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NASA Dryden Flight Research Center

"An Overview of Integrated Flight–Propulsion Controls Flight Research on the NASA F–15 Research Airplane"

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Abstract

The NASA Dryden Flight Research Center has been conducting integrated flight-propulsion control flight research using the NASA F-15 airplane for the past 12 years. The research began with the digital electronic engine control (DEEC) project, followed by the F100 Engine Model Derivative (EMD). HIDEC (Highly Integrated Digital Electronic Control) became the umbrella name for a series of experiments including: the Advanced Digital Engine Controls System (ADECS), a twin jet acoustics flight experiment, self-repairing flight control system (SRFCS), performance-seeking control (PSC), and propulsion controlled aircraft (PCA). The upcoming F-15 project is ACTIVE (Advanced Control Technology for Integrated Vehicles) This paper provides a brief summary of these activities and provides background for the PCA and PSC papers, and includes a bibliography

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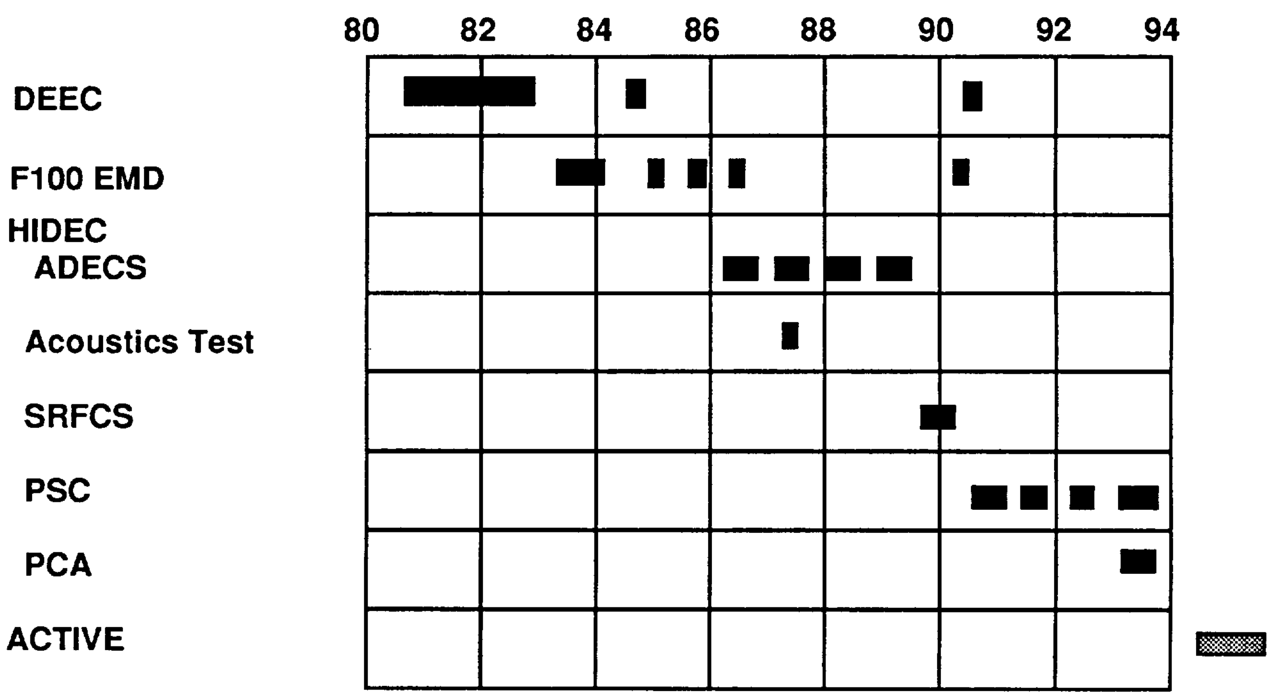
F-15 Research Flight Periods



