F-15 Flight Test Experience with the F100 Engine

Donald B. Hamer*
McDonnell Douglas Aircraft Company, St. Louis, Mo.
and
Gilbert B. Ballard†
Pratt & Whitney Aircraft, West Palm Beach, Fla.

The F-15 aircraft, with P&WA F100 engines, has completed over 2 years of flight test development. Development and demonstration of the propulsion system have been significant parts of this program. In this paper the MCAIR/P&WA team approach to flight development of the F100 engine is discussed. Propulsion system instrumentation, data acquisition, and reduction are described. Up-to-date flight test results of F100 engine operation in the F-15 are given in the areas of steady-state and transient performance, airstarting, and inlet/engine compatability.

I. Introduction

THE F100 engine, developed for the F-15 aircraft, is an advanced, lightweight, high-thrust, turbofan engine. It represents a significant advance in engine design over current operational engines. Although most newly designed engines are flown for the first time in test bed aircraft, the F100 made its initial flight in the F-15. This ambitious feat of flying a new engine and a new airplane together for the first time was made possible by extensive ground test development and qualification prior to first flight. Engine development continued as the flight test program revealed engine problems peculiar to in-flight operations. Solutions to these problems were identified and corrective changes have been incorporated into the F100.

The development program required close working arrangements between MCAIR and P&WA to perform an adequate, efficient, and timely flight test program. The test aircraft and development engines were extensively instrumented to acquire the data necessary to support both the engines and airframe propulsion system development programs.

Some of the most significant aspects of the flight test program are reviewed and the MCAIR and P&WA working relationship is described. The aircraft, engines, and instrumentation employed are discussed; and some of the most pertinent results from the F100 engine flight development are presented.

II. MCAIR and P&WA Integrated Flight Test Program

One aircraft, F-15 No. 2, was assigned for both engine and airframe inlet development. To implement the program, MCAIR and P&WA teams were established both at St. Louis and Edwards Air Force Base (EAFB). Engine and airframe instrumentation requirements were mutually established. A common data acquisition, reduction, and distribution system was agreed upon by MCAIR and P&WA. All data was acquired and reduced by MCAIR flight test engineering. Data tabulations, time history, and parametric plots were distributed to MCAIR and P&WA engineers at St. Louis, EAFB, and West Palm Beach, Fla.

Presented as Paper 74-1162 at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974; submitted January 6, 1975; revision received March 24, 1975.

Index categories: Aircraft Testing (including Component Wind Tunnel Testing); Airbreathing Engine Testing; Airbreathing Propulsion, Subsonic and Supersonic.

*Senior Project Propulsion Engineer, Propulsion Department. Member AIAA.

†Manager, Aircraft/Engine Integration.

III. Description of Test Vehicle and Equipment

The F-15 aircraft used in this program is a nominal production model modified only by inclusion of special flight test instrumentation. Several F100 engine versions and a number of modifications were evaluated in the flight test program. Descriptions of the aircraft, the engine configurations evaluated, instrumentation, and the data acquision system are presented herewith.

Aircraft

The F-15 is a high, fixed wing aircraft with two-dimensional overhead ramp inlets located at the wing roots, as shown in Fig. 1. Twin vertical tails are attached to twin booms that extend past the engine nozzles, which are blended into the aft fuselage and boom contours. Conventional stabilators are attached to the outside of the booms. A 20-mm gun is located in the right-hand wing root, aft of the engine air inlet. Sparrow AIM-7F missiles are ejector launched from the lower corners of the fuselage and Sidewinder AIM-9L missiles are rail launched from the inboard wing pylons. The F-15 is powered by two P&WA F100 engines that produce 23,840 lb of thrust each at sea level static conditions.

The F-15 air inlet provides each engine with the required airflow over a speed range of zero to a Mach number in excess of 2.3. As shown in Fig. 1, the external compression inlet has three, two-dimensional, movable ramps. A unique design feature is the capability of rotating, in-flight, the entire upper cowl and compression ramp system of the inlet. This provides a variable capture area and aligns the inlet with the entering airflow over a wide range of airplane angles of attack and Mach numbers. Therefore, minimum inlet additive drag, maximum total pressure recovery, and low airflow distortion at the engine face are achieved during F-15 maneuvers, as well as during level flight.

The movable inlet ramps and air bypass door are controlled by an electronic computer and hydraulically operated actuators. The computer receives signals from sensors that measure flowfield conditions ahead of and within the inlet and provides signals to the actuators that set the ramps and bypass door to their proper position. Three actuators are used for inlet operation. The inlet control system arrangement is shown in Fig. 2.

Engine

The P&WA F100 turbofan is a twin-spool, high pressure ratio, lightweight engine with a mixed-flow augmentor and variable-area convergent-divergent exhaust nozzle. As shown in Fig. 3, the fan module has three stages and the compressor has 10 stages. The combustor is an annular design. The fan and compressor are each driven by dual turbine stages. Fan and engine core airflows are mixed in the augmentor prior to after-burning. A variable-area convergent-divergent nozzle provides near-optimum flow expansion over a wide range of flight Mach numbers.

