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.

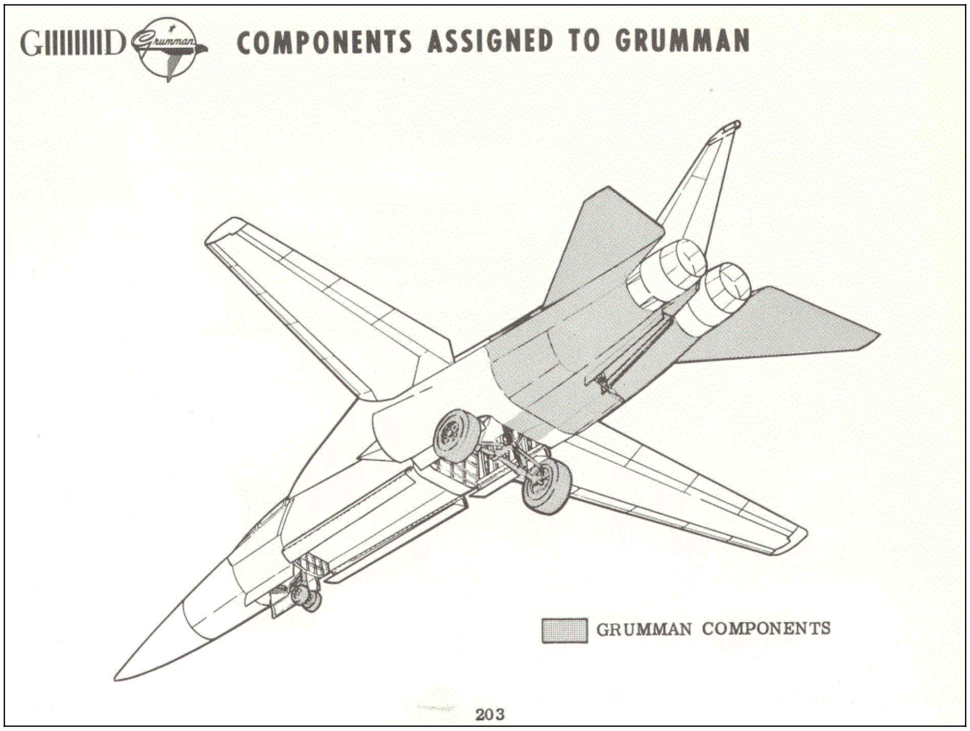
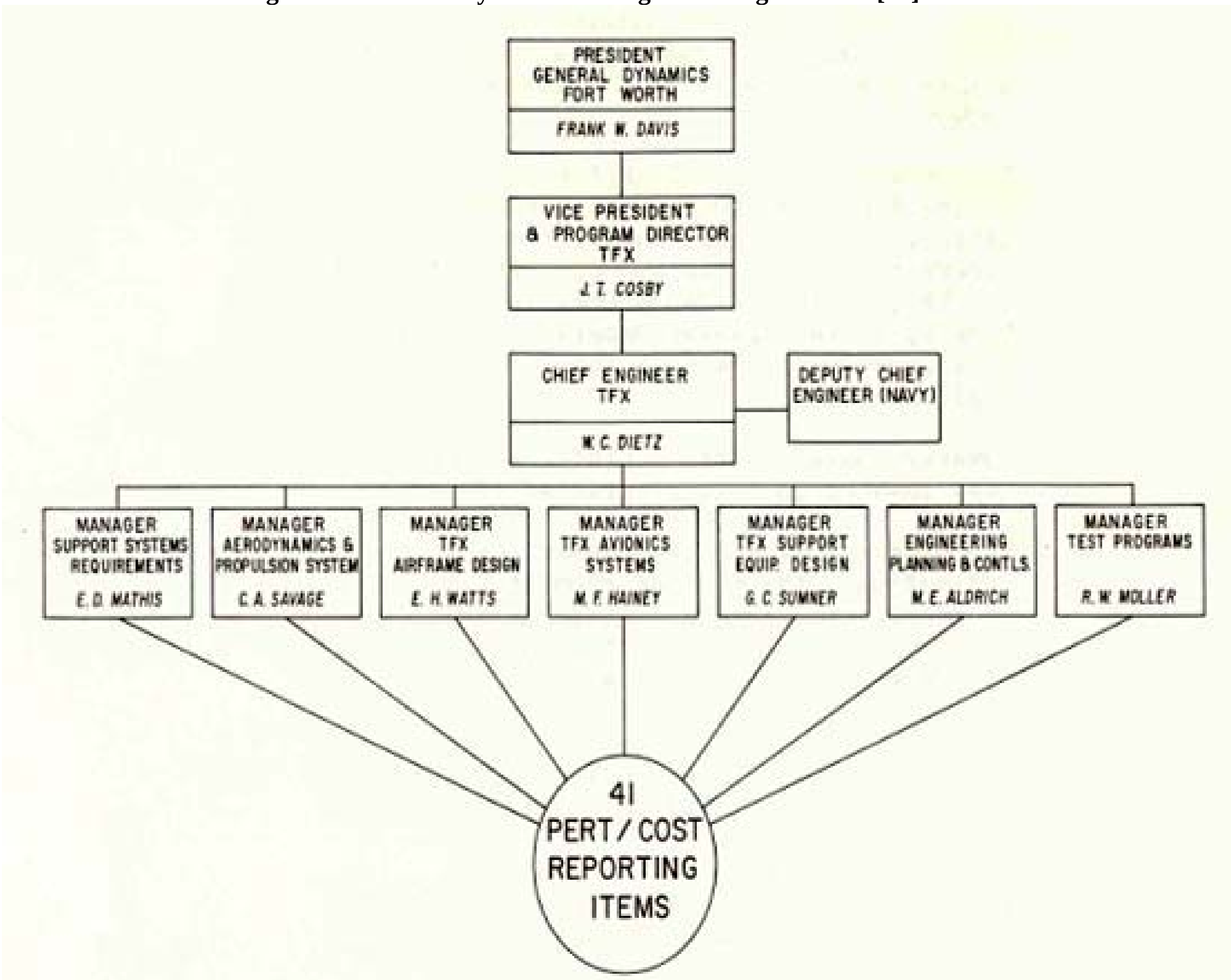