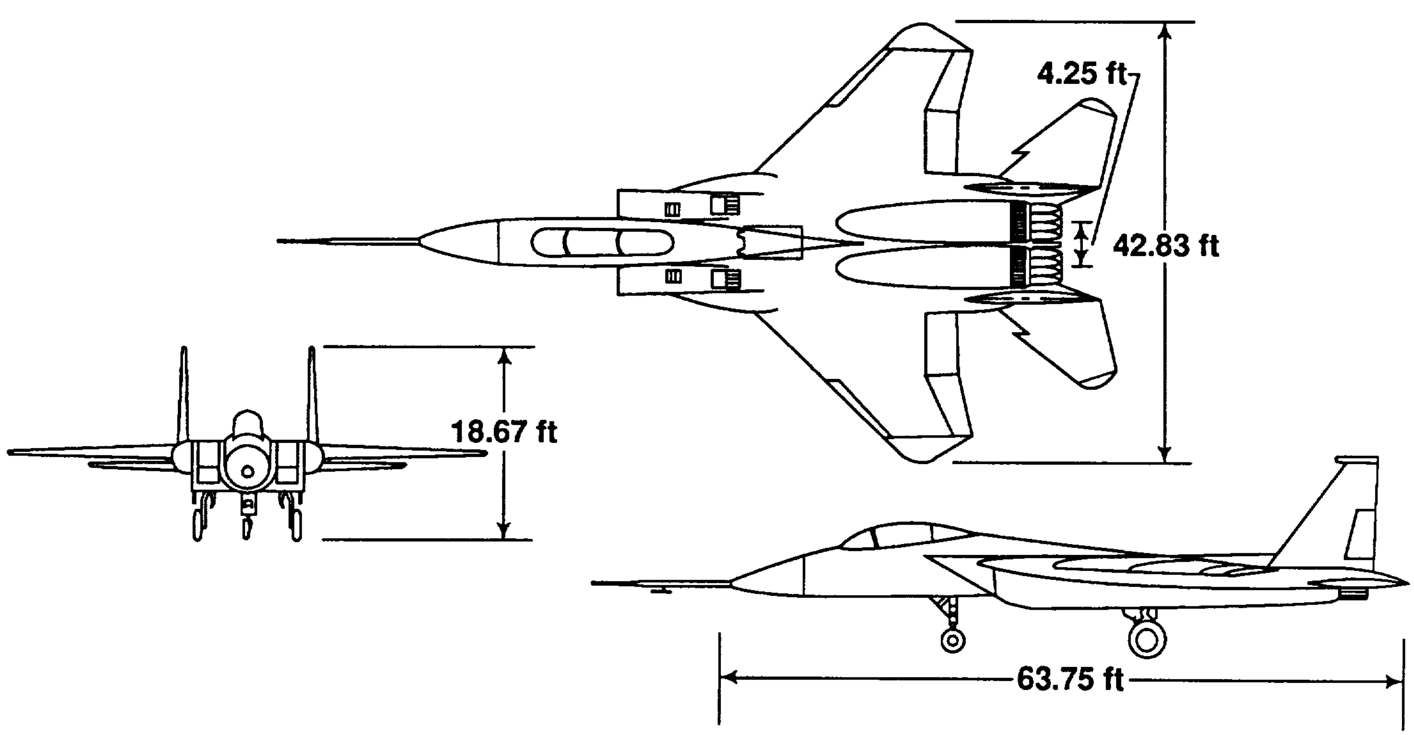
NASA F-15 Research Airplane

The NASA F-15 research airplane (USAF S/N 71-0287) was originally the 8th pre-production F-15 in the USAF test program. It, along with F-15 #2, (S/N 71-0281) came to Dryden in 1976, and was involved in a series of research programs, including flying qualities, buffet, and was the carrier airplane for the 10 deg cone flight experiment, ref 1. In 1980, propulsion experiments were begun on F-15 #8 and in 1985, it received NASA tail number 835.

The NASA F-15 is a single place air-superiority fighter airplane with excellent transonic maneuverability and a maximum Mach number of 2.5. The high-mounted low aspect ratio wing has a 45 deg leading edge sweep and conical camber. Reference wing area is 608 sq. ft. There are twin vertical tails and large all-moving horizontal stabilators. The F-15 propulsion system consists of variable-geometry horizontal ramp inlets on the forward fuselage each feeding afterburning turbofan engines located in the aft fuselage.

The NASA F-15 zero fuel weight is approximately 30,000 lb, and fuel capacity is 11,600 lb. It is equippped with a HUD video camera, and a data system that records digital and analog parameters on an on-board tape recorder, and also telemeters this data to the ground.

NASA F-15 Research Airplane



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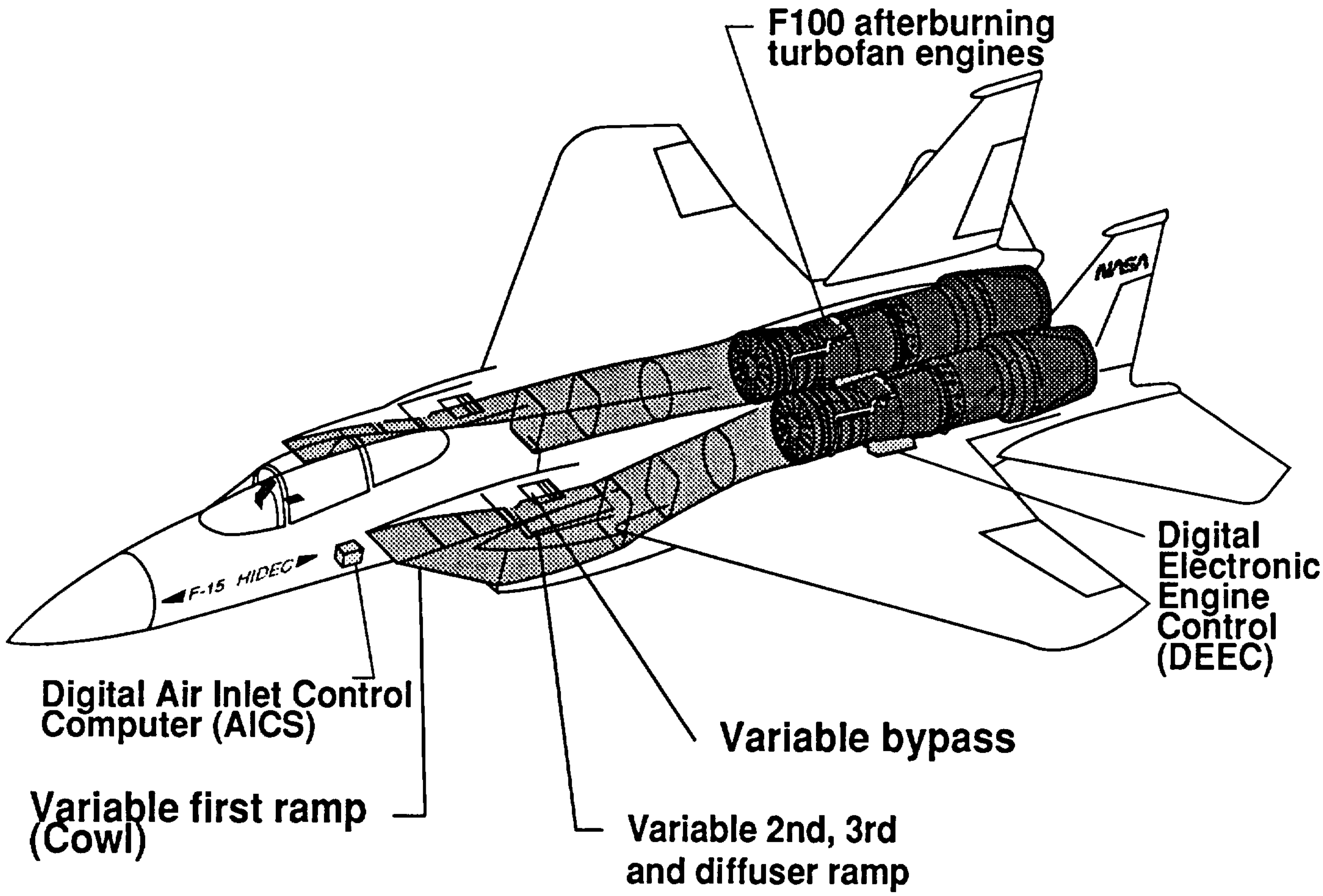
Propulsion System of the NASA F-15

The propulsion system of the F-15 is a highly integrated design consisting of two horizontal ramp inlets each feeding afterburning turbofan engines located in the aft fuselage.

As shown below, the inlets are mounted on the forward fuselage and are of the variable geometry external compression type. The first ramp is pivoted near the cowl lip and provides a variable capture capability to reduce spill drag as angle-of-attack increases. The second and third ramp and diffuser ramp are linked to provide proper compression at supersonic speeds. A bypass door is located on the upper inlet surface for proper airflow matching at supersonic speeds. A digital air inlet control system is provided to position the variable geometry.

