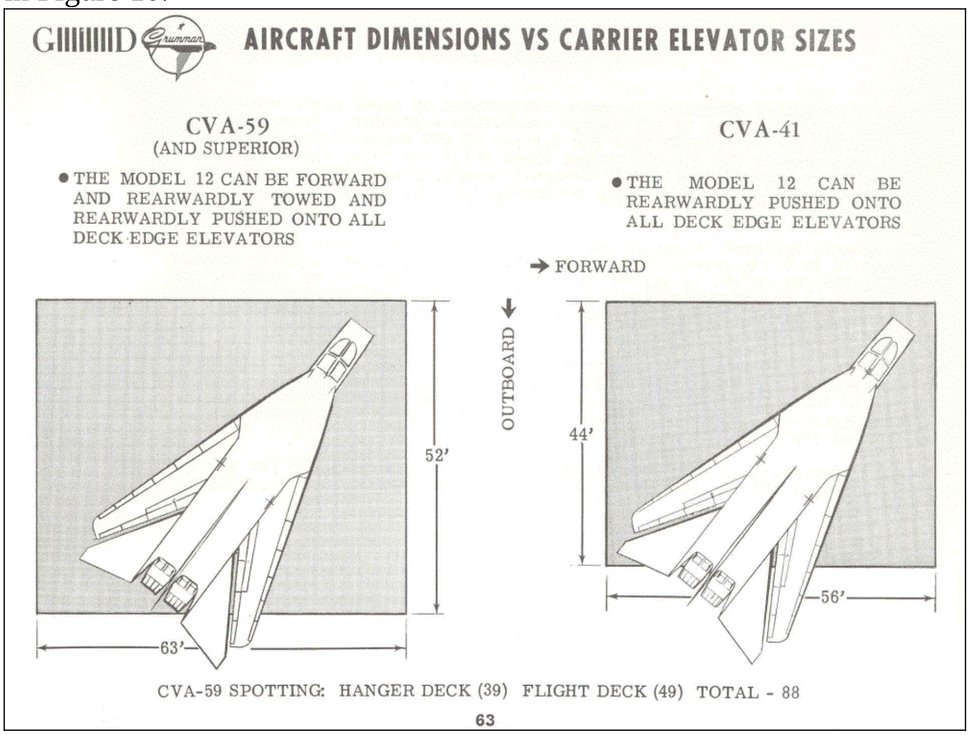


Figure 10: Aircraft Carrier Elevator Sizes [10]

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.

