FLIGHT RESEARCH USING F100 ENGINE P680063
IN THE NASA F-15 AIRPLANE

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ABSTRACT

The value of flight research in developing and evaluating gas turbine engines is high. NASA Dryden Flight Research Center has been conducting flight research on propulsion systems for many years. The F100 engine has been tested in the NASA F-15 research airplane in the last three decades. One engine in particular, S/N P680063, has been used for the entire program and has been flown in many pioneering propulsion flight research activities. Included are detailed flight-to-ground facility tests; tests of the first production digital engine control system, the first active stall margin control system, the first performance-seeking control system; and the first use of computer-controlled engine thrust for emergency flight control. The flight research has been supplemented with altitude facility tests at key times. This paper presents a review of the tests of engine P680063, the F-15 airplanes in which it flew, and the role of the flight test in maturing propulsion technology.

NOMENCLATURE

ADECS	advanced engine control system
AEDC	Arnold Engineering Development Center, Tullahoma, Tenn. (USAF)
COMDEV	Computing Devices of Canada
DEEC	digital electronic engine control
EMD	engine model derivative
FDA	fault detection and accommodation
HIDEC	highly integrated digital electronic control
PCA	propulsion-controlled aircraft
PSC	performance-seeking control
PSL	Propulsion System Laboratory (NASA Lewis)

INTRODUCTION

The value of flight research in developing and evaluating gas turbine engines is very high (Burcham and Ray, 1987). No matter how complete or thorough a ground test series may be, there are often surprises once a new engine takes to the air. NASA Dryden Flight Research Center has been conducting flight research on propulsion systems for many years. The F100 engine has been tested in the NASA F-15 research airplane over the last three decades.

In the early 1970's, the U. S. Air Force began tests of the F100 series afterburning turbofan engine in the F-15 airplane. The F100 represented the first of a new class of high-thrust-to-weight engines. Extensive ground tests had been conducted, but initial flight tests on the F100(1) engines revealed the usual problems with new engines. An improved F100 engine model, called the F100(2), was produced, with serial numbers (S/N) P680050–P680084. One of these was F100 engine S/N P680063. This engine has since been through a long and, perhaps, unique history. Engine P680063 has flown in four major configurations and has been used for several flight research programs—for NASA, NASA/USAF, and NASA/USAF/commercial industry programs. During these tests, major improvements in engine technology have been developed or demonstrated. These improvements included the detailed comparison of flight-to-ground facility tests, the first production digital electronic engine control (DEEC) system, the first active stall margin control system, the first performance-seeking control (PSC) system, and the first use of computer-controlled thrust for emergency flight control. Integrated with the flight tests were ground and altitude facility tests, providing a good balance between the capabilities of ground and flight test.

This paper will present the history of engine P680063 and the NASA F-15 research airplane. Beginning with initial tests in the new F-15 airplane, this paper will cover the four changes in configuration just listed. Discussions will cover the flight evaluation of new technologies, integration, performance optimization, and propulsive flight control.

F100 ENGINE DESCRIPTION

The F100 engine (fig. 1) is a two-spool, low-bypass-ratio-augmented turbofan engine, built by Pratt & Whitney, West Palm

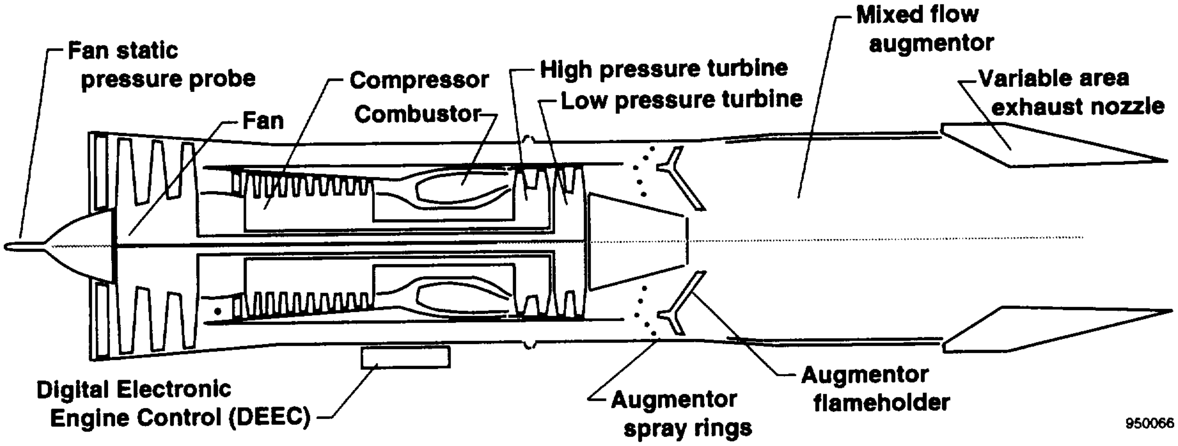

FIG. 1 SECTION VIEW OF THE F100 ENGINE.

