ICAS-84-5.4.2

F404 NEW STANDARDS FOR FIGHTER AIRCRAFT ENGINES

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Abstract

The F404, a fighter turbofan engine which combines high performance with exceptional reliability, maintainability, and low support costs, was designed by balancing advanced technology in many disciplines. The F404's outstanding operability characteristics are reviewed, emphasizing a key attribute: the absence of any pilot throttle restrictions at any point in the envelope. The F404's simple design has twice the pressure ratio, 1/2 the weight, 3/4 the length, and 1/3 fewer parts when compared to the J79 engine. A new Digital Electronic Control improves engine reliability, provides flexibility in tailoring the engine for specific aircraft and missions, and improves engine control capability. A rigorous design-to-cost program, "Bottom Line Measures" goals for reliability and maintainability, and ongoing cost reduction and component improvement programs have resulted in low Life Cycle Costs. The integration of future advances in technology in F404 growth engines is described.

I. Introduction

The F404 is an advanced technology augmented turbofan engine with versions spanning 16,000 to 22,000 pounds thrust. Since its first flight in the U.S. Navy's new F/A-18 fighter/attack aircraft in November of 1978, the F404 has demonstrated an exceptional combination of attributes--outstanding engine performance, high reliability and maintainability, with low acquisition and support costs. The engine is in high volume production at over 20 engines per month for F/A-18s being manufactured for the U.S. Navy, Canada, Australia and soon for Spain.

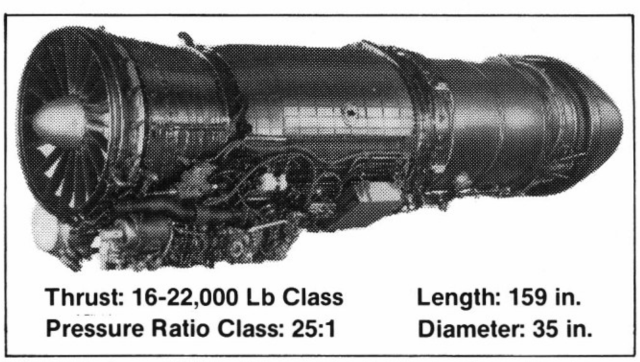

Figure 1. F404 Augmented Turbofan Engine

A derivative and growth program is already well underway. The Northrop F-20 Tigershark has been undergoing an extensive flight demonstration program with the first growth derivative, the F404-GE-100 engine which incorporates improved single-engine reliability features, including a digital electronic control, and delivers 17,000 pounds of thrust.

The second step is the F404/RM12 under development for the Swedish JAS 39 Gripen, again with single-engine features and delivering 18,000 pounds of thrust. A modified version of this engine is scheduled for production Tigersharks. Other applications include the Grumman X-29 Forward Swept Wing fighter demonstrator and the French ACX experimental aircraft. The F404 is also a leading candidate for several other advanced U.S. and international aircraft.

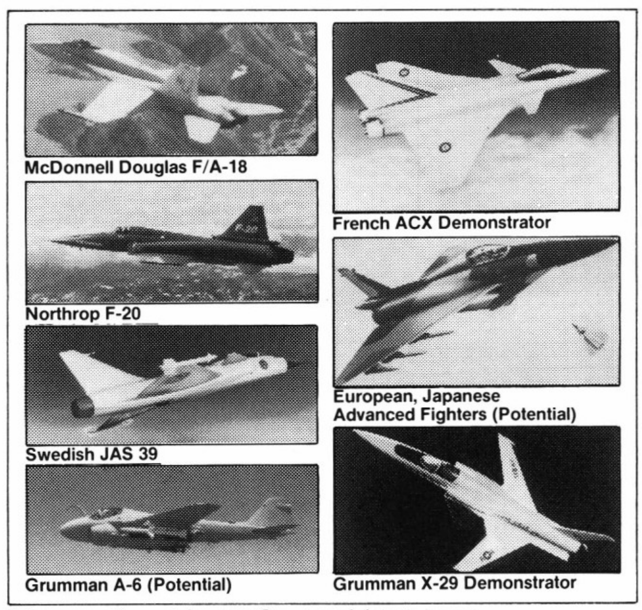

Figure 2. Aircraft Applications

Non-afterburning versions with thrust from 10,500 to 14,000 pounds are being proposed for re-engined models of the McDonnell Douglas A-4 and the Grumman A-6. With advanced technology improvements, these aircraft applications and growth steps are expected to keep the F404 in volume production through the 1990s and beyond.