Engine control is provided by a combined hydromechanical and electric system. The hydromechanical unit, called the unified fuel control (UFC), serves as the primary device that controls the fuel delivered to the main engine combustor and the augmentor as a function of throttle setting. It also controls the nozzle area, and the variable vanes in the high compressor. The electronic engine control (EEC) is used for trimming to optimum performance, precise airflow control, applying override functions to limit maximum speeds and turbine inlet temperatures, and for scheduling the guide vanes at the fan inlet. A functional schematic of the control system is shown in Fig. 3.

During the flight development program, a number of engine hardware changes were evaluated. The engines tested can generally be grouped into the following designations:

YF100(I): The first configuration to be flight tested, qualified under preliminary flight rating tests (PFRT).

YF100(II): An improved YF100 with various changes (Sec. IV) within the engine and its control.

F100: The first production configuration to be flight tested after military qualification tests (MQT).

F100 Improved: An improved F100 with various changes (Sec. IV) within the engine and its control.

Instrumentation

The propulsion development F-15 aircraft, No. 2, is equipped with sufficient instrumentation to establish propulsion system performance characteristics. Both steady-state and high-response instrumentation are utilized. A total of 353 measurement sensors is provided within the test engines, on the exhaust nozzle and aircraft aft fuselage surfaces, and in the left-hand aircraft inlet. Measurements are made within the engine to evaluate its performance in flight and diagnose problems that occur. The aircraft inlet system is instrumented to indicate the physical position of all variable geometry components and to provide pressure readings in all the key areas necessary to evaluate flow conditions. In addition, sensors for measuring Mach number, angle of attack, and temperature used for the air inlet controller are provided. A 48-probe total pressure rake[1] is mounted at the F100 fan face to measure the steady-state total pressure recovery and time variant distortion characteristics of airflow entering the engine. High-frequency-response transducers capable of measuring pressure fluctuations up to 1000 Hz are used. Any airflow distortion pattern that may form and dissipate within the time of one fan revolution, approximately 200 hz, is recorded.

Exhaust nozzle and aft fuselage surface instrumentation consists of static pressures on both nozzles, on the aircraft fairings between the outside of the nozzles, and on the aircraft nacelles ahead of the nozzles, as shown in Fig. 4. These pressure measurements are used to determine aft-end flow quality and nozzle external loading.

Data Acquision System

The F-15 integrated data system is shown schematically in Fig. 5. This system records and processes the large number of measurands described earlier. It consists of an airborne data system, an instrumentation ground equipment set, and a data processing system.

The airborne data system includes a 14-track magnetic tape recorder, time and frequency division multiplex systems. The multiplex units are remotely located through the aircraft and process individual measurand data from nearby sensors. The sensor signals are converted from analog to digital form, multiplexed, and then transmitted to a central unit that processes the signals and inputs them onto the 14-track tape recorder. In addition to this primary airborne data acquisition system, a UHF telemetry system for real-time air-to-ground data monitoring is used.

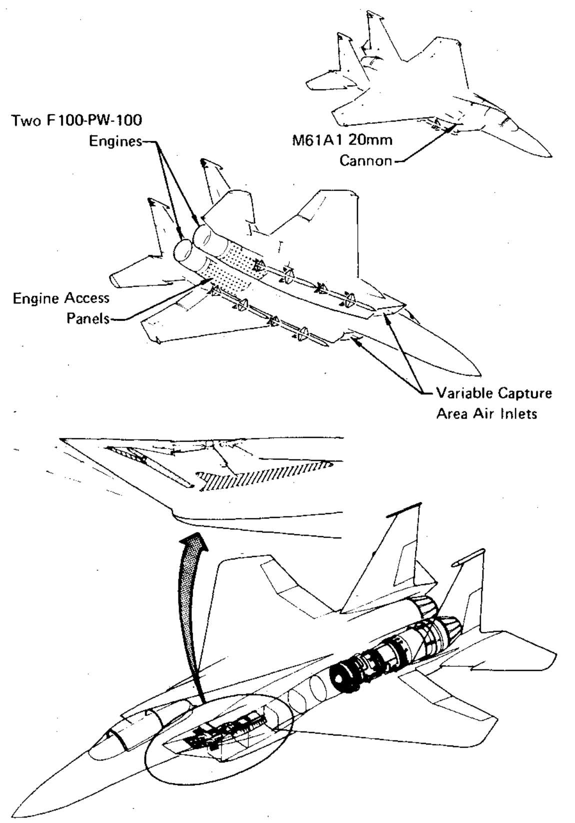

Fig. 1 F-15 Eagle propulsion system.

The instrumentation ground equipment system set is designed to interface with the airborne data system. It provides for instrumentation checkout, equipment calibration, and troubleshooting.