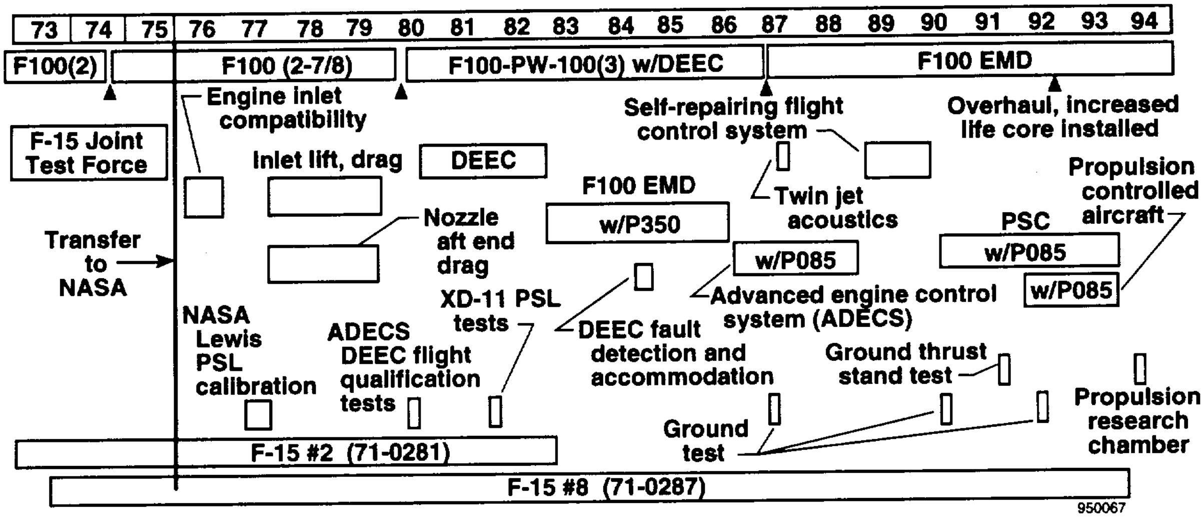

FIG. 2 ENGINE P680063 TESTS AND FLIGHT RESEARCH IN THE NASA F-15 AIRPLANES

Beach, Florida. This engine consists of a 3-stage fan, 10-stage compressor, annular combustor, 2-stage high-pressure turbine, and 2-stage low-pressure turbine. A mixed-flow augmentor exhausts through a variable-area balanced beam nozzle.[1]

DESCRIPTION OF F-15 AIRPLANE

The F-15 airplane is a high-performance, air-superiority fighter airplane with a maximum Mach-number capability of 2.5. The F-15, manufactured by McDonnell Douglas Aerospace, St. Louis, Missouri, has a high wing and twin vertical tails. The propulsion system is highly integrated into the fuselage; thrust is provided by two F100 afterburning turbofan engines mounted close to the centerline in the aft fuselage.

HISTORY

Figure 2 illustrates the history of engine P680063. Engine P680063 was manufactured in 1972 as an F100-PW-100(2) (called arab 2), and it was flown many times in the F-15 USAF Combined Test Force flight evaluation.

Configuration Changes

F100-PW-100(2-7/8) Configuration. In 1973, fan and control system improvements for the F100 were ready, and engine P680063 was one of four engines rebuilt with this fan (bulged inner diameter) and control system in 1974; these engines were called "F100 two-and-seven-eighths." These engines were flown in the

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[1] Bushman, M., and Nobbs, S., 1994, "F100 Engine Description," F-15 HIDEC Electronic Conference, Sept. 12–30, 1994, available as an archived workshop accessible through the Dryden WWW home page and as a compact disk. The URL address through the NASA Dryden home page is http://www.dfrf.nasa.gov/dryden.html.

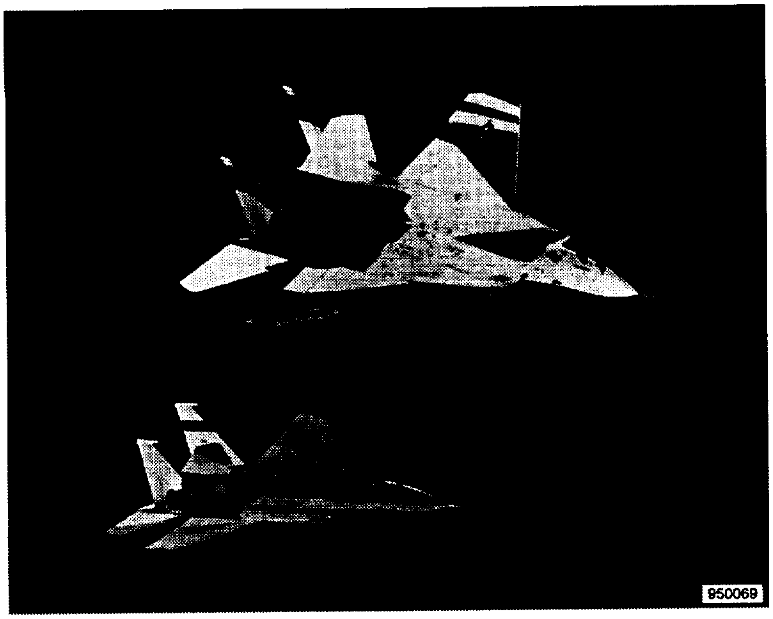


FIG. 3 F-15 #2 AND #8, ENGINE P680063 IN F-15 #2, BACKGROUND (1976).

F-15's during a period when NASA was a member of the joint test force participating with the USAF.

In 1976, the USAF had equipped the production F-15 airplanes with F100-PW-100(3) engines and had agreed to loan NASA two preproduction F-15 airplanes and four engines for a NASA/USAF research program. The airplanes were F-15 #2 (S/N 71-0281), which was the initial propulsion test airplane, and F-15 #8 (S/N 71-0287), which was the #8 airplane used for agility and high-angle-of-attack testing. The four engines included two F100-PW-100(2-7/8) engines: P680063 and P680059. Thus, engine P680063 ended its career as a USAF engine. However, its value to the USAF and to the nation was far from ended. Figure 3 shows the two NASA F-15's with engine P680063 installed in F-15 #2 (ship 281). Ship 281 can be identified by its wingtips, which are not rounded or raked as ship 287's and the production F-15's are.

NASA and the USAF had planned a comprehensive flight/ground test facility correlation program on the F-15 inlet and nozzle, using the F-15 #2 and F100 engine (Webb and Nugent, 1982). Objectives included the determination of the effects of model scale, Reynolds number, and flight simulation techniques. For the first part of this research program, NASA arranged to calibrate the two F100(2-7/8) engines, P680059 and P680063, at the NASA Lewis Research Center. The Lewis test provided detailed airflow and thrust calibrations over the flight envelope, thus enhancing the value of the flight tests results for comparison with wind-tunnel results. An additional objective was to evaluate a new thrust calculation technique developed by the Computing Devices of Canada (commonly referred to as "COMDEV"). The COMDEV instrumentation consisted primarily of augmentor liner static pressures.