The F404 is fast becoming an international engine. F404 components are made in Canada. Co-production is in progress in Australia and planned for Spain. Sweden will be involved in the development and co-production of the advanced F404, and we are looking into ventures with several other countries.

This paper explores the General Electric approach to developing and using the best technology available to achieve such a successful modern turbofan engine. With a bow towards our Aircraft Engine colleagues at General Electric in Cincinnati, the preeminent augmented fighter engine of the previous generation is widely regarded as the J79. Selected to power the famed F-4 Phantom and F-104 Starfighter, the J79 is still operated by 17 countries on over 4,500 aircraft. In the initial design phase of the F404, a balanced set of objectives was chosen for the engine that included operability, reliability, maintainability, low acquisition and low support costs, and high thrust-to-weight ratio. Our goal for the F404 was to do better than the J79 in each of the above categories by using the best technology available.

II. Operability

The users of the aircraft, the pilots, consider the J79 to be the benchmark against which all other jet engines are judged for operability; that is, giving the pilot the power he needs when he needs it--with rapid acceleration and deceleration and without stalling. By combining wide chord, low aspect ratio fan blading, advanced aerodynamics and careful control system design which preserves stall (surge) margin while providing high performance, the F404 has demonstrated the following outstanding operability characteristics:

- Unrestricted throttle movement at any point in the envelope
- Rapid acceleration (an average of 3.25 seconds from idle to maximum power) and deceleration
- Very high inlet distortion tolerance--which allows the aircraft to maneuver at unusually high angles of attack and sideslip without affecting engine operation; that is, no stalls--at any altitude or aircraft attitude or speed within the flight envelope
- Reliable air starts
- Superior augmentor light capability and stability--which means the pilot can get afterburner power at any speed or altitude in the envelope without special throttle restrictions and without worrying about engine stalls or afterburner blowouts.

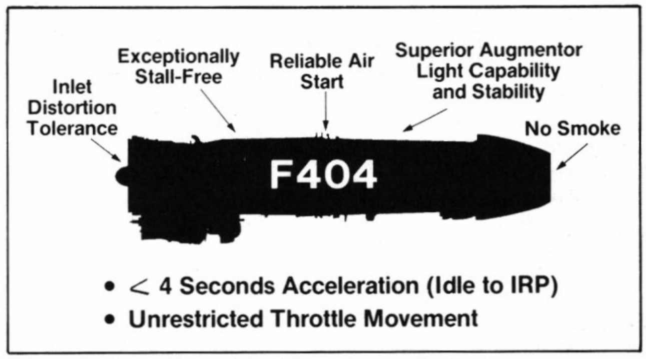

Figure 3. Outstanding Operability Characteristics

And there are additional engine attributes. The F404's advanced technology combustor emits no visible smoke, reducing aircraft visibility and vulnerability.

The low bypass turbofan engine cycle enables the F404-powered F/A-18 and F-20 to achieve supersonic speed without augmentation, while the attendant low specific fuel consumption, both with and without augmentation, improves the long-range mission capability of the aircraft.

The overriding goal of the engine design for operability was to achieve a high performance engine without throttle restrictions. Fighter pilots do not have time to think about the engine while engaged in fighter or attack missions. They need to be able to ask for power and maneuver without looking at their instruments. With the above operability characteristics, the F404 pilot can snap his throttle to any power setting without restrictions--and get the power he needs to win at any point in the flight envelope.

Figure 4. No Throttle Restrictions

III. Simplicity Through Advanced Technology

Because of its heavy impact on overall engine reliability, a major design goal of the F404 was to simplify the engine design by dramatically decreasing the total number of parts while reducing the complexity of the individual components.

Advanced General Electric high speed aerodynamic, mechanical, materials, and cooling technologies reduced the number of engine rotating stages to three in the fan and seven in the compressor, with each rotor driven by only a single turbine stage. Complexity, weight, and spare parts costs are reduced. In addition, the resulting compact rotor system eliminated the need for a supporting frame, sump, and bearing system between the combustor and turbine. Compared to the J79, the advanced technology paid off by doubling the pressure ratio with seven fewer compression stages and by reducing turbine stages by one. Overall, the F404 delivers the same thrust as the J79 with one half the weight, three fourths the length and one third fewer parts.