The data processing system is designed to provide final decision data within 24 hr of flight and final data presentations simultaneously at St. Louis and EAFB. Rapid data processing is achieved through the use of an IBM 370-145 digital computer located in St. Louis and directly connected with EAFB by means of a high-speed telephone transmission line.

IV. Flight Results

During the first two years of the F-15 flight test program, the aircraft designated for both engine and airframe propulsion system development completed over 325 flight-hr of testing. The aircraft achieved an average fly rate of 15 flights per month. Contributing to F100 flight development are the total F-15 program flights, which now exceed 2700 at a fly rate that averages 130 flights per month. The total F100 engine flight time over the test period exceeds 5750 hrs, involving 87 different engines of the 4 basic configurations previously discussed. The ease of F100 installation in the F-15 has contributed to this successful experience. Engine removal and replacement can be accomplished in less than 20 minutes.

The F100 powered F-15 has been operated at speeds in excess of Mach 2.3, altitudes exceeding 60,000 ft, and load factors greater than 7 *g*. The F-15 speed-altitude and load factor flight experience is summarized in Table 1.

The F100 engine development has concentrated in five areas. The problems defined and their resolutions are discussed under the following subjects: engine acceleration from idle, thrust response, augmentor lighting, airstarting, and steady-state performance.

Engine Acceleration from Idle

Responsive engine acceleration and thrust output during throttle advancement from idle is a very critical factor in high-

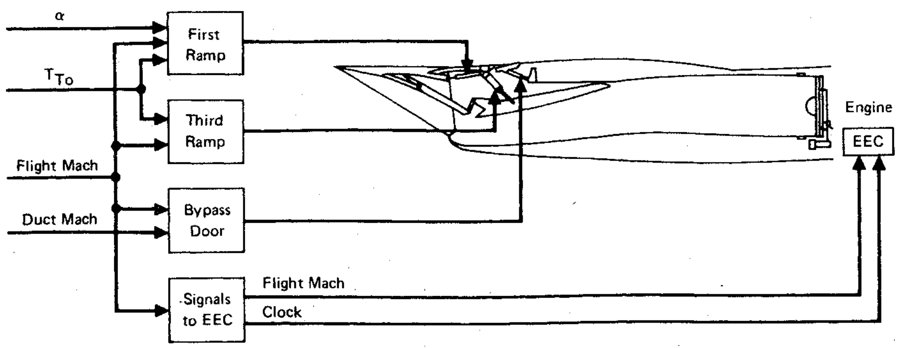

Fig. 2 F-15 inlet control.

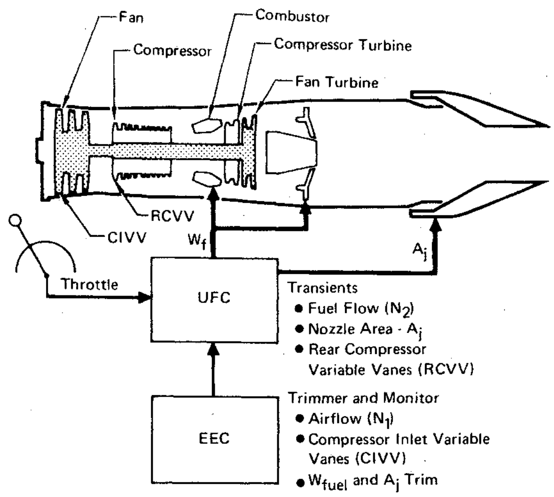

Fig. 3 F100 engine and controls.

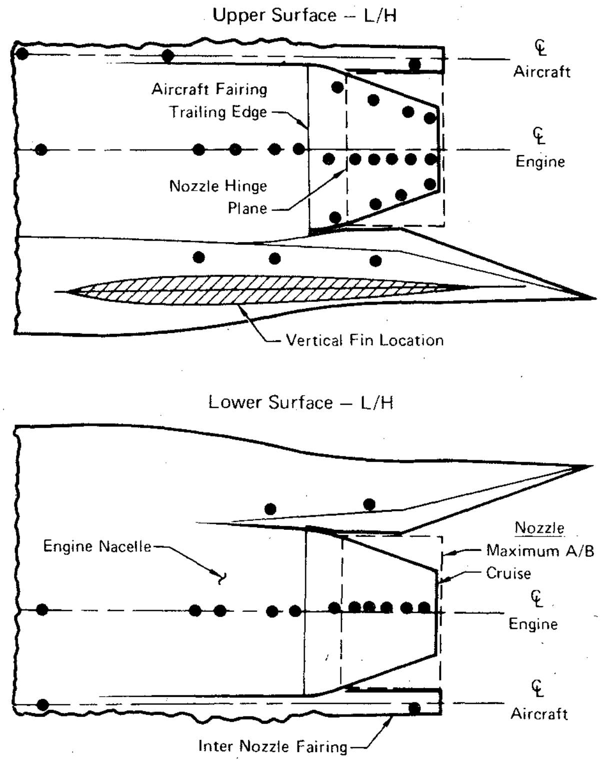

Fig. 4 Aircraft no. 2 aft-end instrumentation; • static pressure tap.