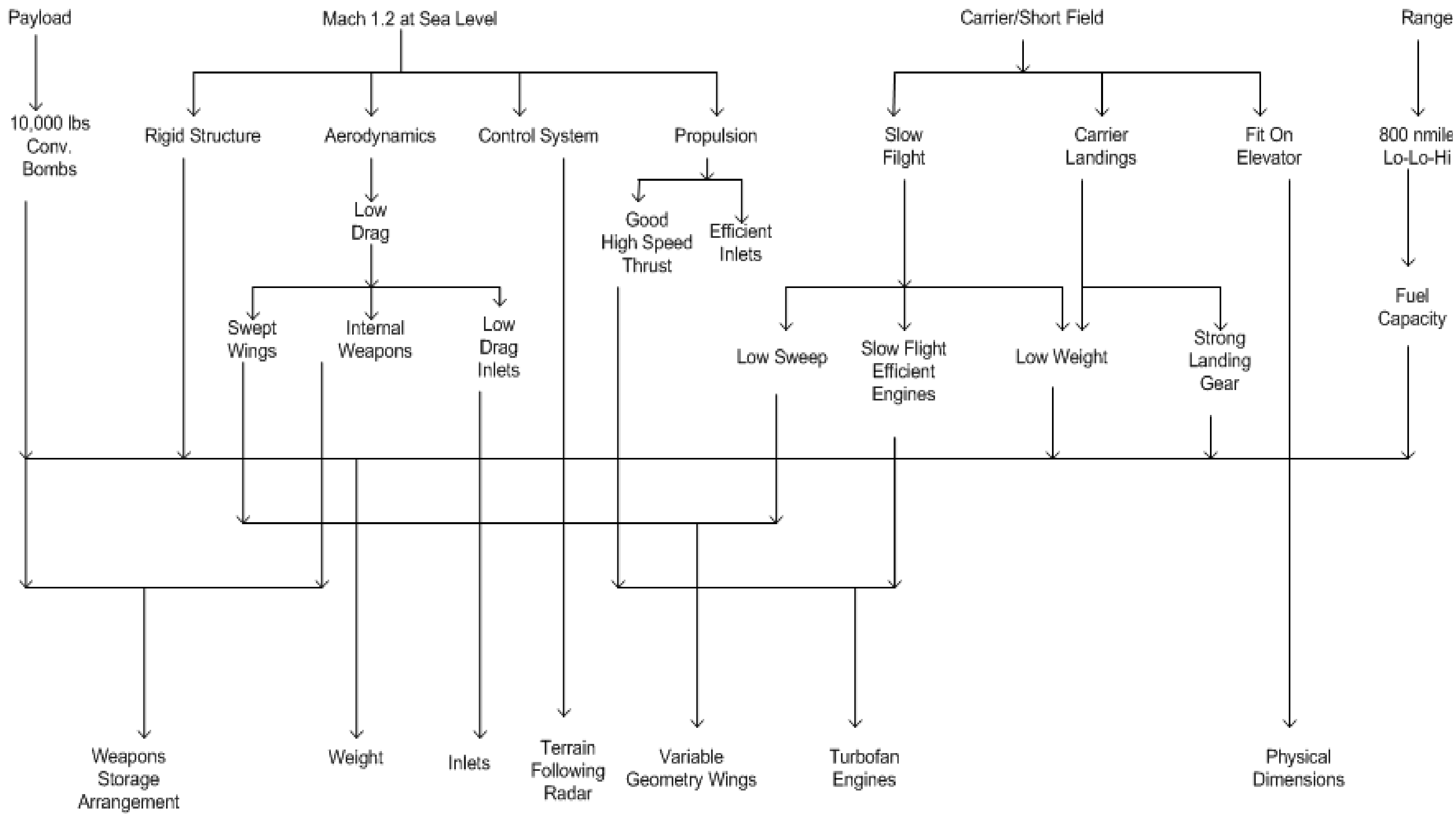


Figure 11: Flowdown of Four Key Requirements

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.

- <u>Variable Sweep</u>: 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.
- <u>Flaps and Slats</u>: Chosen to provide high lift configuration for short field. Added weight.
- <u>Turbofan engines</u>: Chosen to provide short field and supersonic capability.
- <u>Engine inlet</u>: Assumed to be optimized for sea level supersonic dash. Not optimized for high angle of attack flight.
- <u>Structure</u>: 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.

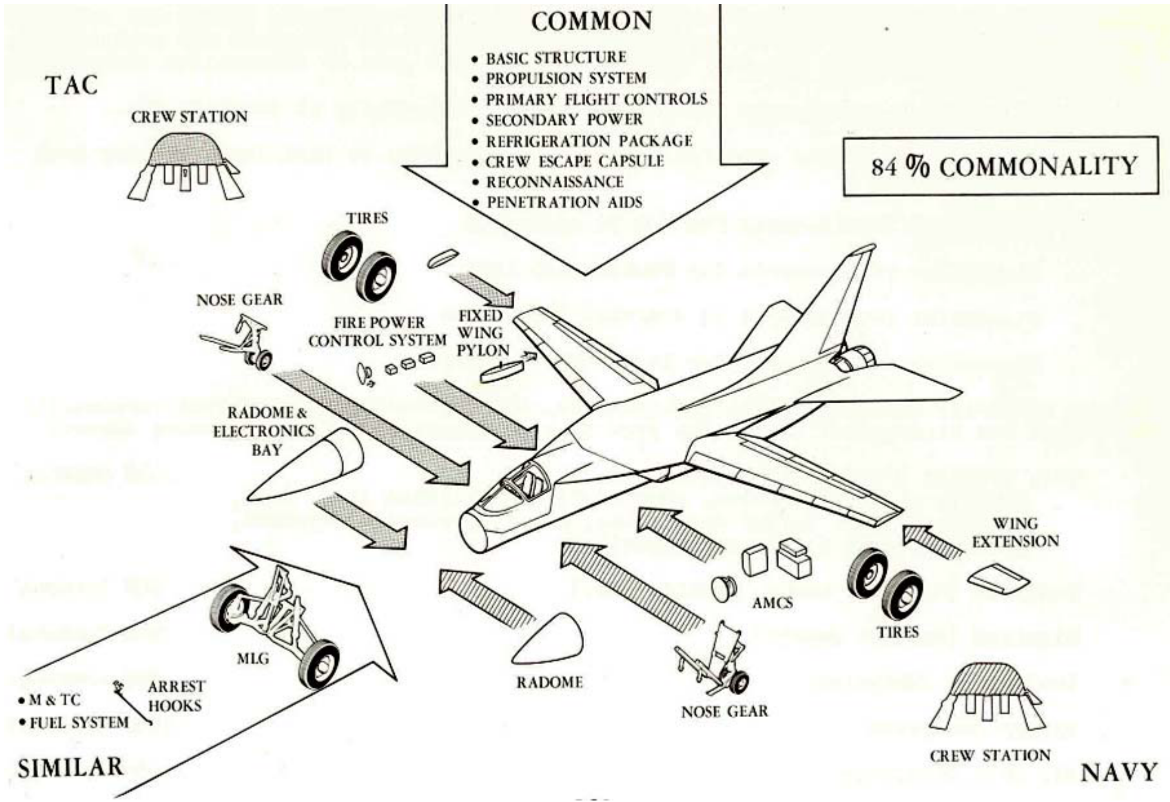


Figure 12: Air Force and Navy commonality [10]

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.