This calibration was conducted at the NASA Lewis (LeRC) Propulsion System Laboratory (PSL), in 1977 (Biesiadny et al., 1978). Figure 4 shows the engine installed in the PSL facility. Excellent-quality thrust and airflow calibrations were obtained. The in-flight thrust calculation agreed with the test-cell-measured thrust to within ±2.5 percent over the test envelope. Thrust and airflow calibration results were given by Kurtenbach (1978) and Kurtenbach (1979). The COMDEV system initially had problems, but after some analysis and recalibration, these were later resolved.

The engine was returned to NASA Dryden and installed in F-15 #2 to participate in the flight program. Engine P680063 flew behind a 40-probe inlet rake (fig. 5), and an engine-inlet compatibility program was conducted, which included an inlet dynamics study and a stability audit (Stevens et al., 1979). Good agreement between wind-tunnel and flight data was shown. The effects of sample rate and filtering on dynamic distortion were quantified. Then, an inlet drag (Webb et al., 1979) and nozzle-afterbody drag (Nugent et al., 1983) flight program was flown. The inlet test results were the first flight measurements of inlet drag and showed good agreement with the force results of the wind-tunnel tests. The pressure-integrated flight data agreement with wind tunnel was not so good, probably because of the limited number of pressure orifices in the cowl lip region. The nozzle drag differed from the tunnel data because of different aft-end boundary-layer thickness that was traced to the use of a faired inlet in the tunnel tests.

Engine P680063 in the F-15 also flew with the COMDEV system; this evaluation was completed in 1978 (Kurtenbach and Burcham, 1981). The COMDEV technique was also used on the J85 engines in the T-38 airplane and, later, on the F404 engines in the X-29 and F-18 airplanes.

F100-PW-100(3) Digital Electronic Engine Control (DEEC) Configuration. In 1980, NASA, the USAF, and Pratt & Whitney jointly conducted the first evaluation of the DEEC. The

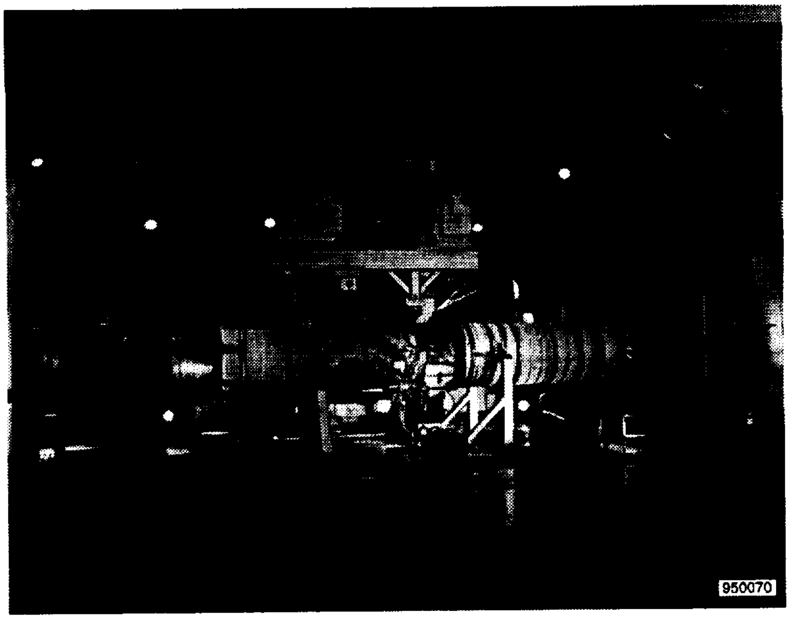


FIG. 4 ENGINE P680063 IN PSL FOR THRUST AND AIRFLOW CALIBRATION (1977).

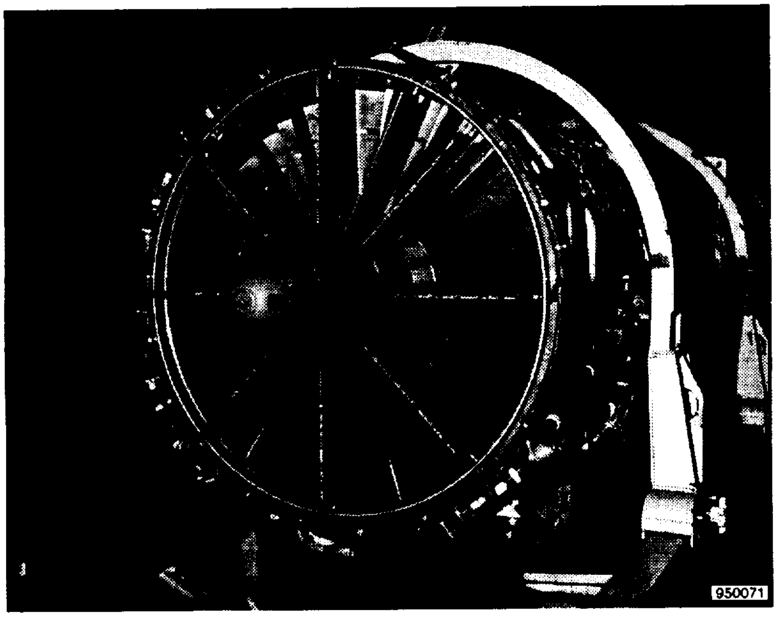


FIG. 5 ENGINE P680063'S 40-PROBE RAKE (1979).