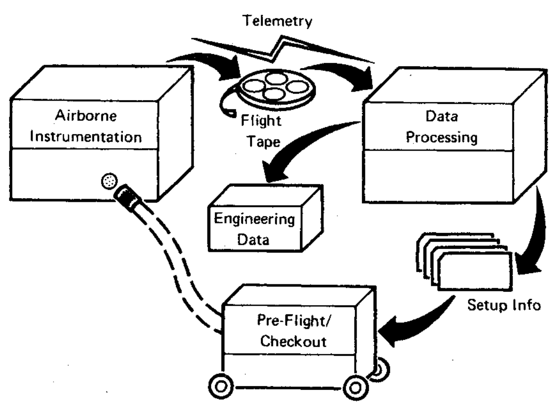

Fig. 5 F-15 integrated data system.

performance aircraft. Initial F-15 flight testing in the upper-left portion of the speed-altitude envelope with the YF100 prototype engine revealed an operational anomaly when the engine was accelerated from idle power settings. In this region rapid transients generally initiated engine stall. An investigation determined that idle engine speed commanded by the engine control, at higher altitude conditions, was near 68% of maximum design compressor speed instead of the design objective of 75%. At this low idle speed the compressor surge margin is insufficient to accommodate fast engine acceleration schedules as illustrated in Fig. 6. Two approaches to the problem were considered: 1) rescheduling the variable vanes at the compressor entrance to a more cambered position, and 2) increasing the engine idle speeds at altitude operating conditions. Rescheduling the variable vanes increases the compressor surge margin by raising the surge line, and allows more margin for acceleration transients, as shown in Fig. 7. This provided some improvement but did not completely eliminate the problem. The complete solution involved a choice between increased idle speeds at altitude, where more surge margin is available, or decreased engine acceleration from idle power settings. Increased idle speed was selected as the preferred approach because the resulting higher idle thrust at altitude was determined to have no adverse effects on flight operation and to match the aircraft requirement for engine airbleed. Production F100 engines now flying with the revised control schedule are completely free of this problem as shown in Fig. 8.

Table 1 F-15 flight experience

Altitude ft	Speed	Maximum load factor, g
Sea level-20,000	0-over 1.6 Mach	Less than -2g to greater than +7
20,000-40,000	Less than 50 knots-over 2.3 Mach	Less than -2 g to greater than +7
40,000-60,000	Less than 150 knots -over 2.3 Mach	Greater than +6
Above 60,000	Supersonic	

Thrust Response

Fast thrust response to engine throttle movement is a critical need for combat maneuvering, formation flying, in-

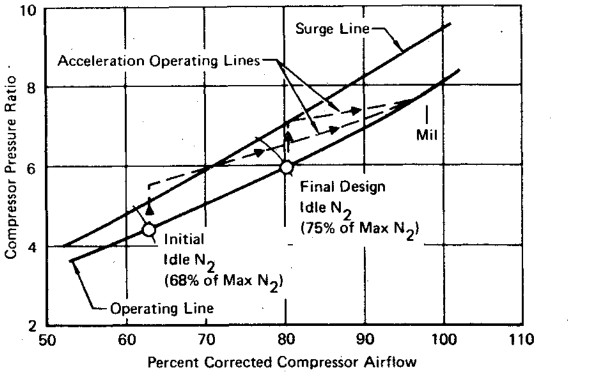

Fig. 6 Compressor map showing acceleration from idle compressor stall problem (M_0/Alt = 0.6/40K).

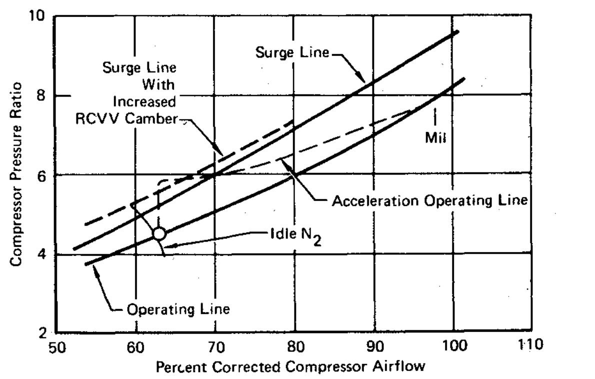

Fig. 7 Compressor map showing surge margin increased with RCVV camber.