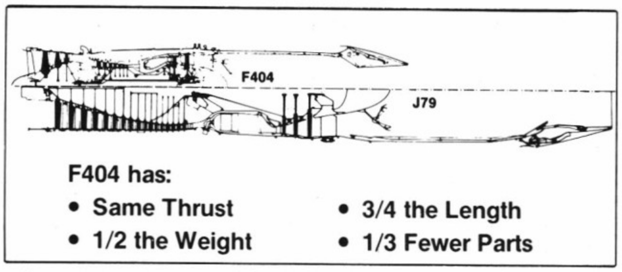

Figure 5. Simplicity - Through Advanced Technology

The selection of a low bypass turbofan cycle permitted a simplified afterburner and afterburner fuel control. The resulting design features a turbojet type flameholder and simplified nozzle with attendant stability and improved operability. In contrast, one F404 competitor requires a multi-stage, multi-flameholder, mixed-flow afterburner design with a more complex control system.

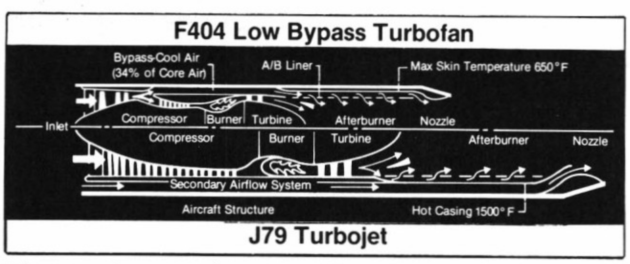

Figure 6. Engine Cooling Comparison - F404 Requires No Secondary Airflow System

The low bypass turbofan cycle also led to the elimination of the extra complexity, weight, cost, and drag penalty associated with the secondary airflow system required to provide adequate cooling of the engine casing, jet nozzle, and aircraft structure in a turbojet engine installation. A turbojet must use relatively hot turbine exhaust gas to cool the afterburner liner and casing internally while the F404 uses relatively low temperature fan bypass air to cool the liner, casing, and jet nozzle, enhancing its inherent growth capability.

A Digital Electronic Control (DEC) under development for the F404 will simplify the design, airframe integration, operational use and maintenance of the F404 control system. F404 digital controls currently have logged more than 500 flight hours during the F-20 flight demonstration program and are soon to begin flight testing on the F/A-18 aircraft. The DEC has evolved from General Electric's advanced digital technology and is built around two multi-layer ceramic modules (MCM)--one the digital processor and one the memory. Programmable Read Only Memories (PROMs) make schedule and logic changes much easier for the designer, allowing greater flexibility in matching the engine's performance characteristics to the particular aircraft application involved.

In addition, backup control schedules can easily be added to the DEC to improve single-engine aircraft reliability. For example, the F-20 digital control performs many engine control functions during normal operation in conjunction with a hydromechanical control. In the event of a hydromechanical component or sensor malfunction, however, the backup control mode in the DEC takes over full authority of engine schedules and can deliver the full range and modulation of engine thrust without throttle restrictions.

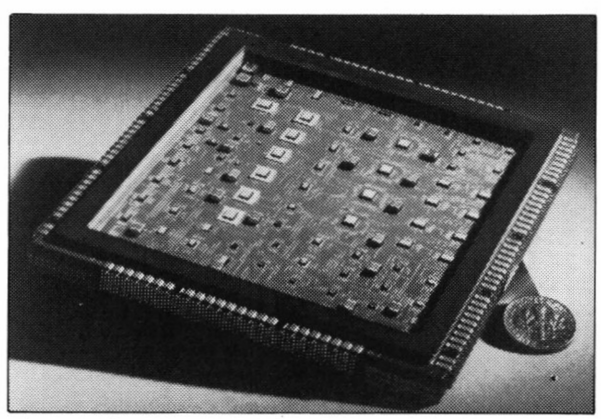

Figure 7. Multi-layer Ceramic Module From F404 Digital Electronic Control

Built-in test features of the DEC constantly monitor electrical control system functions and provide automatic switching to backup modes if necessary. With no throttle restrictions and automatic switching, the pilot's control tasks are minimized, allowing him to concentrate on completing his mission.

IV. Low Acquisition Cost

Low life cycle cost has been an overriding consideration in the evolution of the design and manufacturing processes of the F404. A rigorous design-to-cost process was imposed very early in the program to trade off the ultimate in achievable thrust-to-weight ratio and specific fuel consumption to produce an engine that has excellent performance in combination with low acquisition and operating costs. While the simple design and low parts count of the F404 contribute to inherently lower manufacturing costs, the early interaction of manufacturing and design engineers to develop components with low manufacturing cost made significant contributions. As an example of design to cost, a four-stage fan and two-stage low pressure turbine would have resulted in somewhat better engine performance, but the three-stage fan and single-stage turbine design selected resulted in significant cost benefits.

