

DIGITAL ELECTRONIC ENGINE CONTROL
F-15 OVERVIEW

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SUMMARY

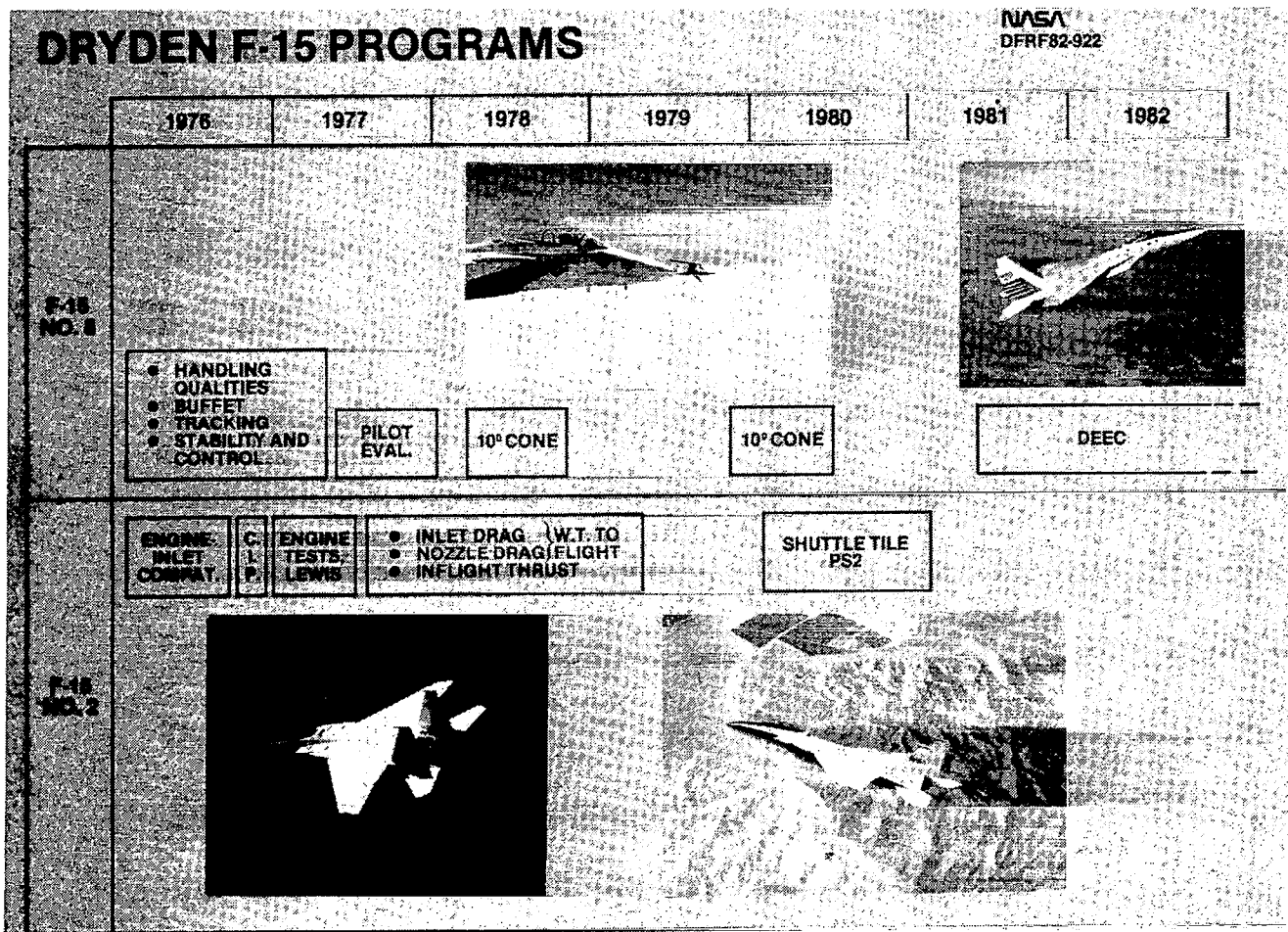
NASA Ames Research Center's Dryden Flight Research Facility, in cooperation with the U.S. Air Force and Pratt and Whitney Aircraft, conducted a flight test evaluation of the digital electronic engine control (DEEC) system. This paper presents an overview of the flight program. The introduction describes the roles of the participating parties, the system, and the flight program objectives. The test program approach is discussed briefly, and the engine performance benefits are summarized. A brief description of follow-on programs is also included.

DRYDEN F-15 PROGRAMS

NASA Ames Research Center, Dryden Flight Research Facility (DFRF) has operated two F-15 aircraft since 1976. One of these, the #2 F-15, was the propulsion test airplane in the full scale development program. The other, the #8 F-15, was the spin test airplane. NASA obtained these airplanes on loan to support a wide range of technology programs.

F-15 #2 supported a number of engine/inlet tests and engine component tests. Its major function was as the test aircraft for an extensive wind tunnel to flight correlation of pressure distributions and drag build-up data for the F-15 airplane. This program focused on the inlet and nozzle areas of the airplane. The airplane also supported a test of the shuttle tile system. A number of installations were made that simulated both the shuttle installation and induced the air loads the tile would experience while in flight. As a piggy-back experiment a probe that measured engine face static pressure (the PS2 probe) was tested. This probe later became one of the DEEC sensors. The airplane was retired following the shuttle tile/PS2 test program.

F-15 #8 was obtained to support a variety of handling qualities, buffet, tracking, and stability and control studies for this class of airplane. A major program, a test of a 10° included angle cone, is a standard wind tunnel calibration system for documenting turbulence. The flight program provided baseline data for tunnel to flight correlations. When the DEEC program began, the F-15 #2 was not available. The DEEC propulsion program was put on ship #8 as a matter of convenience.