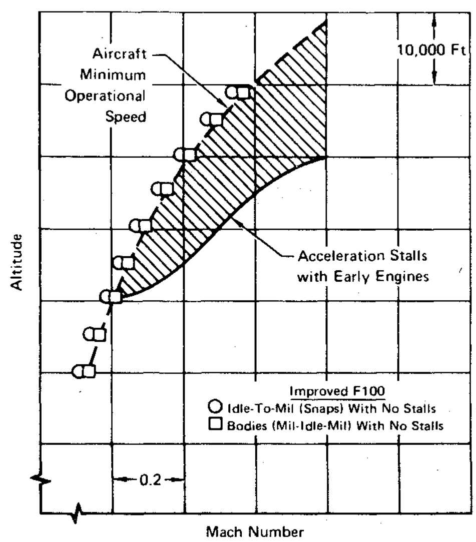

Fig. 8 Acceleration from idle flight experience.

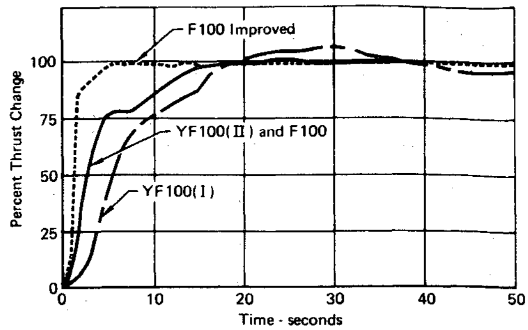

Fig. 9 Percent thrust change vs time (see level static conditions).

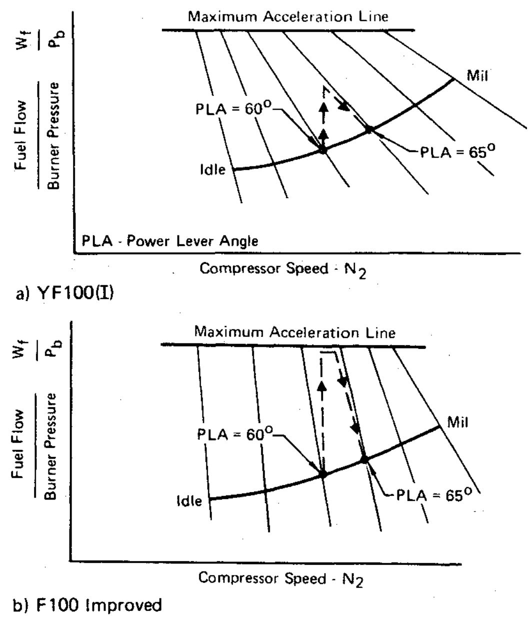

Fig. 10 Slow thrust response.

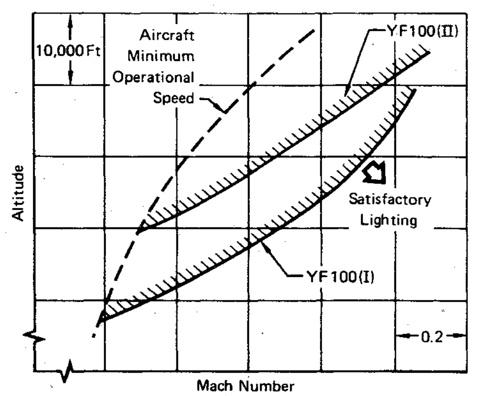

Fig. 11 Augmentor lighting (mil-to-max snaps).

flight refueling, and good aircraft handling. Early flight testing with the YF100 prototype engines revealed that thrust response to small throttle movements was inadequate. During formation flying and in-flight refueling operations MCAIR pilots found it difficult to achieve and maintain precise positions because of the slow thrust response. Thrust increase with time after throttle advancement for these early engines is shown in Fig. 9. The relatively low thrust-time slope characteristic exhibited was unsatisfactory. The problem was found to be caused by low slopes of the speed governing line scheduled in the engine fuel control. The scheduled fuel flow vs compressor speed for YF100 engines is shown in Fig. 10a. It can be seen that, for small power level angle (PLA) changes, maximum acceleration fuel flows were not commanded because of the low slope of the speed-governing schedules. The correction made in the control schedule was to increase these slopes so full acceleration fuel-flow levels would be commanded for small PLA movements, as shown in Fig. 10b. This control schedule change was made incrementally and flight tested at each step. This procedure was necessary, since an increase in acceleration fuel flow results in reduced compressor surge margin during a transient, and engine stalls could occur if the acceleration schedules are increased too much. The progression of thrust response change is shown in Fig. 9. The final F100 engine control schedule improved the thrust response to a level satisfactory for both formation flying and in-flight refueling operations.

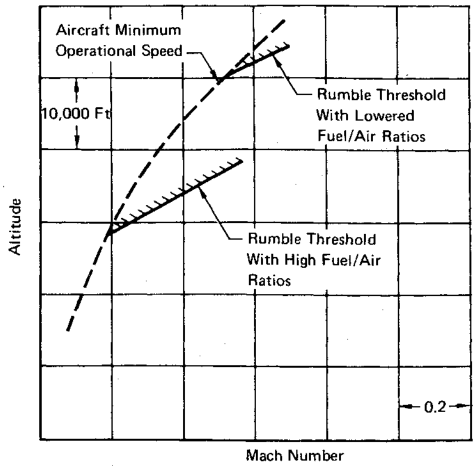

Fig. 12 Augmentor rumble—YF100(II).