DEEC was a full-authority digital control with a hydromechanical backup. The DEEC incorporated new control software, hardware, and closed-loop control logic. For this evaluation, it was necessary to have the engine represent the gas path of the production F100(3) engine; so, Pratt & Whitney modified the engine P680063 to incorporate many production F100(3) parts. These modifications included replacement of the compressor's 7th- and 8th-stage disk and blades and its 13th-stage disk, the combustor, the fuel nozzles, the turbine's 1st- and 2nd-stage disks and its 3rd- and 4th-stage disk and blades, and the nozzle divergent actuator. The engine, equipped with the DEEC hardware and software, went through a flight qualification altitude test at the Arnold Engineering and Development Center (AEDC). New "partial swirl" augmentor hardware and improved prefill and sequencing augmentor software

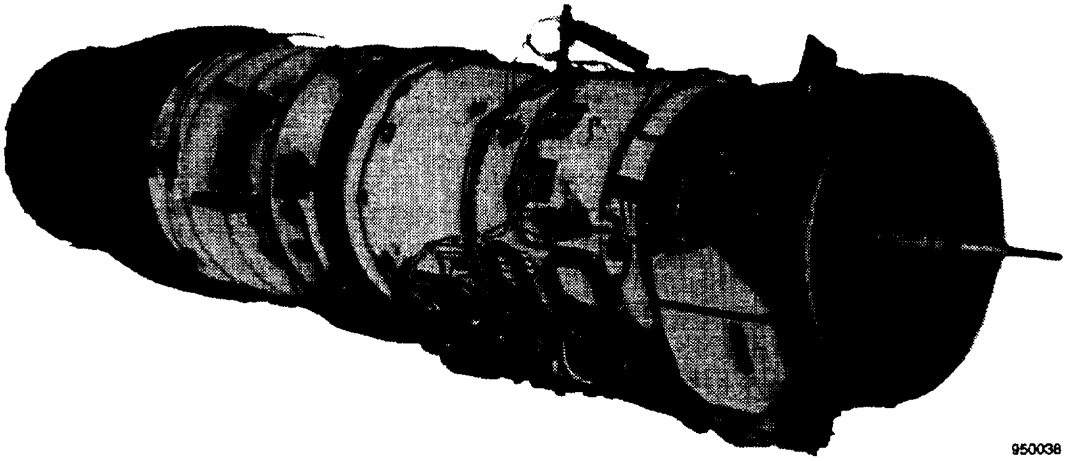


FIG. 6 ENGINE P680063 IN AEDC TEST (1980).

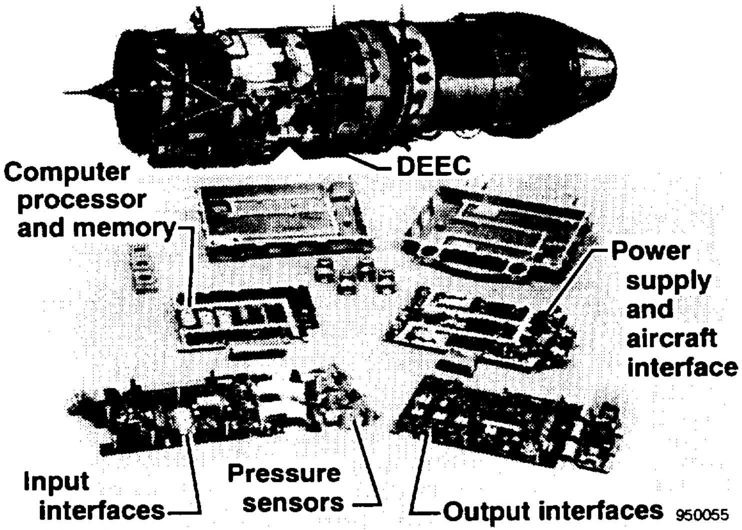


FIG. 7 ENGINE P680063 WITH DEEC (1981).

were also evaluated. New fiberglass wrapping for protection against the test cell acoustics was installed, along with added instrumentation (fig. 6).

Engine P680063 returned to NASA Dryden with the full authority DEEC installed. A gray containment band was also installed on the case in the turbine area (fig. 7; this figure also shows an exploded view of the DEEC). The engine was soon installed in F-15 #8 (F-15 #2 had been retired), and it first flew in 1981. At the end of these tests, which were conducted over four phases, the F100-DEEC worked very well. The airstart envelope was improved by 100 knots, and the fault detection and accommodation logic worked well. The engine pressure ratio-mode, with no trim required, was a major improvement.

The initial phase-1 DEEC tests in the middle part of the flight envelope were very successful. In the second phase, as tests were flown in the upper left-hand corner of the flight envelope, problems were encountered that were not observed in the AEDC tests. These included augmentor blowouts, mislights, and stalls. As problems and causes were identified, software and hardware changes were incorporated into the flight engine. During the four test phases, engine P680063's augmentor lighting envelope was gradually expanded. Figure 8 shows the 100-percent success boundaries for idle-to-maximum power throttle transients. During the phase-2 and -3 tests, an augmentor/nozzle limit-cycle oscillation was encountered that caused stalls and blowouts. This oscillation was not predicted from the tests at AEDC. Another F100 engine (XD-11)