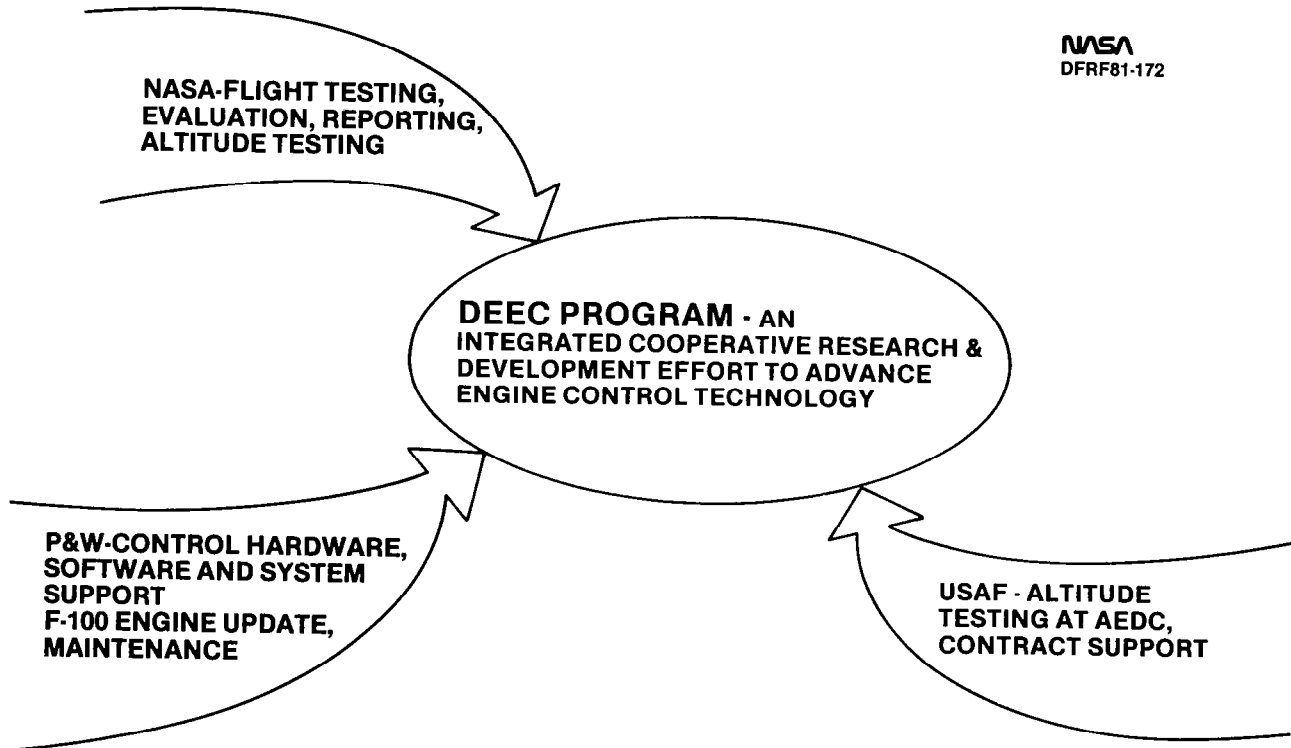


DIGITAL ELECTRONIC ENGINE CONTROL PROGRAM

The DEEC program was a cooperative endeavor of the National Aeronautics and Space Administration (NASA), the U.S. Air Force (USAF), and Pratt and Whitney Aircraft (PWA). Each party had a desire to pursue the development of the DEEC through a technology development program that included flight test, but each party had limitations on its ability to support such a program. By combining forces in a cooperative program, the goals could be achieved.

NASA brought to the program a flight and ground test capability; Pratt and Whitney provided the engine control system and engine modification, along with engineering and technical support; and the USAF provided flight clearance support at Arnold Engineering Development Center (AEDC). From NASA's viewpoint, this was a nearly optimum way to conduct a program such as the DEEC flight test.

Because of the absence of written contracts outlining restrictions, a considerable amount of flexibility was allowed in the management of the program. This created an environment of mutual cooperation and support, and increased the productivity of individuals involved in the test program. In addition, this type of management allowed a quick response to technical concerns, a latitude in program adjustments when unforeseen circumstances occurred, and a lack of pressure, from a schedule viewpoint.



DIGITAL CONTROL FOR THE F100

The DEEC is a full authority digital control system for the F100 Turbofan engine. It incorporates extensive fault detection and accommodation features that allow for safe and reliable operation on a single digital channel. The digital computer system also permits much simpler hardware to be used in the engine control system by the elimination of cams, valves, and other components that are necessary in a hydro-mechanical control system. The DEEC system does incorporate a backup control (BUC) that is used if the primary digital control should fail. The BUC is a simple hydro-mechanical system usable over the entire envelope; however, maximum thrust available is only about 80 percent of the DEEC intermediate thrust.

The benefits postulated for the DEEC system were numerous. Benefits assessed in the NASA program included increased thrust, faster response times, improved afterburner operation, improved airstart envelope, elimination of ground trimming, and the fail-operate capability. In addition, the DEEC system promised improved reliability over the basic F100 control system, and, because of a combination of factors, lower overall life cycle costs. The NASA program only addressed the performance aspects of the DEEC benefits.