Figure 60: Grumman Components [10]

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.

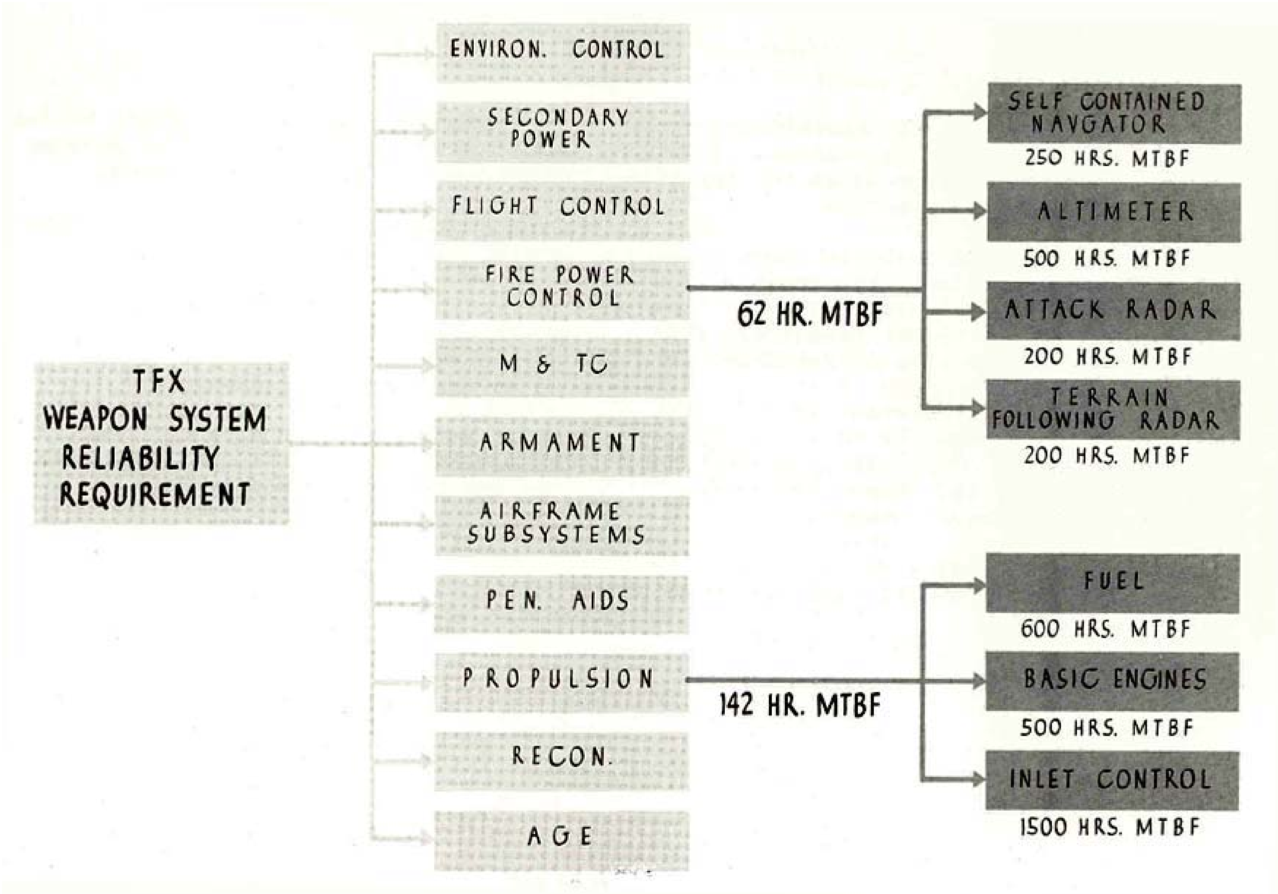


Figure 62: Quantitative Reliability Management [10]