Augmentor Lighting

Achievement of good augmentor lighting and operational characteristics in the high-altitude, low-speed corner of the flight envelope has required flight test development. Turbofan engine augmentor lighting creates pressure pulses that feed upstream through the open flow path to the fan. Fast lighting produces pulses of sufficient magnitude to stall the fan, while slow lighting to maintain small amplitude pulses increases thrust reponse time. A balanced design divides the lighting process in small enough increments to keep pressure pulses low while achieving full augmentation within the required time (4 sec for F100), and provides reliable lighting and stable burning in the very low-pressure and low-temperature corner of the flight envelope. In addition, the structural integrity and durability of the augmentor fuel sprayrings, flameholder, tailpipe, liner, and nozzle flaps must be maintained.

Initial F-15 flight tests with prototype YF100 engines revealed augmentor operational deficiencies. Engine stalls, augmentor flame blowouts and unstable burning occurred during augmentor lighting in the upper left-hand corner of the flight envelope. P&W and MCAIR conducted an extensive combined ground test and flight test program to solve this problem.

The initial flight tests with the YF100(I) engines revealed two problems: 1) fan stall caused by pressure pulses during augmentor lighting, and 2) flow instability (rumble) at or near maximum augmentor settings. To solve the first problem, the fan design was modified to provide greater tolerance to augmentor pressure pulses. In addition, the fuel supply system was redesigned to reduce the rate of fuel discharge into the augmentor. The second problem was traced to excessive fuel/air ratio occurring at the maximum power setting. The total fuel quantity supplied at higher altitudes was found to be above design requirements, and this was corrected. These modifications were incorporated in the YF100(II) engines. Flight testing with the YF100(II) engine demonstrated significant improvements in the flight envelope for satisfactory augmentor lighting and stable flow characteristics, as shown in Figs. 11 and 12.

Additional improvements also were incorporated in the production F100 engines to improve the augmentor lighting characteristics even more. Design improvements were made to the controls, sprayrings, flameholder, and fan. The controls were modified to a) reduce fuel control gains to eliminate variable nozzle instability during augmentor lighting, b) schedule nozzle area as a function of altitude, c) control fuel/air ratios in the augmentor more precisely, d) improve fuel distribution to the sprayrings, and e) compensate control schedules for Reynolds number.

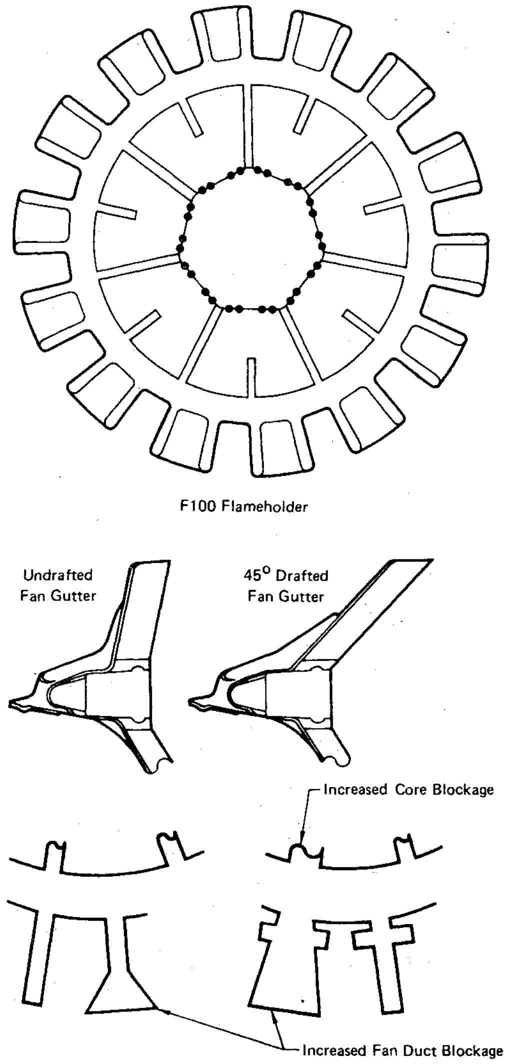

Fig. 13 F100 flameholder development.