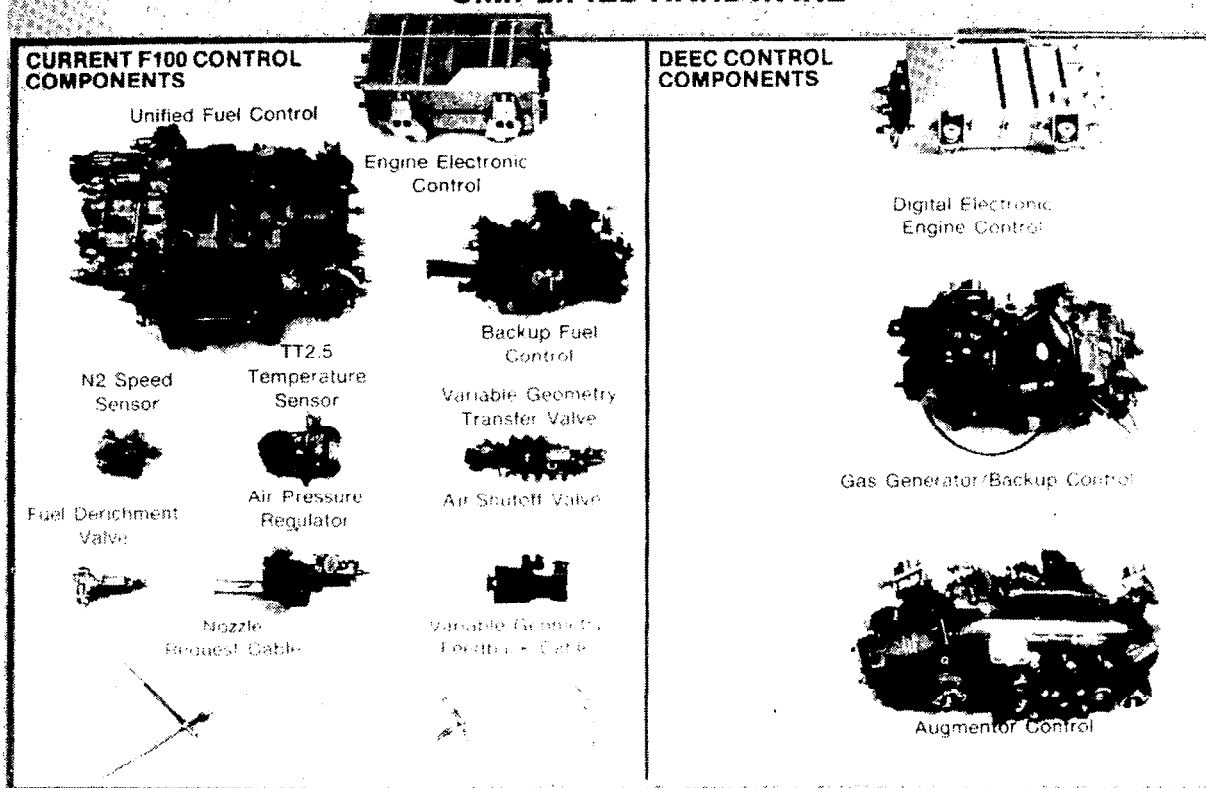
DIGITAL ELECTRONIC ENGINE CONTROL BENEFITS

NASA
DPRF82-228

- NO TRIM
- IMPROVED TRANSIENT RESPONSE
- IMPROVED AFTERBURNER ENVELOPE
- IMPROVED AIRSTART ENVELOPE
- INCREASED MAXIMUM THRUST
- SIMPLIFIED HARDWARE