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.

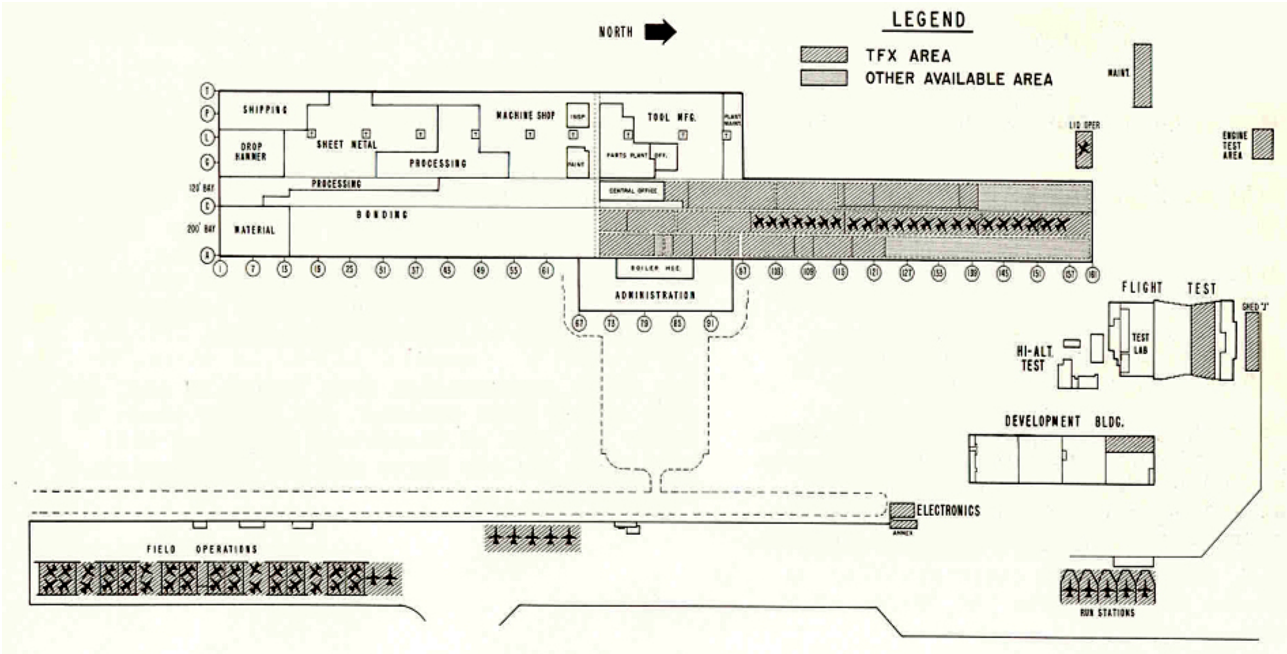


Figure 63: General Dynamics Forth Worth Production Facility [10]

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.