The ducts, which are approximately seven diameters long, provide air to Pratt and Whitney F100 afterburning turbofan engines. These engines are low bypass ratio (approximately 0.5) and have a high thrust-to-weigh-ratio of approximately 8. For most tests, these engines were controlled by digital electronic engine control (DEEC) systems.

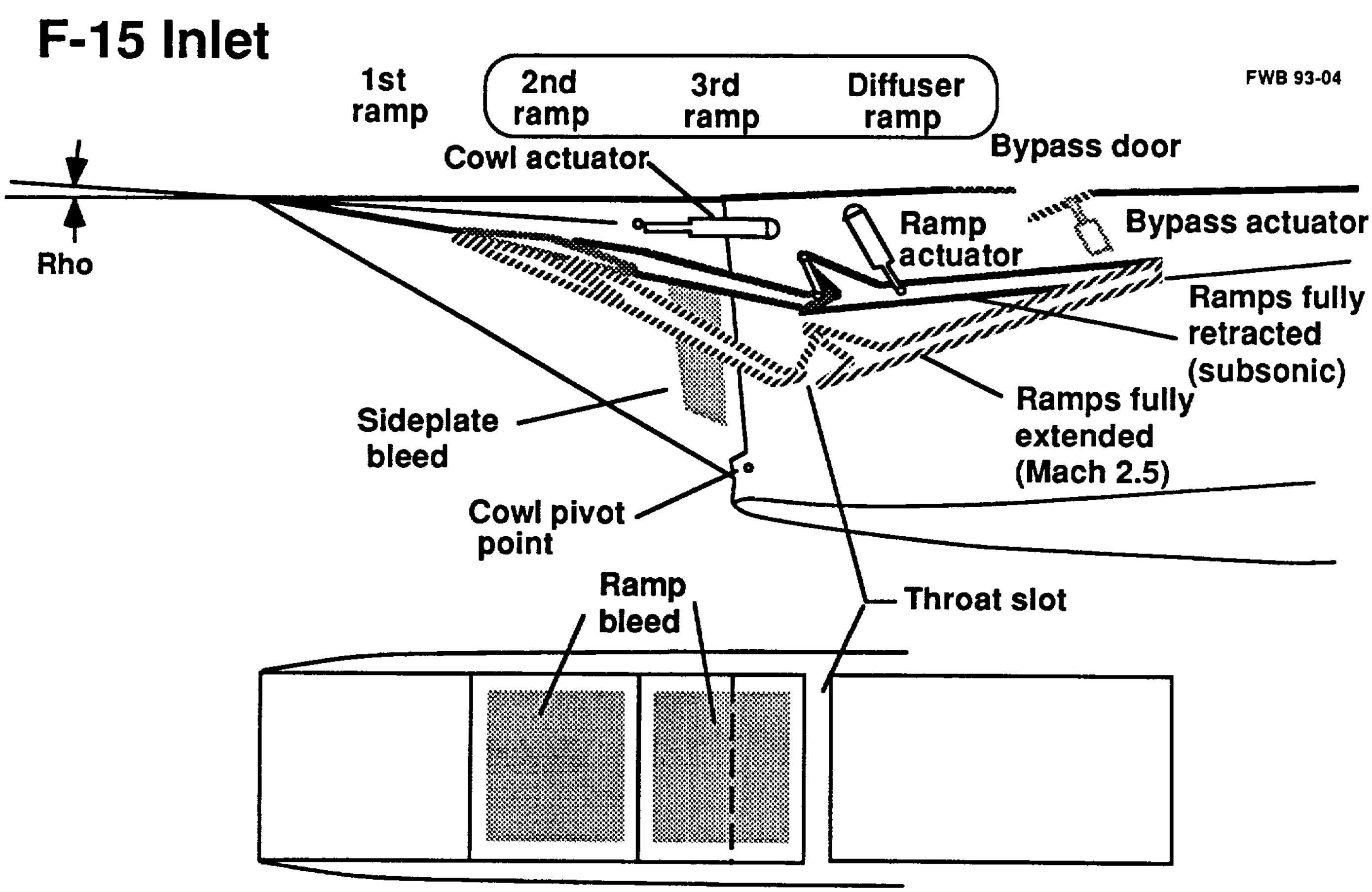
NASA F-15 Propulsion Sytem



F-15 Inlet

The F-15 variable geometry two-dimensional, external compression horizontal ramp inlet system is designed to provide high recovery, low distortion, and low spillage drag over the F-15 flight envelope. The variable first ramp, or cowl, rotates around a pivot located near the lower cowl lip to provide variable capture, and prevent excess inlet spillage drag at high angles of attack. The variable 2nd, 3rd, and diffuser ramps are linked to provide efficient compression at supersonic speeds. Boundary layer bleed is provided to improve recovery, distortion, and stability, using porous surfaces on the ramps, and the sideplates; and at the throat by a flush slot . A bypass door is provided to improve performance and provide airflow matching at Mach numbers above 1.6.