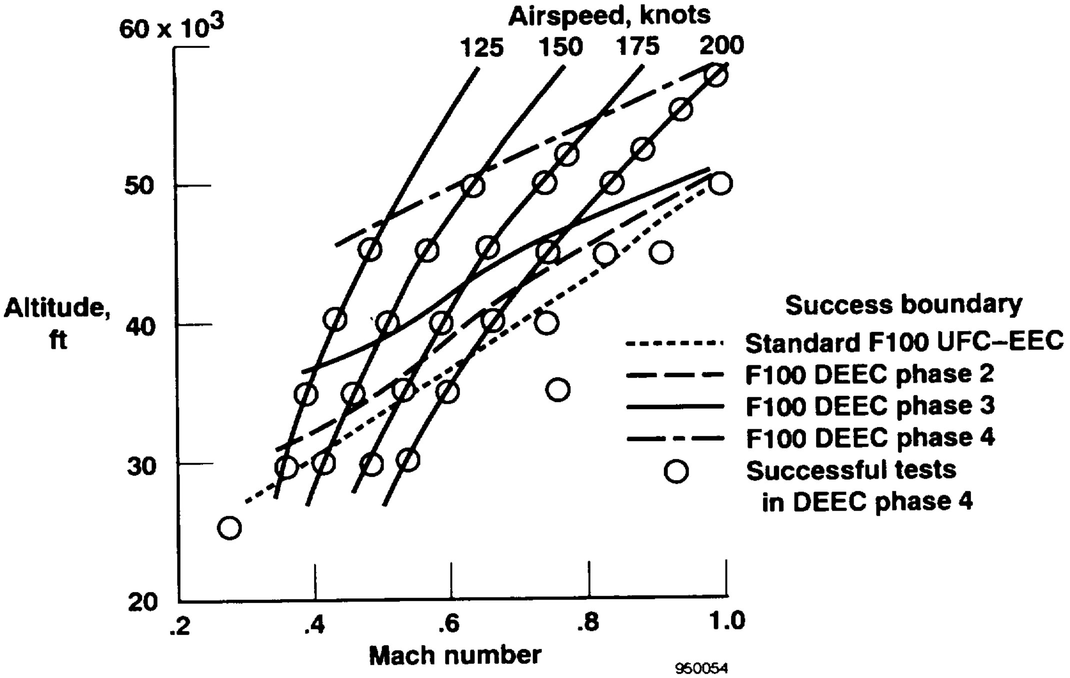


FIG. 8 SUCCESS BOUNDARIES FOR ENGINE P680063 AUGMENTOR TESTS; F100(3) CONFIGURATION (1983).

was being tested at NASA Lewis. This engine was tested at the flight conditions at which the oscillation occurred. While it was not possible to duplicate the observed flight instability, it was possible to investigate the effects of gain and deadband variations on stability. With these data in hand, the flight program was able to evaluate software changes that solved the problem (Burcham and Zeller, 1984).

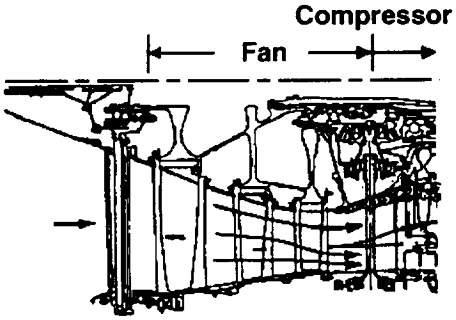
Soon, a second DEEC engine accompanied engine P680063 on F-15 research flights. In 1986, the USAF decided to put the DEEC into production for the F100-PW-220 engine and acknowledged the contributions of NASA and the early flight evaluation of the DEEC as having accelerated DEEC production by at least a year. The "nonthreatening NASA research environment" allowed the engine manufacturer to evaluate engine and DEEC concepts that might not have tried in a Department of Defense test. DEEC flight results are summarized by Burcham et al. (1985).

During the DEEC testing, composite nozzle external flaps were installed on P680063 and remained on for all succeeding tests except for later acoustic tests on the flaps. An improved fan inlet static pressure (PS2) probe was also installed and tested; it later became the production sensor.

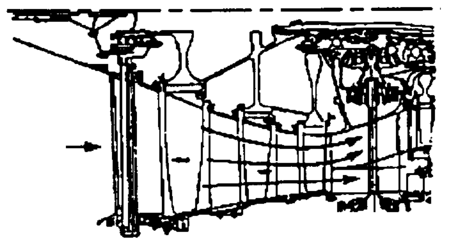
In 1983, NASA, the USAF, and Pratt & Whitney evaluated the F100 engine model derivative (EMD) engine, S/N P680350, in the NASA F-15. For these tests, which included throttle transients in the extreme upper left-hand corner of the flight envelope, a nontest engine with excellent operability was desired; engine P680063 was selected. Stalls occurred on the EMD engine, but not on engine P680063. The search for the cause and solution of the stall problem was a long, involved process. As in previous times when unexpected problems were found in flight, additional altitude tests were run at AEDC. The flight results could not be duplicated, possibly because the very cold temperatures encountered in flight could not be duplicated in the altitude facility without icing problems. After additional flight tests with added instrumentation and after much detailed data analysis and correlation with similar data on another ground test engine, a fan/compressor diffuser flow separation, occurring only during decelerations, was found. A software fix was implemented to avoid the problem (fig. 9), and a later redesign of the diffuser solved the problem (Burcham and Ray, 1987). The technology developed in the F100 EMD program was later incorporated into the F100-PW-229 engine, providing major performance improvements.

In 1984, a DEEC fault detection and accommodation (FDA) test was conducted on engine P680063. The DEEC flights up to this point had only encountered two minor failures, both of which had been correctly detected and accommodated. To further investigate the DEEC FDA, plumbing and wiring on the engine were modified to permit the introduction of simulated pressure and electrical faults to the DEEC. An extensive simulation evaluation was initially conducted. No problems were predicted; however, in ground tests on P680063, several unexpected FDA problems occurred (Myers et al., 1985). The flight evaluation verified the ground test results; this resulted in several changes to the DEEC FDA, which have been incorporated into the F100-PW-220 software. The concept of using plumbing and wiring to introduce faults rather than software was also proven.

F100 EMD Configuration. In 1985, NASA, in conjunction with the USAF, McDonnell Douglas Aerospace, and Pratt &



Throttle reduction (with separation)