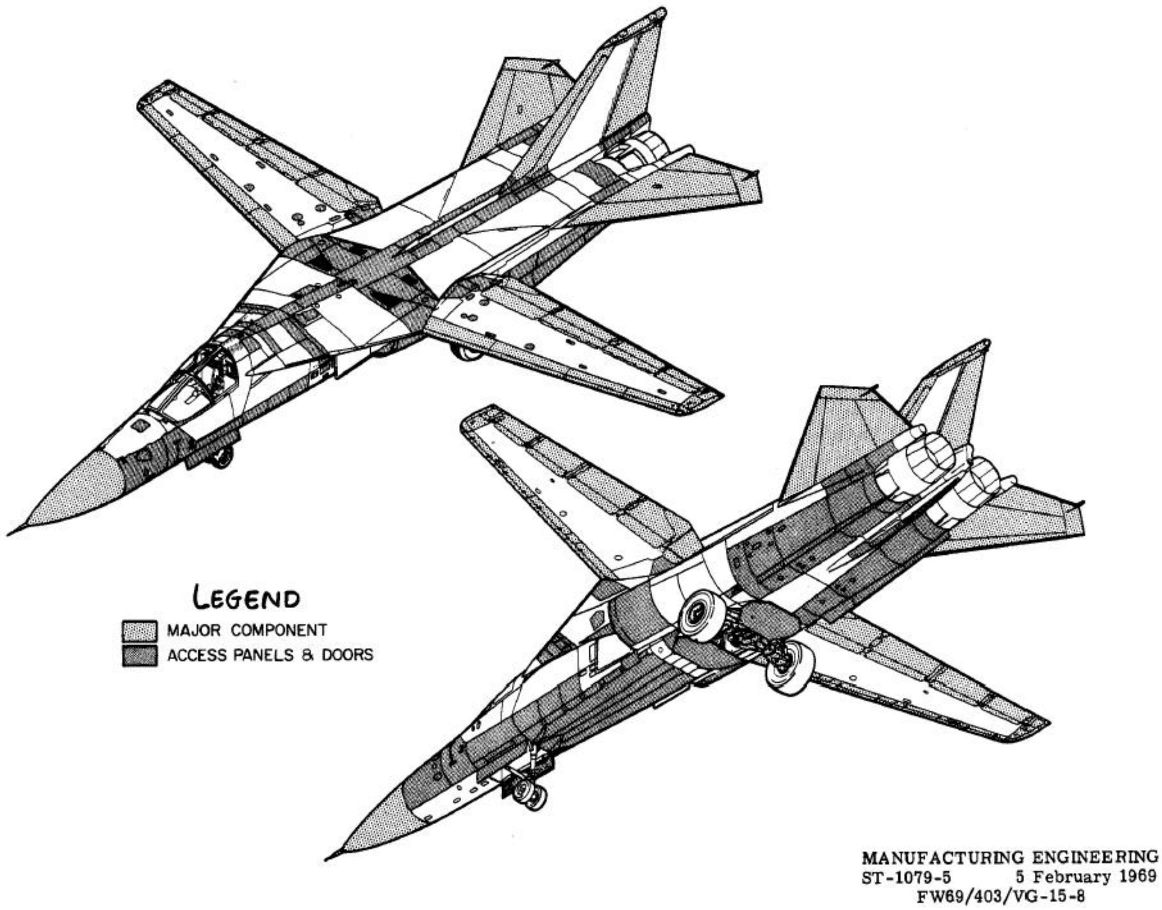


Figure 64: Access panels and major components [33]

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].

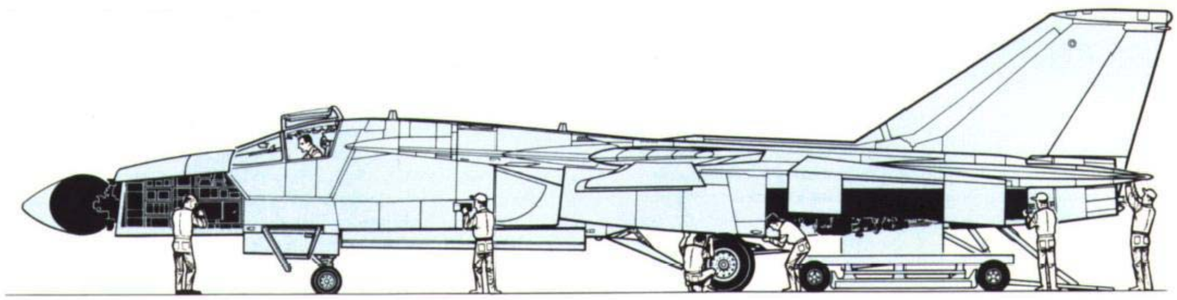


Figure 65: F-111A's maintenance [12]

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.