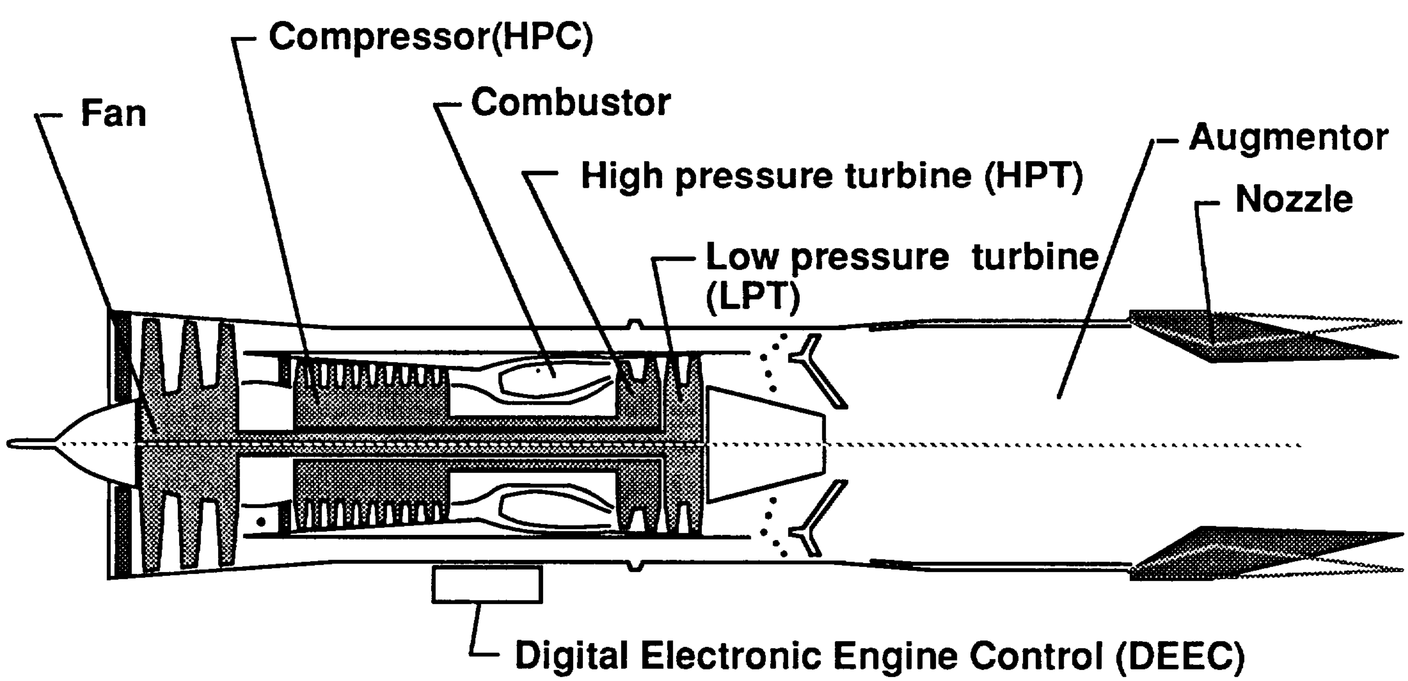
A digital control system positions the cowl, bypass and ramps as a function of local Mach number, local angle of attack, total temperature, and throat total and static pressure. The geometry is positioned by hydraulic actuators; if hydraulic pressure should be lost, the cowl and ramps drift to the full-up (emergency) position. In case of a malfunction, the pilot may also select the emergency position with a cockpit switch. At subsonic speeds, the ramps are fully up and the cowl schedules as a function of angle of attack. At supersonic speeds, the ramps extend primarily as a function of Mach number.



F100 engine

The F100 engine, shown below, is a low-bypass ratio, twin-spool, augmented turbofan engine. The three-stage fan is driven by a two-stage, low-pressure turbine. The 10-stage, high-pressure compressor is driven by a two-stage cooled turbine. The engine incorporates variable geometry (shown in red); compressor inlet variable vanes (CIVV) and 4 stages of rear compressor variable vanes (RCVV) to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a mixed flow augmentor and a variable area convergent-divergent balanced-beam nozzle. For the DEEC tests, an F100(3) engine, (P&W S/N- 680063) was used. This engine was later modified to the PW1128 configuration. For all PSC and PCA testing, F100 Engine Model Derivative (EMD) engines were used. These engines had a company designation of PW1128, and were development engines for the F100-PW-229 engines. The PW1128 was derived from the F100-PW-220, and features an increased airflow 248 lb/sec fan, single-crystal blades and vanes in the high pressure turbine, a 16 segment augmentor, and an improved DEEC.

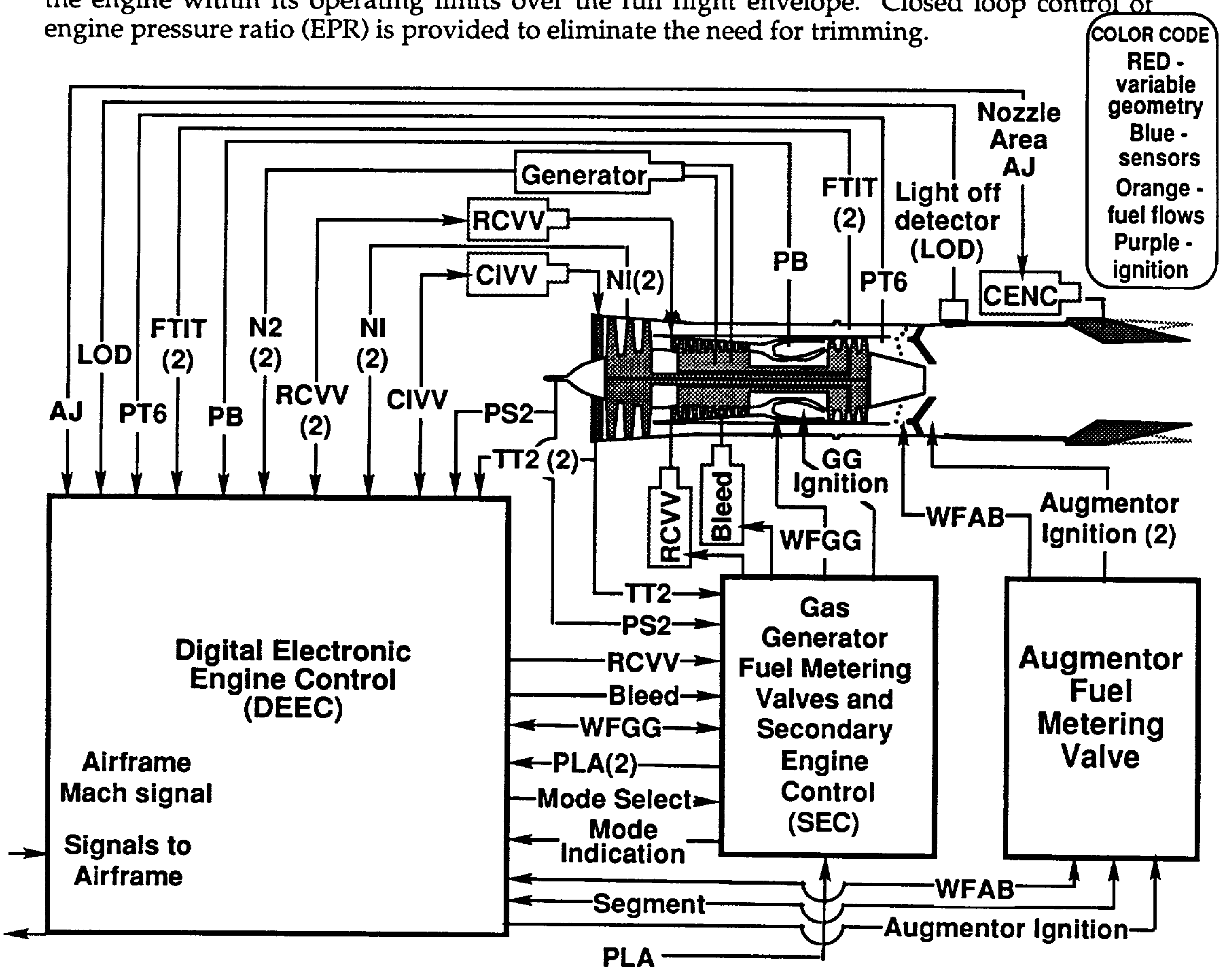
Cutaway view of the F100 engine



Digital Electronic Engine Control (DEEC)