- FULL ENVELOPE DISSIMILAR BACKUP CONTROL
- EXTENSIVE FAULT DETECTION & ACCOMMODATION
- LOWER IDLE THRUST

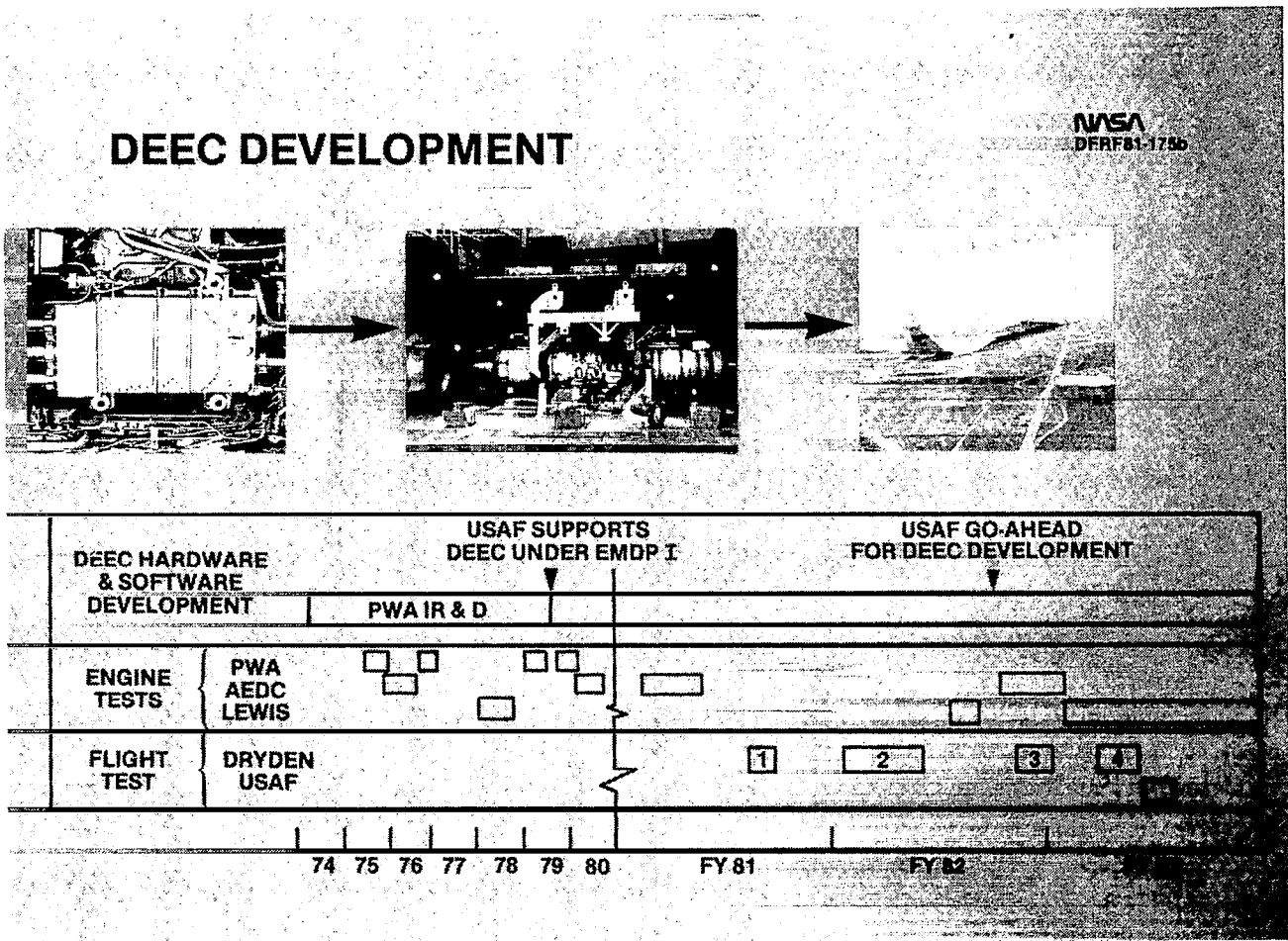
SIMPLIFIED HARDWARE



DEVELOPMENT

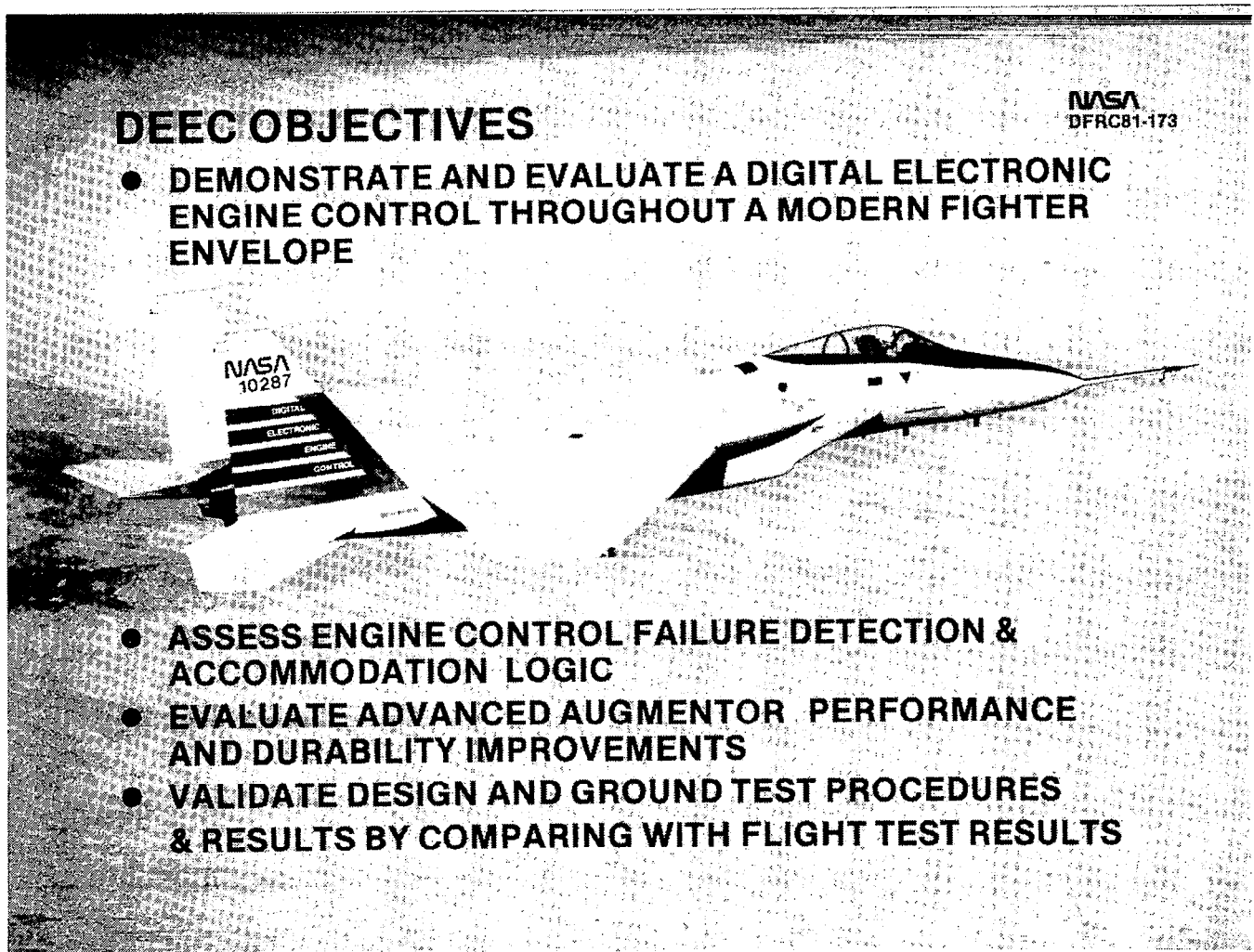
The DEEC development started in the mid-1970's, largely through Pratt and Whitney independent research and development (IR&D). A series of sea level and altitude facility tests led to the USAF supporting the effort under the Engine Model Derivative Program (EMDP). At the same time the USAF was supporting the program, Pratt and Whitney and NASA were developing an approach that would permit a flight program to take place.

As illustrated, the flight program began in 1981. The program was broken into four phases, resulting in an orderly approach to maturing the system technology. The program was completed in early 1983.



FLIGHT TEST OBJECTIVES

The objective of the program, from NASA's perspective, was to demonstrate and evaluate the DEEC system as applied to a modern turbofan engine and flown throughout the envelope of a high-performance fighter. Included within that overall objective were several subelements: to assess the fault detection and accommodation logic (which, as it turns out, was not a focus of the flight program); to evaluate the augmentor performance and durability improvements; and to validate the design and ground test procedures by comparison to flight tests. As shown later in the proceedings, the flight program surfaced some problem areas that were not predicted in ground facilities.