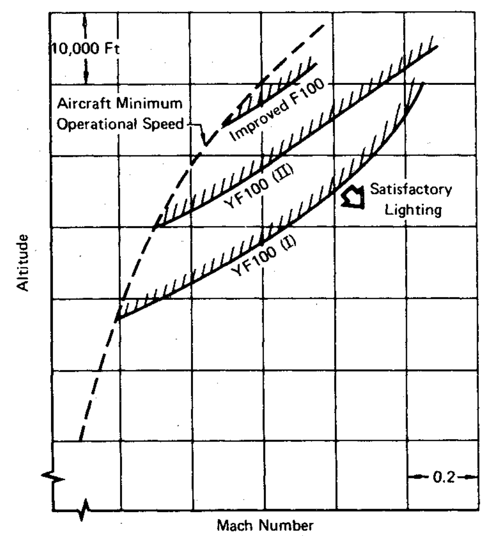

Fig. 14 Augmentor lighting (mil-to-max snaps).

The sprayring hardware was tailored to inject fuel at different rates across the augmentor. This was done to match fuel to airflow quality variations cased by upstream obstructions so nearly constant fuel/air ratios are maintained. The flameholder configuration was developed to provide the best possible flame retention and to eliminate rumble and blowouts. The flameholder design details are shown in Fig.

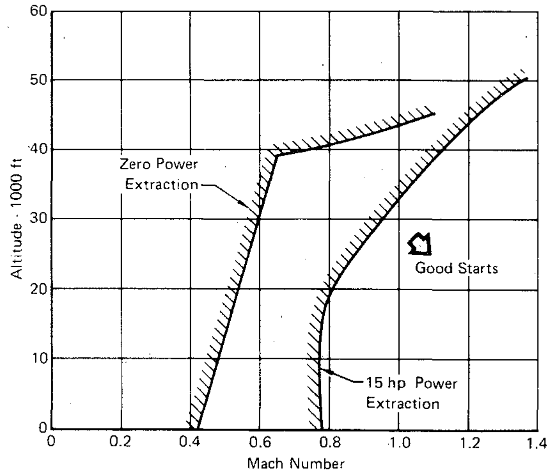

Fig. 15 **Ground tests of F100 airstart capability (windmilling), showing effect of horsepower extraction.**

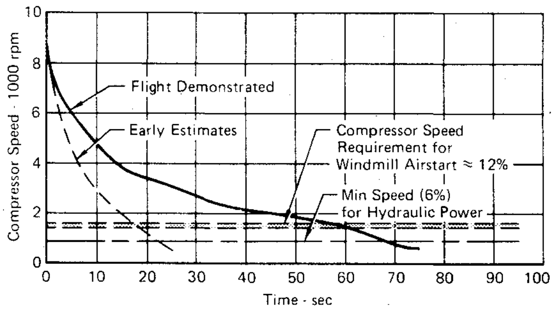

Fig. 16 **F100 spooldown time.**

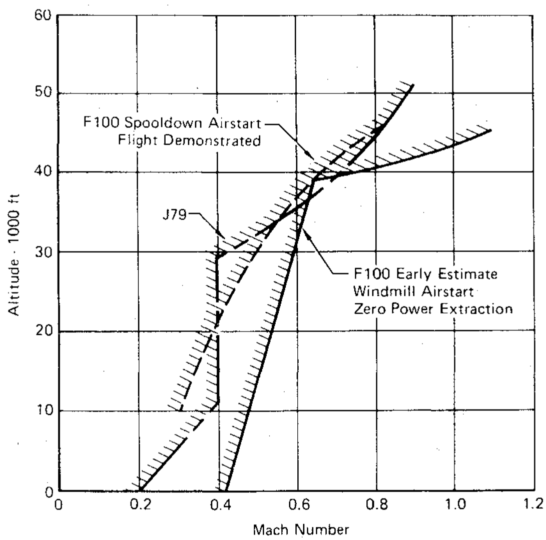

Fig. 17 **F100 airstart comparison.**

13. A design change was made to the fan to increase fan stall margin. This made the engine more tolerant to pressure pulses created during augmentor lighting. The demonstrated performance of the improved F100 is shown in Fig. 14. Further improvements to the augmentor are being incorporated, and satisfactory augmentor lighting to minimum aircraft operational speeds is expected to be achieved prior to delivery of F-15 aircraft to the using Air Force Commands.

Airstarting

In-flight engine start capability is required at low aircraft flight speeds and high altitude. This provides the pilot with the opportunity to execute an engine restart after the loss of

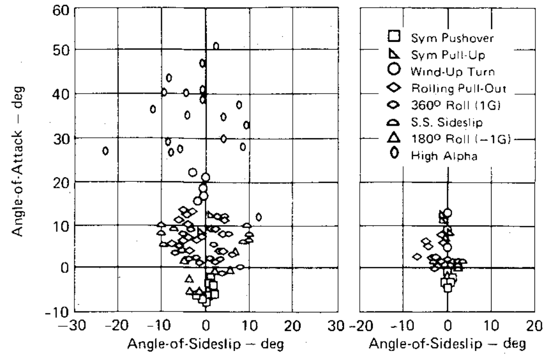

Fig. 18 **Angle-of attack/sideslip flight experience: (left) subsonic, (right) supersonic.**