The first full authority production-like digital engine control system flown was the P&W DEEC. It controls the major controlled variables on the engine, and replaces standard F100 engine control system. The DEEC is engine-mounted, and fuel-cooled, and consists of a single-channel digital controller with selective input-output redundancy, and a simple hydromechanical secondary engine control (SEC)

The DEEC system is functionally illustrated below. It receives inputs from the airframe through the power lever angle (PLA) and Mach number (M). Engine inputs are received from pressure sensors; fan inlet static pressure, (PS2), burner pressure, (PB), and turbine discharge total pressure, (PT6); temperature sensors, fan inlet total temperature, (TT2), and fan turbine inlet temperature, (FTIT), fan rotor speed sensors (N1) and core rotor speed sensors, (N2). It also receives feedbacks from the controlled variables through position feedback transducers indicating variable vane (CIVV and RCVV) positions, metering valve positions for gas-generator fuel flow (WFGG), augmentor fuel flow(WFAB), augmentor segment-sequence valve position, and exhaust nozzle position (AJ). The input information is processed by the DEEC computer to schedule the variable vanes (CIVV and RCVV), position the compressor start bleeds, control WFGG and WFAB, position the augmentor segment-sequence valve, and control the exhaust nozzle area. This logic provides linear thrust with PLA, rapid and stable throttle response, protection from fan and compressor stalls, and keeps the engine within its operating limits over the full flight envelope. Closed loop control of engine pressure ratio (EPR) is provided to eliminate the need for trimming.

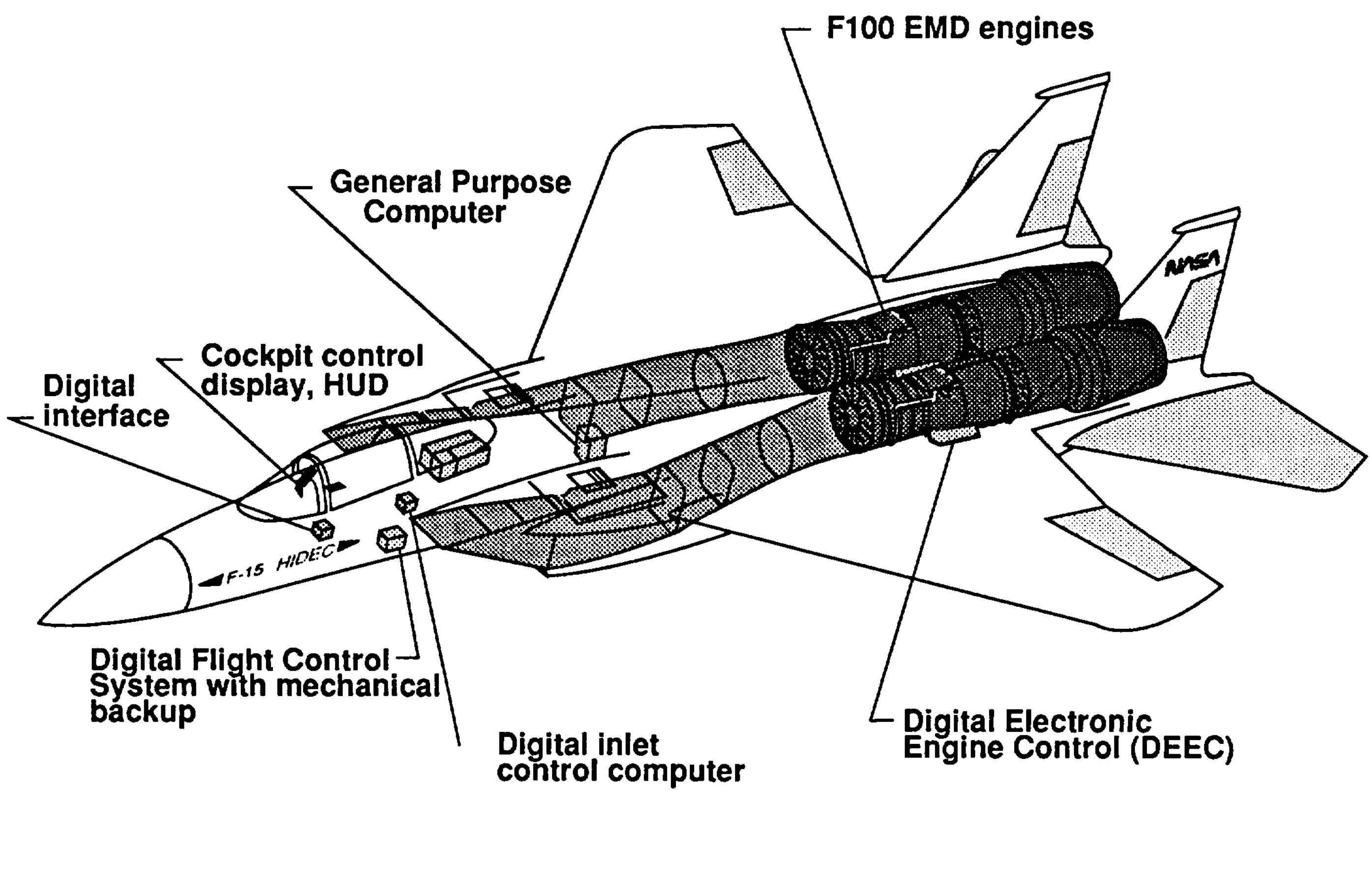


Integrated Control Features of the NASA F-15

The F-15 HIDEC airplane configuration has evolved over the years and is well-suited for integrated controls flight experiments. The features, shown below, include the F100 EMD engines with DEECs, the digital electronic flight control system (DEFCS), the digital inlet control computers, and an interface to allow these systems to communicate. Initially, control laws were hosted in the DEFCS, this configuration is shown on next page. Later, the general-purpose computer was added, and hosted the control laws for more complex integrated control algorithms, For the last tests, the vehicle management system computer replaced the DEFCS, and hosted the digital flight control system. The cockpit interfaces included the navigation control panel for inputs and the HUD for displays.