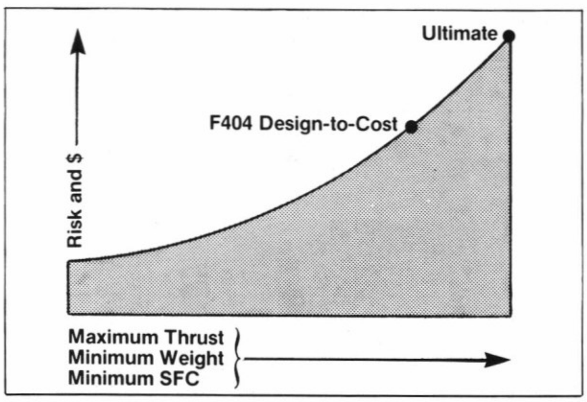

Figure 8. F404 Design to Cost

General Electric continues to drive down engine cost with a multiple-pronged attack. First, a component improvement program continues to develop new component designs which perform their roles as well or better than the original design, but can be manufactured more easily and at lower cost. An example is the fan bypass air duct. Currently, this is a lightweight, chemically milled titanium structure designed to direct fan bypass air to the afterburner and to mount accessories, piping, harnesses and other configuration equipment. A composite duct is now undergoing engine endurance testing prior to production release. The composite outer duct is expected to reduce the cost of manufacturing this part by more than 20%, in addition to reducing duct weight.

GE is also reducing engine costs by the application of advanced manufacturing technologies to achieve cost superiority. The high volume production base makes investment in highly automated, high capacity machining centers cost effective, while management initiatives and incentives are helping drive F404 costs down a steeper cost improvement curve than in prior engine programs.

Thus, the original design to cost program, and ongoing programs to further reduce production costs, have resulted in an advanced technology fighter engine with low acquisition cost.

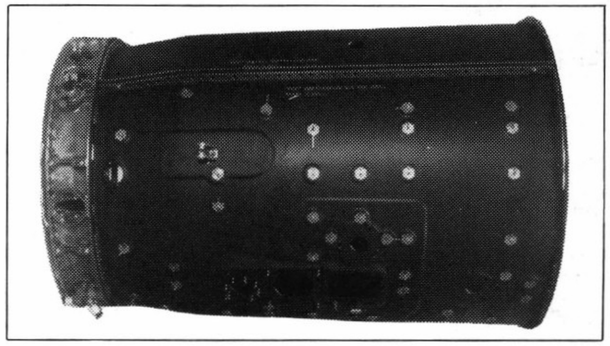

Figure 9. F404 Component Improvement Program-New Composite Fan Bypass Outer Duct

V. "Bottom Line" Measures

Besides low acquisition costs, the other goals of the original program were outstanding durability, reliability, and maintainability, the latter being a measure of how easily and quickly an engine can be repaired. The U.S. Navy placed a high priority on these design characteristics when setting the requirements for the engine development program in order to obtain an engine with low operating cost and high mission readiness. Among these requirements were accelerated testing, reliability tracking, and maintainability demonstrations. Incentive awards were funded to encourage the achievement of reliability and maintainability goals.

GE established a rigorous set of goals to measure and track engine reliability, maintainability and operating costs in operational service. These are called "Bottom Line" measures because of their direct effect on the customer's operating cost budget and ability to perform the intended mission. These measures fall into three categories--operating costs, readiness, and mission completion--as listed below:

- o Operating Costs
  - -Shop Visit Rate - rate at which the engine must be removed from the aircraft and sent to the shop for repair
  - -Line Replaceable Unit Removal Rate - rate at which components, which can be replaced "on wing," require replacement
  - -Maintenance Man-Hours Per Flight Hour
  - -Parts Consumption Costs
  - -Parts Consumption and Labor Costs
- o Readiness
  - -Mean Time Between Maintenance Action - mean time that the engine operates between unscheduled repair
- o Mission Completion
  - -Mission Abort Rate - rate at which a mission is terminated on the ground or in flight because of an engine problem
  - -In-Flight Shutdown Rate - rate at which an engine problem causes the engine to be stopped in flight

Monthly reviews and high management visibility in setting and meeting a very challenging set of goals have resulted in very significant improvements in customer operating costs and readiness over previous generation engines and over other advanced technology engines. F404 progress in achieving these goals has been very encouraging. The F404 earned 98% of the available U.S. Navy incentive award fees for reliability and maintainability following an Accelerated Service Test simulating several years of in-service use. The key goal -- a Shop Visit Rate of less than 2 shop visits per 1,000 engine operating hours -- was met in February 1984. For reference, the J79 has stabilized at about 3.5 shop visits per 1,000 engine hours. The accomplishment of this goal after only 100,000 engine service hours is a very significant achievement for a supersonic fighter engine.