DEEC OBJECTIVES

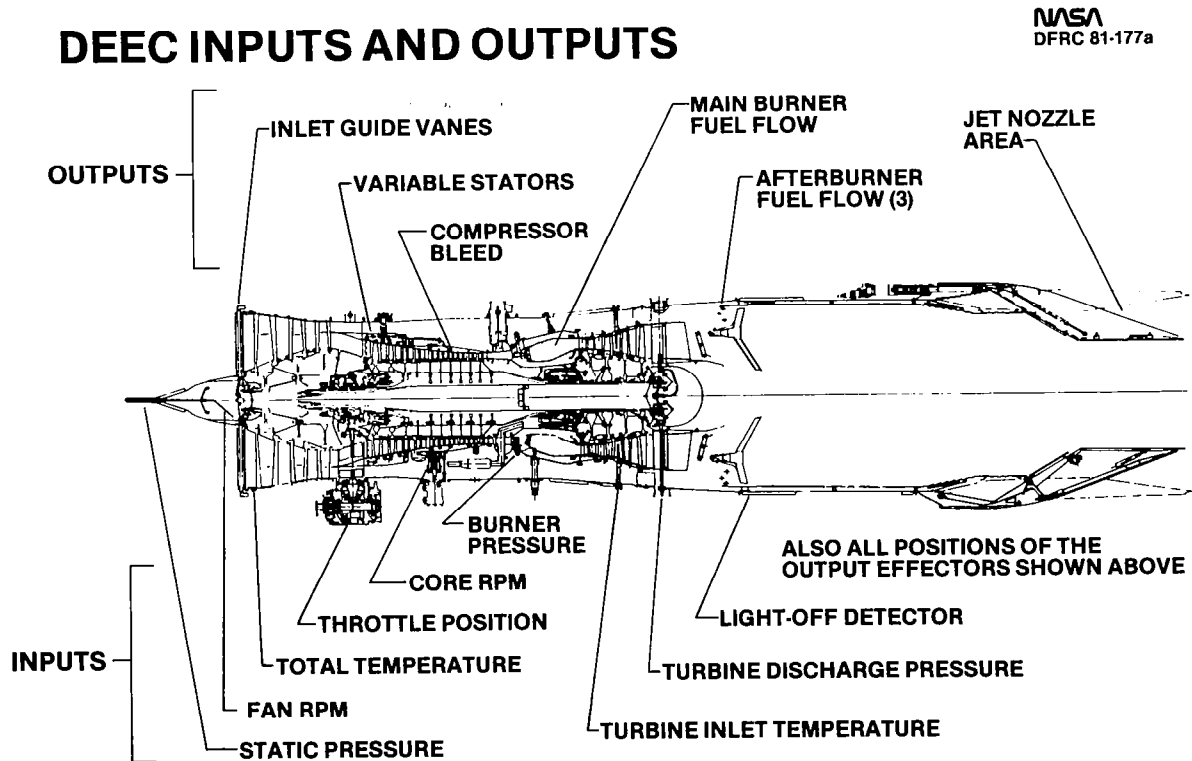
NASA DFCR81-173

- **DEMONSTRATE AND EVALUATE A DIGITAL ELECTRONIC ENGINE CONTROL THROUGHOUT A MODERN FIGHTER ENVELOPE**
- **ASSESS ENGINE CONTROL FAILURE DETECTION & ACCOMMODATION LOGIC**
- **EVALUATE ADVANCED AUGMENTOR PERFORMANCE AND DURABILITY IMPROVEMENTS**
- **VALIDATE DESIGN AND GROUND TEST PROCEDURES & RESULTS BY COMPARING WITH FLIGHT TEST RESULTS**

INPUTS AND OUTPUTS

A modern turbofan engine has a large number of control variables and input parameters to the control laws. The DEEC system can control, over the entire range of authority, all the variables in the F100 engine. These include inlet guide vanes, compressor stators, bleeds, main burner fuel flow, the afterburner fuel flows, and the nozzle area. The inputs include static pressure at the compressor face (which is used to compute total pressure at that location), fan and core rpm, compressor face total temperature, burner pressure, turbine inlet temperature, turbine discharge pressure, an ultra violet detector in the afterburner to determine whether a flame is present, and the throttle position.

The extensive list of inputs and outputs graphically illustrates the difficulty of hydromechanical control system design and the need for digital controls.



BASIC CONTROL MODES

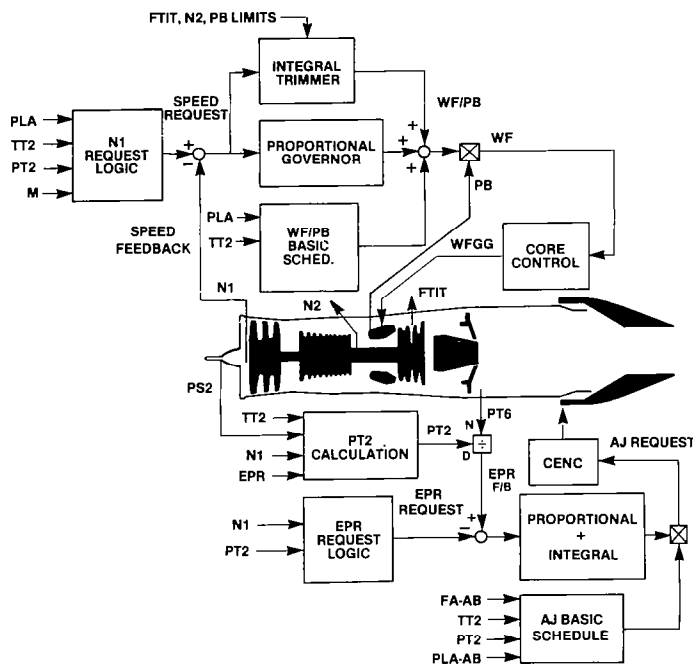
The DEEC system has two basic control modes for the gas generator portion of the engine. The airflow control mode uses core fuel flow to control fan rotor speed (N1). The control mode transitions at military power to an engine pressure ratio (EPR) control, which uses the nozzle to maintain the proper turbine discharge total pressure/fan inlet total pressure (PT6M/PT2) relationship.

The logic involved in implementing these control modes is quite complex as is illustrated on the chart. Many inputs are required, which generate the engine state requests. These requests are compared to the actual conditions and then, through a series of schedules and closed-loop control algorithms, appropriate actions are implemented to bring the engine to the desired operating condition.

In addition to these functions the augmentor controls are resident in the DEEC system.