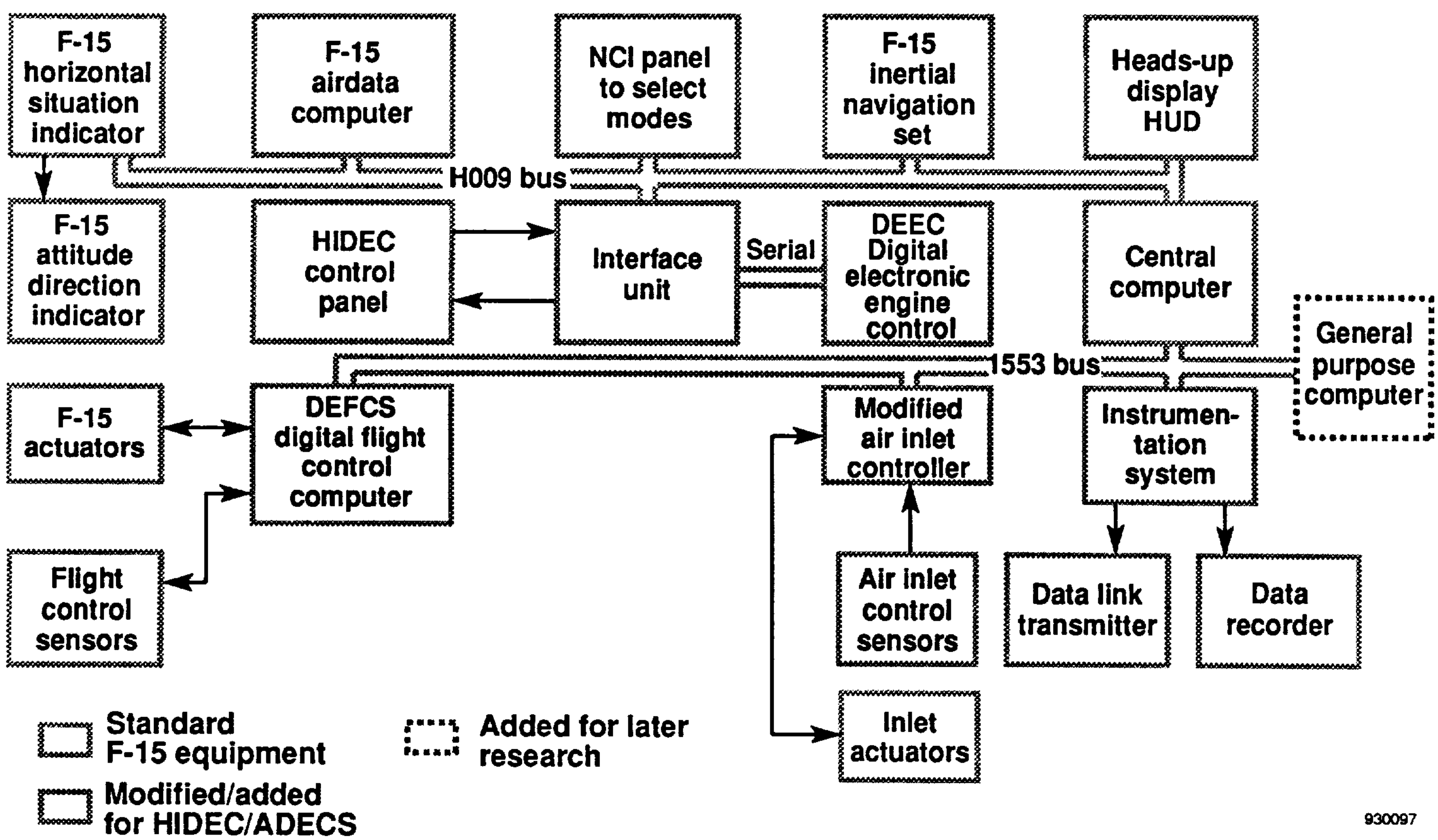
The digital flight control system, and the DEEC included backup dissimilar mechanical controllers so that the digital system software was not flight-safety critical, thus simplifying the software verification and validation process, and allowing research effort to be concentrated on control law research.

F-15 HIDEC Integrated Control Features



HIDEC System Architecture

The HIDEC system architecture is shown below, as it was arranged for the ADECS research with the inlet included. A key avionics box added was the interface unit that allowed the DEECs to communicate with the other F-15 systems and the Digital Electronic Flight Control System (DEFCS) that had excess capacity for research control laws. The various avionics units communicated with each other via H009 and 1553 digital data buses. Digital inputs were received from the digital flight control system, the inertial navigation set, the air data computer, the digital engine controls, commands were sent to the DEECs and inlets during ADECS operation. Later, the general purpose computer was added to accommodate more complex control laws programmed in FORTRAN.