Throttle increase

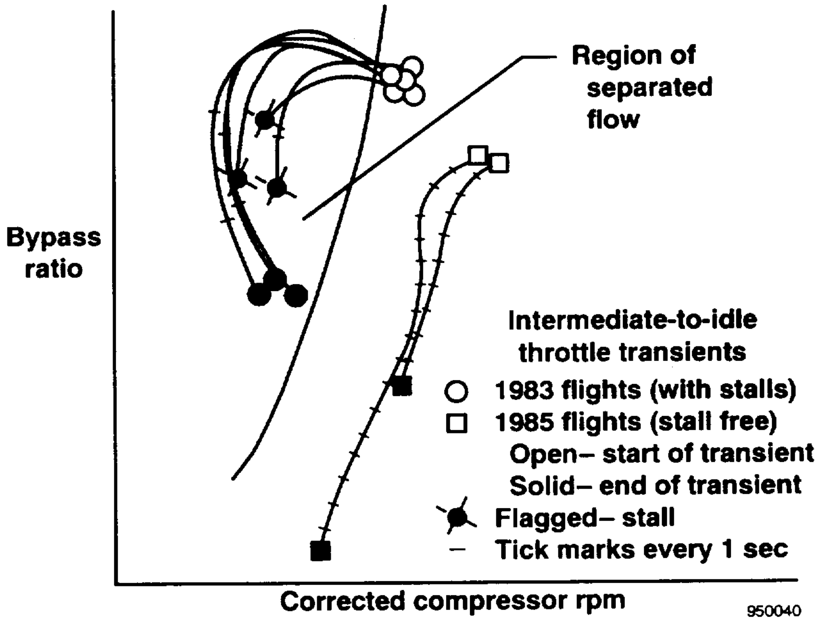


FIG. 9 F100 EMD CONFIGURATION STALL CAUSE AND SOFTWARE FIX (1985).

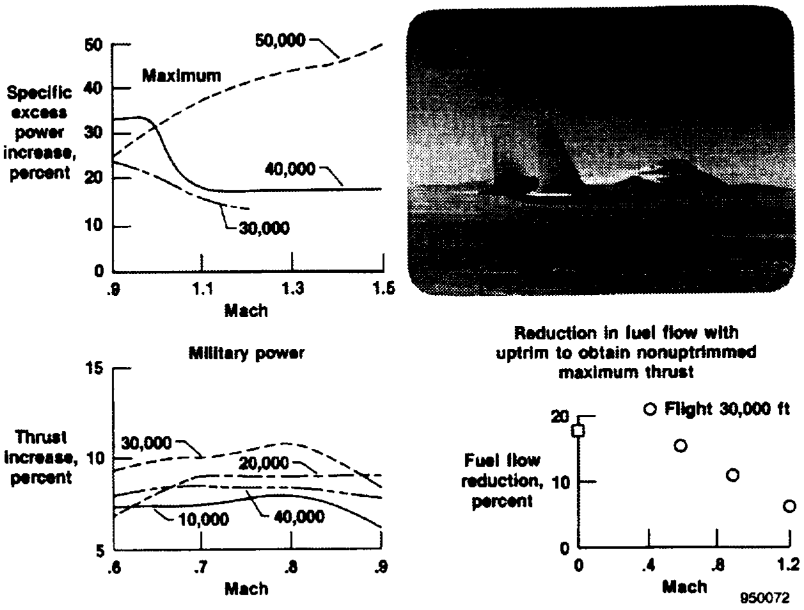


FIG. 10 RESULTS FOR ENGINE P680068 ADECS (1987).

Whitney, began the highly integrated digital electronic control (HIDEC) program. In this program, the DEEC was modified to accept commands from a digital flight control system that was installed on the NASA F-15. This allowed fan stall margin to be traded for operation at higher engine pressure ratio at times when the full stall margin was not required. Engine P680085 was first used; later, P680063 was used in this evaluation. Engine P680063 was updated to its fourth configuration: the F100 EMD configuration with the EMD fan, the single crystal turbine blades and vanes, and the 16-segment augmentor. With the HIDEC advanced engine control system (ADECS) operational, thrust increases of 5 to 10 percent and fuel flow decreases at maximum power of 5 to 15 percent were found, as figure 10 shows (Ray and Myers, 1986). The F100 EMD fan has approximately 25 percent stall margin and about

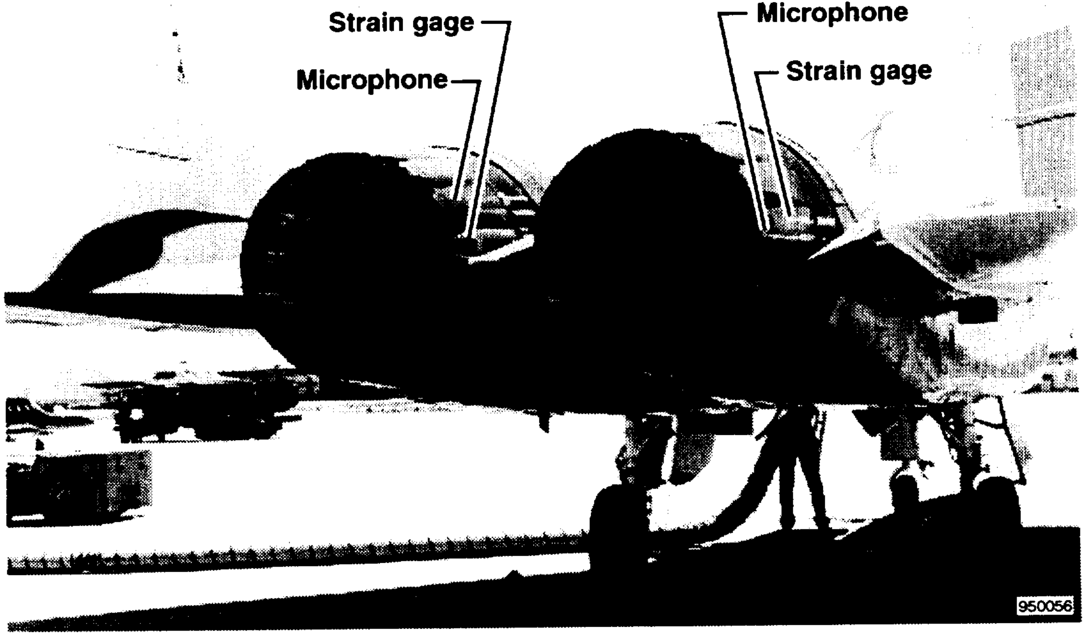


FIG. 11 ENGINE P680063 NOZZLE FLAP ACOUSTICS (1987).

one-half of this was typically traded for performance. This ADECS mode was later broadened to include an extended engine life mode, in which stall margin was traded for reduced turbine inlet temperature. Temperature reductions from 20 to 80 °F (7 to 27 °C) were found in flight tests in 1989 (Burcham and Ray, 1987). The ADECS tests were conducted without a specific altitude test for flight clearance. The allowable uptrims were initially limited until proper system operation was demonstrated; then the limits were removed. This use of engine P680063 as a "flying altitude test facility" saved costs and time and proved to be successful enough that it was used in later projects.