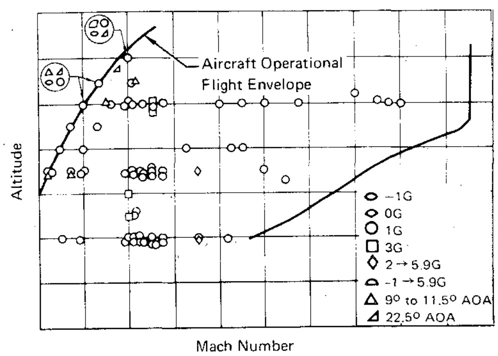

Fig. 19 **F-15 20-mm gunfire flight experience (no engine anomalies).**

an engine and still maintain sufficient altitude for safe operation of the aircraft. Predictions of F100 airstarting capability made by P&WA and MCAIR prior to flight testing indicated a potential problem. Ground tests and analytical estimates showed the F100 airstart capability to be sensitive to the amount of mechanical power being extracted from the engine. The ground test demonstrated airstart capability with no power extraction was very good, as shown in Fig. 15. However, when approximately 15 hp was extracted to provide minimum electrical and hydraulic power needed for F-15 flight control, the airstart capability deteriorated. During steady-state windmilling after the compressor has slowed down, power extraction affects airstart capability adversely. On the other hand, when the compressor is slowing down from higher operating speeds, power extraction is relatively insignificant.

Early flight testing of F100 airstarting capabilities revealed two unpredicted characteristics that provided a good solution to the anticipated airstart problem. First, the F100 engine primary combustor does not flame out dur to ambient conditions, maneuvers, or weapon fire disturbances. To date, not a single in-flight flameout of the F100 engine has occurred in the F-15 flight program. Secondly, the rate of compressor speed decay from an operating power setting to windmilling is much slower than had been predicted, as shown in Fig. 16. Before windmill speeds are reached,60 sec or more elapse. The slow compressor speed decay rate gives the pilot ample time to effect an engine restart while compressor speeds are relatively high. As shown in Fig. 17, starting characteristics at these higher compressor speeds are significantly better than the predicted characteristics for windmilling speeds, producing a satisfactory start envelope.

Steady-State Performance

Development to improve steady-state operation has generally not been necessary in the F-15 flight program. The

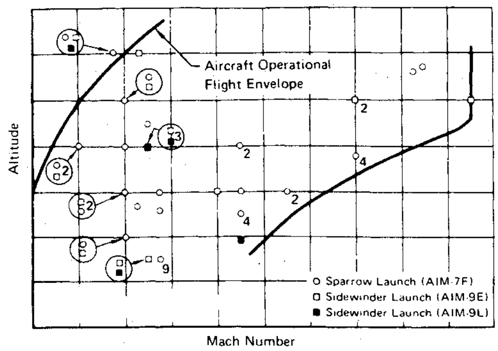

Fig. 20 F-15 missile launch flight experience. Sidewinder and Sparrow missiles. Launches from -0.5 to 7.3g (no engine anomalies) (subscript denotes number of launches).

F100 engine has performed properly and dependably throughout the F-15 flight envelope. Engine operation during takeoff and landing operations has been routinely normal since the first flight of the F-15. Some isolated incidents of engine control function failures occurred in the course of over two years of testing on all F-15 aircraft. The F100 engine has performed normally in the F-15 speed-altitude and load factor experience envelopes shown in Table 1.

No inlet-engine compatibility problems have occurred during the F-15 flight program. No inlet distortion induced engine stalls have been experienced during aircraft operation, including the most adverse operational maneuvers. In addition to the speed-altitude experience shown in Table 1, the angles of attack and sideslip angles shown in Fig. 18 have been flown. Unrestricted throttle movements were allowed during this experience except as limited by earlier augmentor lighting constraints.

The F100 engines have had no occurrence of stalls or other anomalies during gun or missile firings. The F-15 gun fire and missile firing experience is shown in Figs. 19 and 20.

V. Conclusions

The F100 engine has provided the necessary operational reliability and performance to make the F-15 flight development program one of the most successful in MCAIR's history of fighter aircraft development. Part of this success is attributed to close cooperation and a close team working relationship between engine and airframe manufacturer personnel. A well-developed and planned instrumentation, data acquisition, and reduction system for the propulsion system development aircraft provides the data needed for complete and timely evaluations. The F-15 flight test program directed at F100 engine development has provided the data needed to identify improvements for engine transient operation. These improvements have been incorporated in the final production engines. The good steady-state operation of the F100 engine, together with this improved transient performance, makes the F100 an excellent fighter engine.

Reference

[1] Farr, A. P. and Schumacher, G. A., "System for Evaluation of F-15 Inlet Dynamic Distortion," *AIAA Progress in Astronautics and Aeronautics: Instrumentation for Airbreathing Propulsion,* Vol. 34, edited by A. E. Fuhs, MIT Press, Cambridge, Mass, 1974, pp. 59-76.