All Causes, Events	J79 Field Status	F404 Maturity Goal	
• Shop Visit Rate per 1,000 EFH	3.12	<2	Goal Met Feb. 1984
• LRU Rate, per 1,000 EFH, Including Engine Removals for Access	3.5	<2	
• MMH, per EFH (Including Depot)	3.19	1.2	
• Ground Test Time, per EFH — Engine Maintenance	0.01	0.01	
• *Parts Consumption Cost, per EFH	$218	$120	
• *Parts Consumption and Labor Costs, per EFH at $36/Man-Hour	$334	$164	
• Engine Holes/Percent	0/0	0/0	
• MTBMA, Hours	93	175	
• Mission Abort Rate, per 1,000 EFH	0.84	<0.5	
• In-Flight Shutdown Rate, per 1,000 EFH for Twin Engine Aircraft	N/A	<0.1	

*1984$

Figure 10. J79 and F404 Bottom Line Measures

VI. Low Life Cycle Costs

Low acquisition and operating costs result in low life cycle costs -- the total cost of ownership of the engine over its lifetime. As an example, with a fleet of 100 single engine aircraft, flying 24 hours per month, over a representative 20 year period, an operating country is expected to save nearly $700M by using the F404, versus a competitor high technology engine. This is driven by low initial acquisition costs, low spare engine and spare parts requirements due to high engine reliability and maintainability, and low fuel consumption.

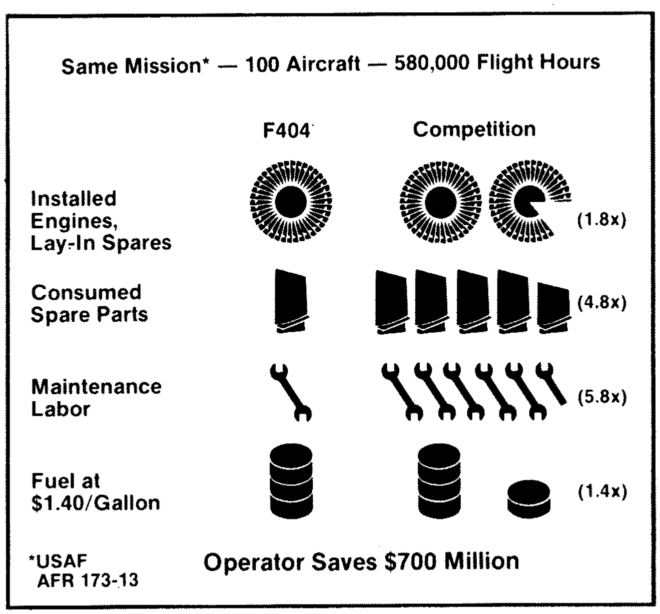

Figure 11. F404 20-year Engine Life Cycle Cost

VII. Growth

General Electric has established a long range growth program for the F404. Augmented engines are under development to meet customer needs from 16,000 to 22,000 pounds thrust and non-augmented engines will be available from 10,500 to 14,000 pounds thrust. Besides meeting the requirements for higher performance versions of existing F404 aircraft, these growth engines will meet the needs of aircraft planned for production through the 1990s.

Each step of the F404 growth program has defined milestones incorporating proven advanced technology, carefully balanced to achieve increased performance while maintaining the engine's outstanding reliability, maintainability and durability.

The following methods are being used to achieve the defined growth steps:

- Increased fan and core airflow
- Increased turbine inlet temperature using advanced materials and cooling techniques
- Component improvement and redesign for better efficiency
- "Tuning" the engine to match the aircraft mission
- Advanced control design

The first growth step, the -100 engine for the F-20, integrated a digital electronic control system and single-engine dependability features with a higher turbine inlet temperature during augmentor use to raise maximum thrust. In addition, the control system was "tuned" to improve engine performance at envelope points as specified by the customer to better match the aircraft mission requirements. Finally, component improvements were incorporated in the form of a more reliable gear fuel pump and an improved turbine blade material.