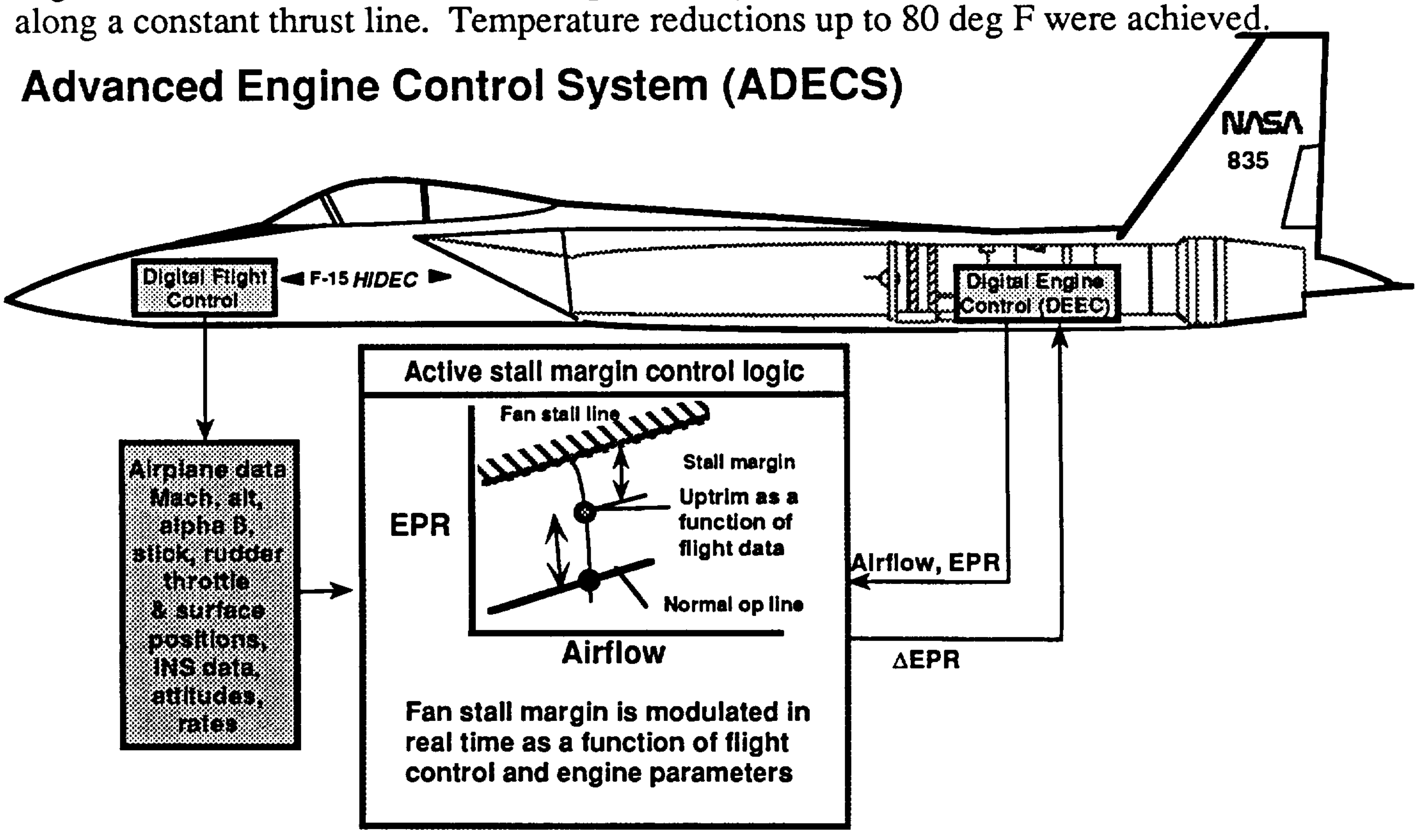
Advanced Engine Control System (ADECS)

As part of the HIDEC program, an advanced engine control system (ADECS) mode was incorporated on the F-15 airplane. McDonnell Douglas, USAF, and Pratt and Whitney assisted NASA in developing and testing ADECS. In ADECS, shown below, airframe and engine information is used to allow the engine to operate at higher performance levels at times when the inlet distortion is low and the full engine stall margin is not required. The ADECS mode increased thrust levels as shown in the fan map by increasing EPR at constant airflow (EPR uptrim). Fuel flow reductions could also be obtained by holding thrust constant as EPR was increased. In essence, ADECS traded unneeded stall margin for thrust. Schedules of EPR uptrim as a function of engine conditions, angle-of-attack, sideslip, and pilot's stick position were stored in the on-board research computer and the uptrims were computed and sent to the DEECs 4 times per second.

In the flight evaluation, the ADECS system was evaluated on the F100 EMD engines on the F-15. Significant performance improvements were demonstrated. Thrust improvements and constant-thrust fuel flow reductions were determined, and compared to predictions. The ability of the ADECS to accommodate rapid aircraft maneuvers and throttle transients was also demonstrated. Intentional stalls were also conducted to validate the stability audit procedures used to develop the ADECS logic.

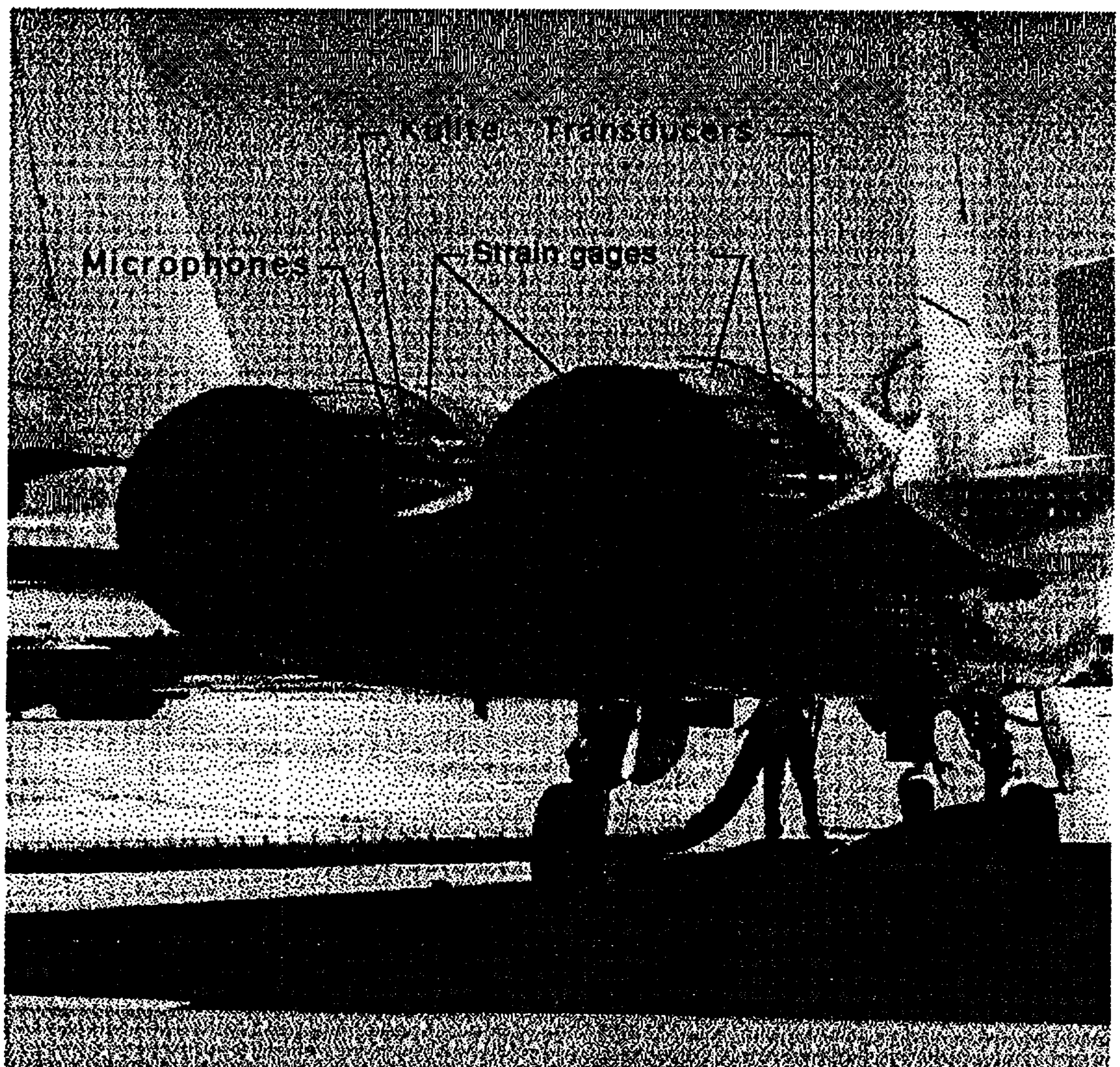
Typical results for an altitude of 30,000 ft. showed increases of 8 to 10 percent in thrust at intermediate power. Fuel flow reductions of 7 to 17 percent were obtained at maximum thrust with the PLA reduced to hold thrust constant. These engine performance improvements resulted in airplane performance improvements (rate of climb, specific excess power) of 10 to 25 percent.