DEEC BASIC CONTROL MODES CORE FUEL FLOW CONTROLS N1, NOZZLE AREA CONTROLS EPR

NASA
DFRF82-344



FLIGHT INSTRUMENTATION

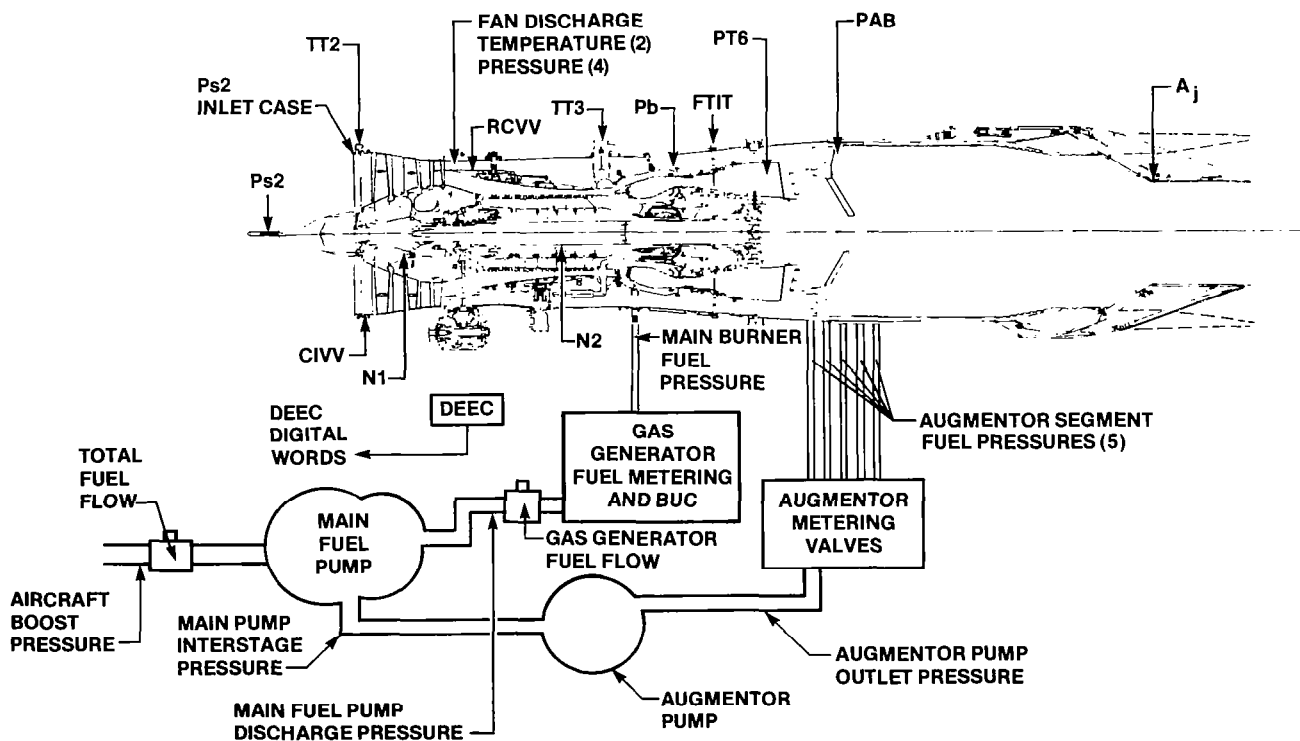
The test airplane was extensively instrumented, both for the engine and the basic airplane itself. The airplane data included airspeed, altitude, body-axis rates and attitude, accelerations, control-surface positions, and other parameters typical of a flight research program. The test engine was in the left side of the airplane and the right side engine had minimal data (that is, sufficient data to ascertain the health of the engine but not sufficient for any test work).

The parameters listed in the chart illustrate the extent of the engine instrumentation. As can be seen, the list is fairly extensive and includes all parameters necessary to monitor the health and performance of the engine. A major source of data was the DEEC digital words. This list grew with time, beginning with 50 words and increasing to 83 words by the end of the program. It has subsequently grown to 100 words. Included in this listing were 11 words (16 bits each) of diagnostic data - bits were turned on to indicate faults (malfunctions). In addition, the data stream output included the values used in the control calculations.

All of these data were recorded on board and were also transmitted to the ground for use in NASA's real-time flight monitoring facility. The format was pulse code modulation (PCM), which permitted relatively quick and extensive post-flight processing.