The second growth engine, designated the F404/RM12, is in the 18,000 pound thrust class and is now under development for the Swedish JAS 39 aircraft. This version includes single engine features with a digital control, a redesigned fan module to increase fan flow and improve birdstrike tolerance, increased turbine inlet temperature with improved high temperature materials and "tuning" to the Swedish mission. The first full engine is scheduled for test this summer.

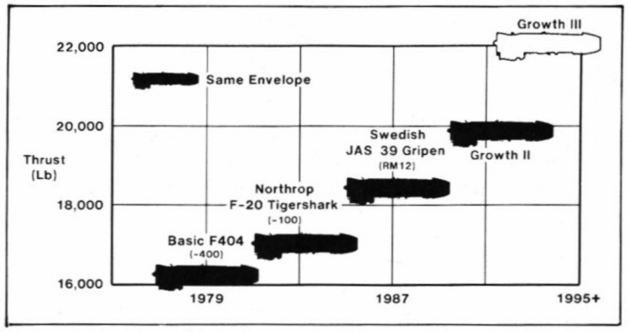

Figure 12. F404 Growth Road Map

The next growth step, called Growth II, will increase thrust to the 20,000 pound thrust class with a redesigned, high flow compressor, improved efficiency components and a further increase in turbine inlet temperature. Component testing is underway and a full core engine test is scheduled for this year. An afterburning version will run in 1985. The following step, Growth III, is planned for the 22,000 pound thrust class with a larger, advanced fan and higher turbine temperatures.

The F404's growth philosophy is to carefully balance improved performance with reliable operation. High parts commonality between growth and current engines will minimize risk, reduce cost impact and ensure the continuation of the engine's outstanding durability and reliability. Planning for growth in this systematic, step-by-step manner, allows General Electric management to define the required advanced technology in advance, so that it may be developed and proven for the future.

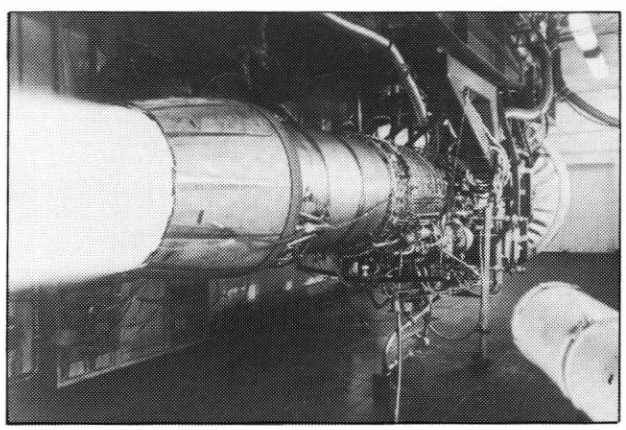

Figure 13. Outstanding Durability and Reliability are Ensured Through Exhaustive F404 Factory Testing.

General Electric advanced technology and our system for planning and implementing that technology are largely a result of setting challenging goals to exceed our customers' expectations. Today, meeting those goals and exceeding those expectations have allowed the F404 to set new standards for fighter engines in operability, reliability, durability and low life cycle costs. By a continuous process of improvement and growth, we at General Electric fully expect the F404 to continue to set standards through the 1990s.

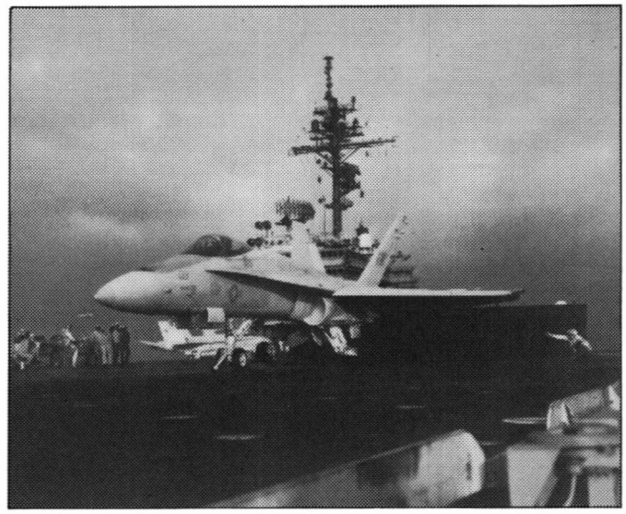

Figure 14. In-Service the F404 is Exceeding Customer Expectations.