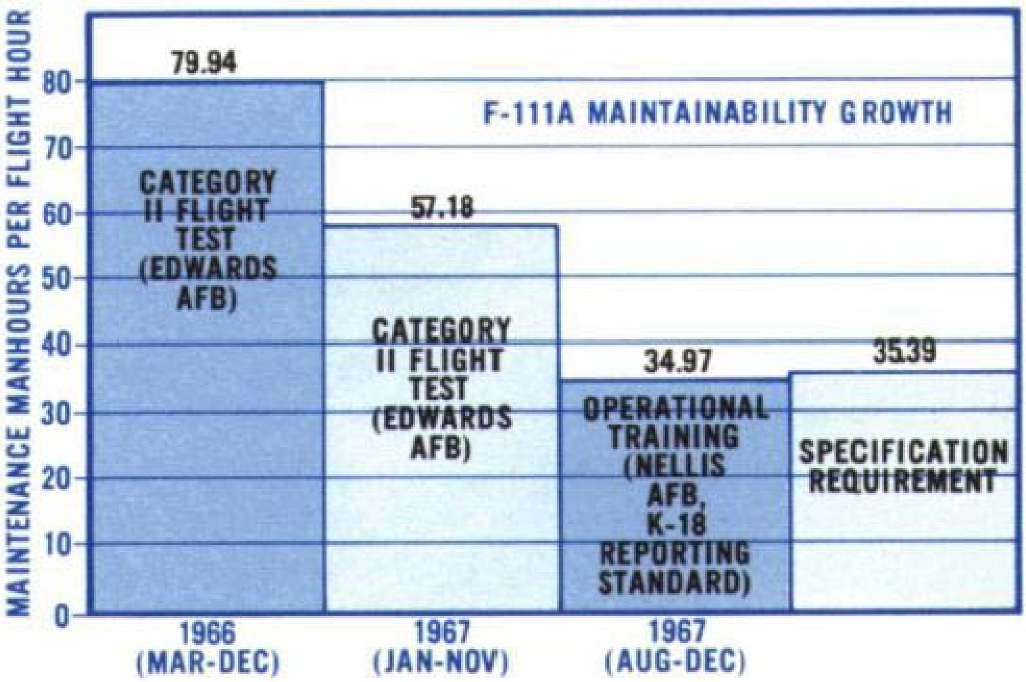


Figure 66: Maintainability growth due to increased maintenance experience [12]

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])

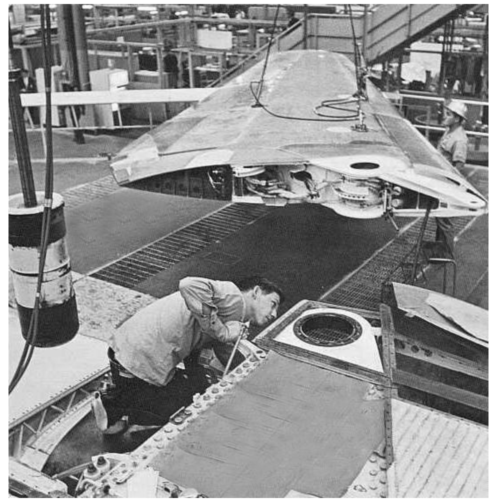


Figure 70: fitting of a wing (from [35])

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])

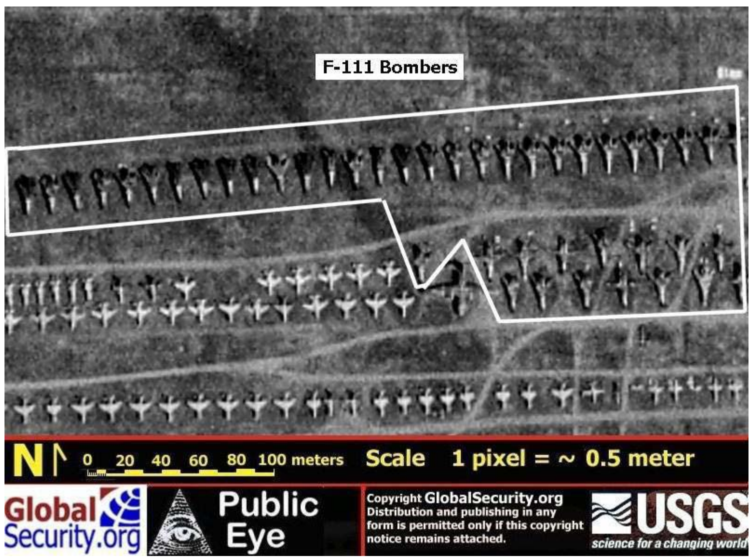


Figure 72: Satellite view of AMARC, showing the F-111 location (from [37])

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 22nd, SAM sites had targeted F-111s 70 times, with 16 SAMs being fired on 8 occasions [20].

After bombing was halted above the 20th 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 18th-29th 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.