DEEC FLIGHT INSTRUMENTATION

NASA
DFRF82-016b

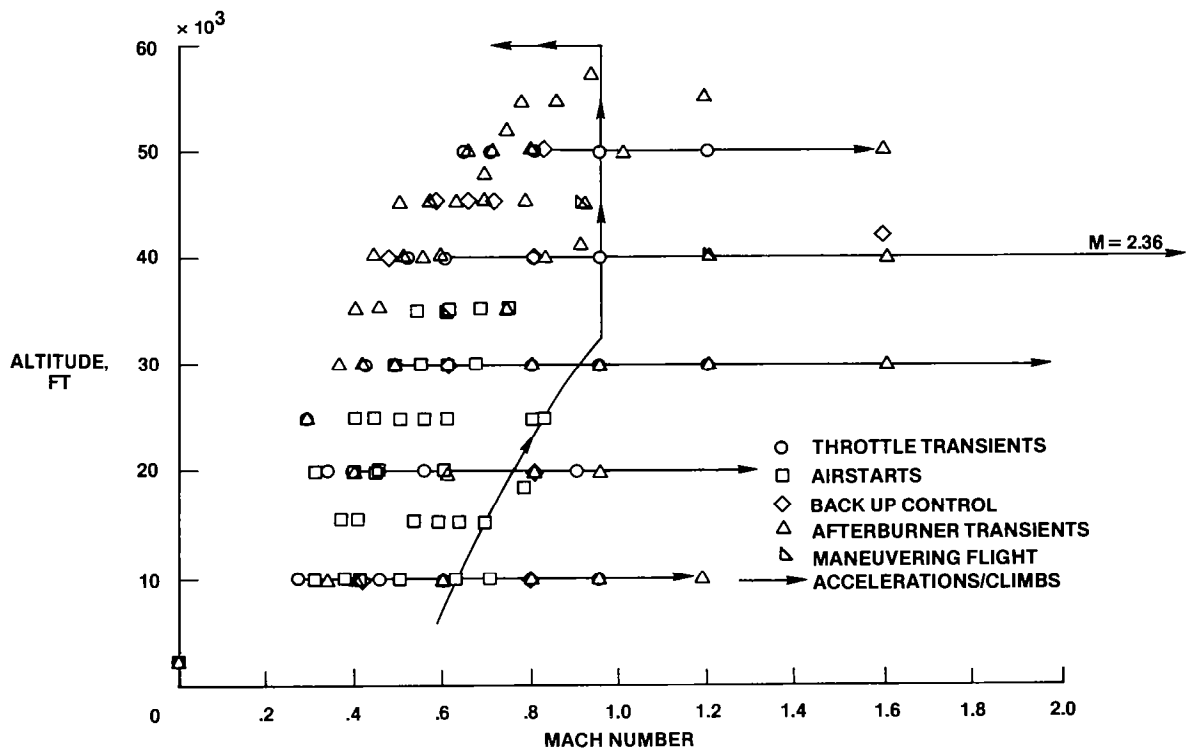


TEST POINTS FLOWN

This chart illustrates the flight envelope and types of tests conducted in the flight program. While the entire F-15 envelope was covered, the emphasis was on the ULHC of the envelope. Evaluation of the DEEC was accomplished through throttle transients, airstarts (spooldown and jet fuel starter (JFS)-assisted in both the primary and backup modes), back up control evaluations, augmentor transients of all varieties, and by maneuvering the airplane through climbs and accelerations. The number of flight conditions and types of evaluations conducted provide a sound basis for evaluating the performance and operability aspects of a DEEC-equipped F100 engine.

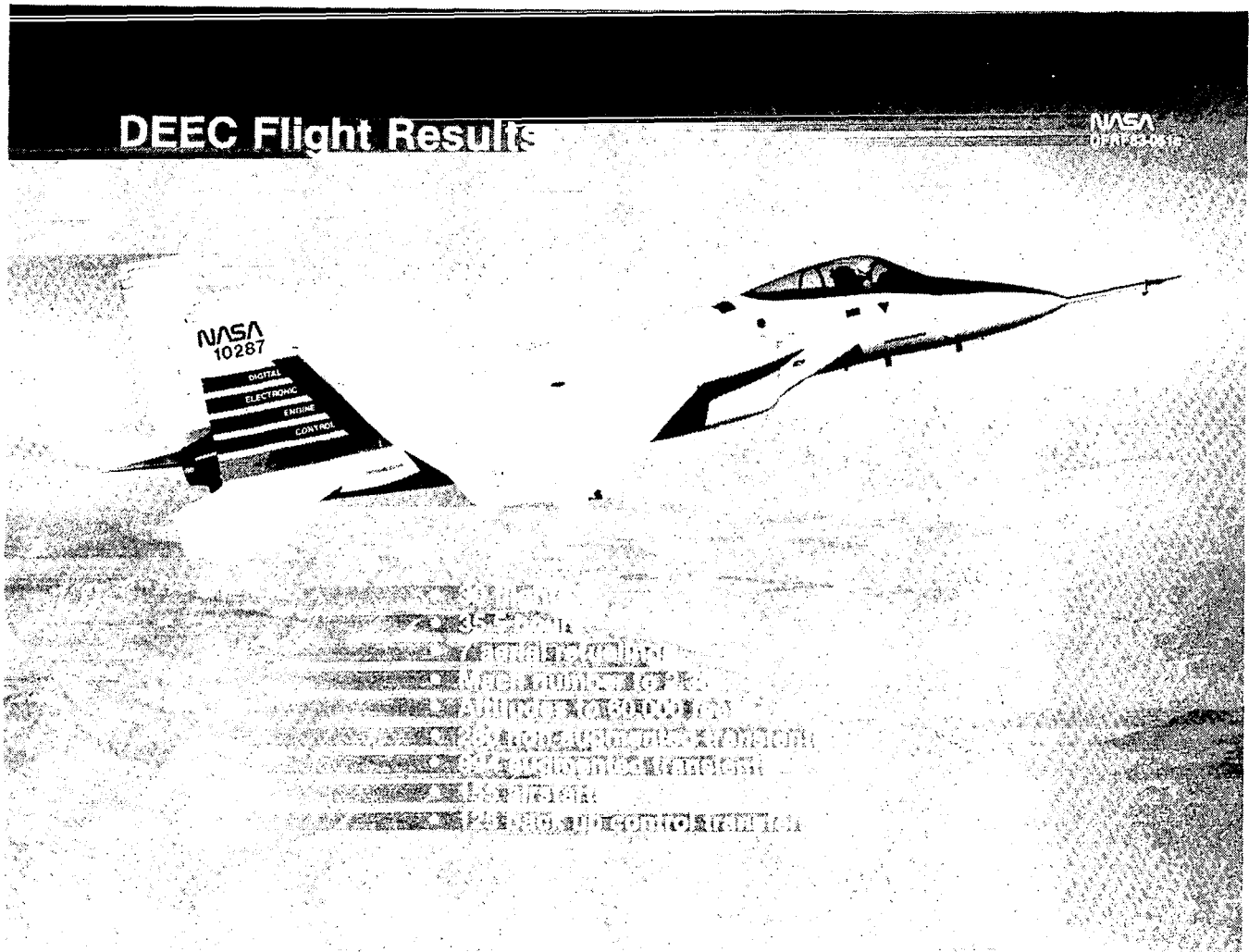
DEEC TEST POINTS FLOWN

NASA
DFRF81-269c



FLIGHT RESULTS

The NASA flight program consisted of 30 flights with a total of 35.5 hours of flight time. This included seven aerial refuelings. The maximum Mach achieved was 2.36 and the maximum altitude was 60,000 feet. A large number of transients, air-starts, and other tests were accomplished during the relatively low number of flights. Almost 1300 total transients, in addition to more than 150 airtasks, were accomplished. BUC was also evaluated through throttle transients and other tests. Because there were no automatic transfers to BUC, the BUC was pilot-selected in each case.