Part-way through the ADECS project, NASA Langley requested that NASA Dryden join with them in an acoustics research program to investigate twin-jet interactions. The F-15 and B-1 installations, with closely spaced engines, had both experienced cracked outer nozzle flaps, whereas a single engine operating in the F-16 did not experience nozzle cracks. NASA Dryden installed about 25 high-frequency microphones, pressure transducers, and strain gages on the nozzle flaps and interfering areas. Figure 11 shows F100 EMD engine P680085 on the left and engine P680063 on the right—both with the instrumented external flaps installed in the F-15. The HIDEC system provided an added capability for this test. NASA Langley's desire to match nozzle pressure ratios closely at the same power setting was satisfied by the ability of the ADECS system to increase engine pressure ratio on one engine until it matched the other. Flights varied Mach number and altitude as well as power setting. NASA Langley took the acoustics data, while NASA Dryden provided the exhaust conditions. The results were correlated with small-scale cold jet test data (Seiner and Burcham, 1988). One of the flow models developed from small scale model jet tests was not substantiated by the flight results.

Other Programs Using Engine P680063

Performance-Seeking Control (PSC). In 1990, engine P680063 was used in still another research program, called (PSC). PSC is a real-time, onboard optimization of engine, inlet, and flight control parameters; it includes a Kalman filter to identify engine deterioration (Burcham and Ray, 1987). PSC features onboard simplified models of the engine, inlet, nozzle, and a real-time optimization algorithm to optimize the variables in the engine, inlet, nozzle, and airplane horizontal tail position. Control modes included maximum thrust, minimum specific fuel consumption, and minimum temperature for constant thrust. Initially, engine P680063 was used to evaluate the Kalman filter and its ability to identify engine component performance with changes in engine bleed (Maine et al., 1990). Engine P680063 was overhauled before the first PSC flights, with the installation of a new increased life core; it represented an engine with little deterioration and better-than-average performance. The engine was tested at sea-level conditions, but the customary altitude test was not conducted. This approach was reasonable because the logic was written so that any PSC failure or stall would immediately cancel the PSC trims. Initial tests were conducted with limited PSC trims to establish proper system operation before allowing full trims to be implemented. This strategy worked successfully.

In late 1991, a ground test on the thrust stand at Edwards Air Force Base was conducted. Measured thrust was compared with the PSC-calculated thrust for the various modes (Conners, 1992). Later, in 1992, engine P680063 was used along with P680085 in a dual-engine PSC flight evaluation—first at subsonic speeds, later at supersonic speeds. The PSC modes were mostly for increased performance, i.e., more thrust or lower fuel flow at the same thrust.

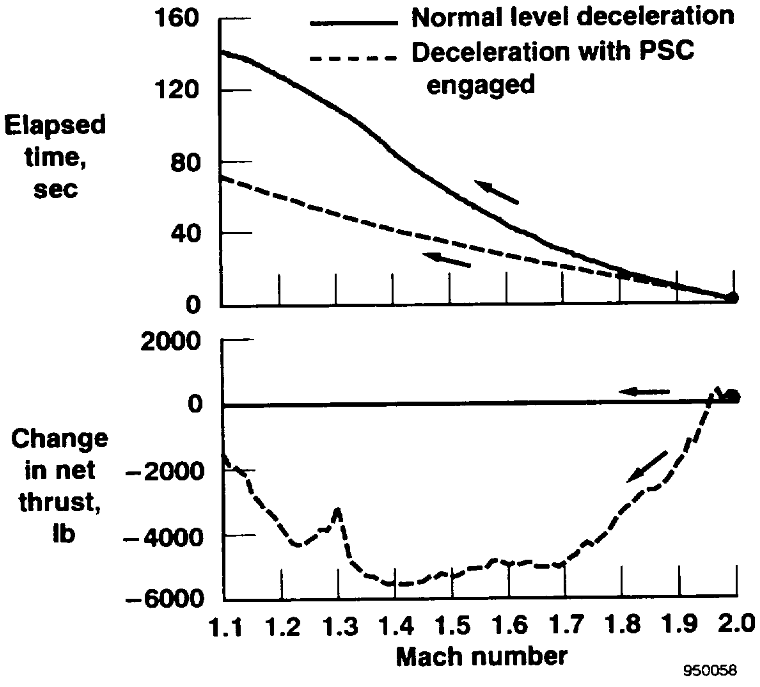


FIG. 12 PSC MINIMUM THRUST MODE RESULTS.

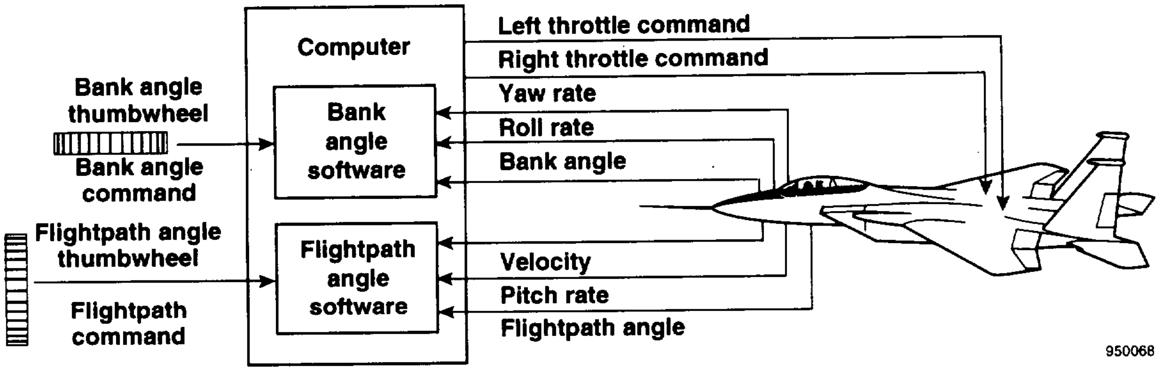


FIG. 13 F-15 AUGMENTED PCA SYSTEM.

A reduced-temperature mode at constant thrust was also tested (Orme and Gilyard, 1993).

Near the end of the PSC program, the opposite type of optimization—minimizing thrust at supersonic speeds to permit faster airplane decelerations—was performed. In this case, the engine airflow was reduced consistent with the inlet buzz boundary, and the variable vanes and nozzle were driven to their low-efficiency settings. In addition to lower thrust, the fuel flow and exhaust temperatures were also reduced (fig. 12).[2] Parts of the PSC technology have found their way into advanced military and commercial turbofan engines, primarily with real-time adaptive engine models used for fault identification and accommodation.

Propulsion-Controlled Aircraft (PCA). The last flight use of engine P680063 was in 1993 in the PCA program. In case of total flight control failure, engine thrust (collective for pitch and differential for roll) may be the only remaining method of controlling an airplane. Engines P680063 and P680085 were used to demonstrate this concept on the F-15. With the onboard computer taking pilot commands and feedback parameters and driving the DEEC electronic throttles (fig. 13), the F-15 was successfully landed without the use of any flight controls (Burcham et al., 1994). The big brute force of engine P680063, with more than 27,000 lb of thrust, was modulated with enough finesse (along with the other

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[2] Conners, T. R., Nobbs, S. G., and Orme, J. S., 1994, "Rapid Deceleration Mode Evaluation," F-15 HIDEC Electronic Conference (see footnote 1).

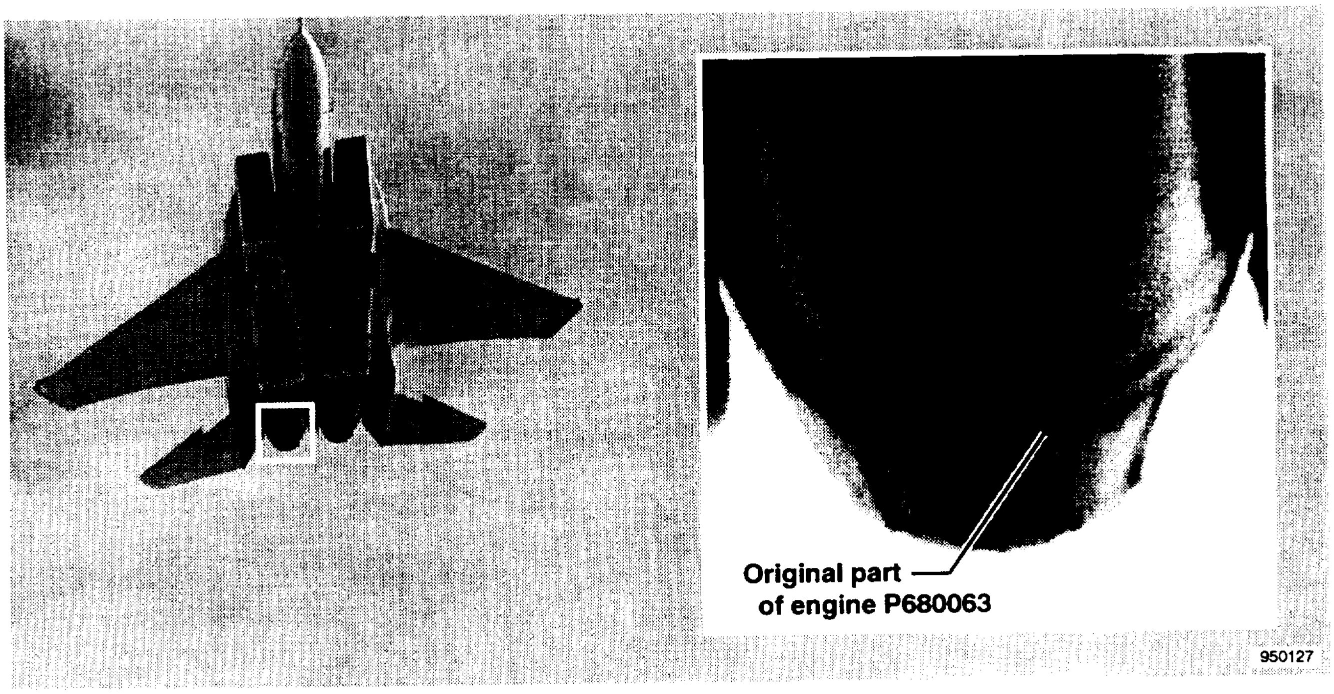

FIG. 14 ENGINE P680063 IN F-15'S FINAL FLIGHT.

engine) to gently nudge the F-15, with flight controls locked, to a safe landing. This use of propulsion technology has been transitioned to the civil sector with tests of a PCA system on an MD-11 aircraft.

Engine P680063 was last used in 1994 for a fit check of a propulsion research chamber in which ground tests of advanced sensors, such as laser Doppler velocimeters, are performed. After that test, the engine was put into storage.

It is now interesting to wonder whether any of the original P680063 parts, other than its nameplate, are still with the engine. Sharp-eyed observers can see one of the original parts of the old F100(2)—the divergent actuator bulge on the lower part of the nozzle static structure—in figure 14, which is a photo of a NASA flyover on the last flight of F-15 #8. This engine, which has been through at least four major configuration changes, still retains at least one original part in addition to the nameplate.

CONCLUDING REMARKS

Flight tests were conducted over three decades on F100 engine P680063, which has evolved through four major configurations. The flight research in the NASA F-15 airplane has matured technology for digital engine control, increased performance (F100-PW-229), active stall margin control, performance-seeking control, and engine thrust for emergency flight control. Making flight test and ground test an interactive process has been shown to be an effective way to mature the development of propulsion technology.

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