TEST PROGRAM

As previously stated, the flight program was broken into four phases. The purpose of Phase I was to verify the airworthiness of the DEEC system. Phase II expanded the program to include the augmentor operability assessment, primarily in the upper left-hand corner (ULHC) of the envelope. While the augmentor worked reasonably well (slightly better than the production system), some problems did occur. These included an instability in the nozzle control loop, some instances of rumble, and some blow-outs. Phase III incorporated fixes to the nozzle instability and other hardware changes in the augmentor, in addition to the second-generation BUC. Phase IV added the light off detector (LOD) to the augmentor control logic, as well as software, to permit augmentor light off at less than military power. The software change in light-off logic (called the fast-acceleration) essentially halved the idle-to-maximum time at high-speed, low-altitude conditions. The time saving was eliminated as the speed dropped and altitude increased. The following papers will report on the results of the program through Phase IV.

Follow-on flight test programs include the F100 Engine Model Derivative (EMD), a DEEC-equipped growth version of the F100 and a program specifically intended to evaluate the fault detection/accommodation logic of the DEEC. In that program, faults will be intentionally induced to cause the DEEC to revert to a mode that will permit continued safe operation in the digital mode.

F-15/DEEC Test Program

NASA
DFRF83-651a

| | | | |
|------|------|------|----|
| 1981 | 1982 | 1983 | 84 |
|------|------|------|----|

Flight clearance configuration 1 6 flights, nonaugmented, airtarts

Augmentor improvements 2 12 flights, ULHC augmentor

 PSL tests, Lewis

Nozzle instability fix group II BUC 3 7 flights, ULHC augmentor BUC evaluation

LOD, fast acceleration 4 5 flights, thrust, ULHC augmentor

Same as phase 4 EMD support

FDA

DESIGN OBJECTIVES MET

The features of the DEEC were verified in the flight test program. For example, the no-trim feature, verified through methods such as computer hardware replacements and engine removals, effected a substantial savings. The operability of the augmentor was improved; for illustration, the idle to maximum altitude capability was increased nearly 15,000 feet. The spooldown airstart airsteps were significantly reduced, thus allowing greater flexibility to the pilot in accomplishing an airstart. The fast-acceleration capability was also demonstrated. The DEEC system met its performance design objectives.

DEEC - DIGITAL ELECTRONIC ENGINE CONTROL

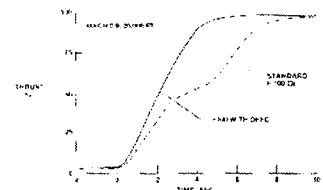
NASA
DPRF83-090

- FULL AUTHORITY DIGITAL - SINGLE CHANNEL
- INTEGRAL HYDROMECHANICAL BACKUP
- EXTENSIVE FAULT DETECTION AND ACCOMODATION
- IMPROVED PERFORMANCE
- NO TRIM

NASA
10207

DEEC D
DEEC E
DEEC C

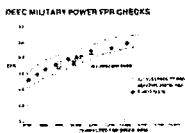
DEEC/F-15 FAST ACCEL CAPABILITY
COMPARISON OF THRUST RESPONSE FOR AN
IDLE-TO-MAXIMUM POWER THROTTLE SNAP



DEEC - NO TRIM

- CLOSED LOOP CONTROL COMPENSATES FOR CHANGES IN ENGINE CONDITION, CONTROL TOLERANCES, AND FUEL CHARACTERISTICS
- ELIMINATES THE NEED FOR PERIODIC RETRIMMING

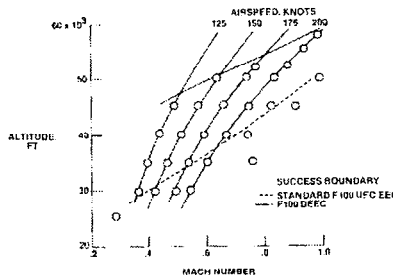
DEEC TEST RESULTS



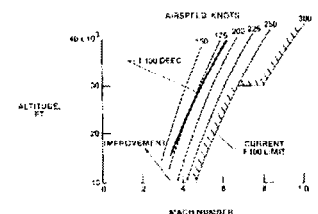
SAVINGS TO U.S. (BASED ON DEEC ON 1/2 OF F-15 FLEET)

- FUEL - \$40 MILLION
- LABOR - \$10 MILLION
- ENGINE HOURS - 50,000
- VALUE OF ENGINE HOURS - \$100 MILLION

F-15/DEEC IDLE TO MAXIMUM TRANSIENTS



DEEC SPOOLDOWN AIRSTARTS



CONCLUDING REMARKS

The DEEC development is a milestone in propulsion control and marks the transition from hydromechanical control to the digital realm. NASA is proud of the technology contributions made to the program. As will be illustrated, the benefits to the F100 engine are substantial and include costs, performance, and operability considerations. The USAF has stated its decision to embark upon a full scale development program that is attributable, in part, to the success of the program reported herein.

From a technology viewpoint, the maturity of the DEEC system will permit follow-on research programs to take place. One of these is the fault detection and accommodation (FDA) program as well as an airframe/engine control integration program called highly integrated digital electronic control (HIDEC). A subsequent paper will address the HIDEC program.

The following papers will, in greater depth, present the results of the highly successful DEEC program.

DEEC SUMMARY

NASA
DFRF82-957

- A MILESTONE IN PROPULSION CONTROL
- NASA TECHNOLOGY CONTRIBUTION VERY IMPORTANT
- BENEFITS TO THE F100 ARE SUBSTANTIAL
- USAF FULL SCALE DEVELOPMENT PROGRAM – DIRECT RESULT OF F-15 FLIGHT PROGRAM
- FOLLOW-ON RESEARCH OPPORTUNITIES