Stall margin could also be traded for reduced temperature, resulting in extended engine life (EEL). EEL was accomplished by increasing EPR and reducing airflow along a constant thrust line. Temperature reductions up to 80 deg F were achieved.



Twin-Jet Acoustic Interactions

During the ADECS project, NASA Langley requested that Dryden join with them in an acoustics research program to investigate twin jet acoustic interactions. The F-15 and B-1 installations, with close-spaced engines, had both experienced cracked outer nozzle flaps, whereas similar engines running in a single-engine installation in the F-16 did not crack. Dryden installed about 25 high frequency microphones, pressure transducers, and strain gages on the nozzle flaps and interfairing areas. The photo below shows F100 EMD engine P085 on the left and P063 both with the instrumented external flaps installed in the F-15. The HIDEC ADECS system provided an added capability for this test. 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 EPR on one engine until it matched the other. Flights varied Mach number and altitude as well as power setting. Langley analyzed the acoustics data while Dryden provided the exhaust conditions. The results were correlated with small scale cold jet test data and are presented in the references.

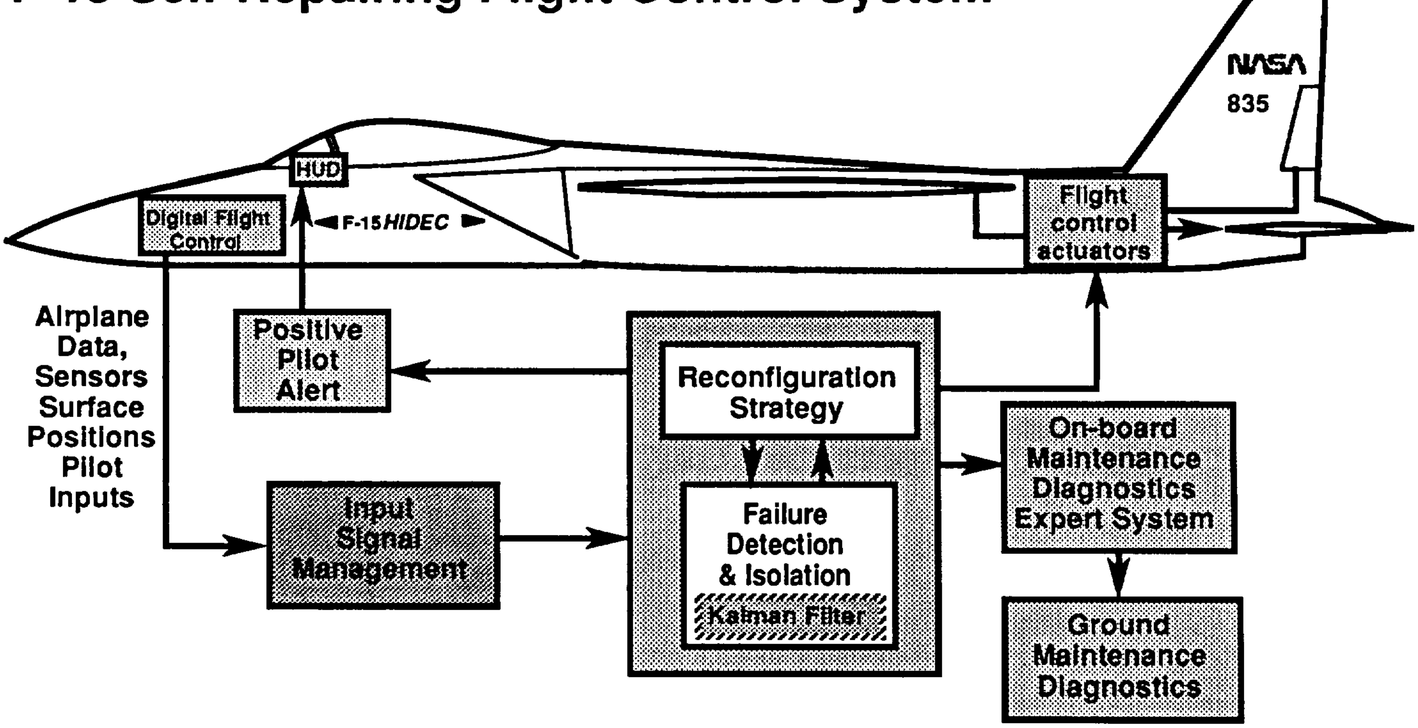


Self-Repairing Flight Control System (SRFCS)

NASA Dryden, in conjunction with the USAF, MDA, GE and other contractors, flew a self-repairing flight control system on the NASA F-15. The system, shown below, used a Kalman filter for fault detection and isolation for locked and floating surfaces and partial surface loss. Upon detecting a failure, the control laws were reconfigured to use the remaining surfaces. The pilot was provided with an alert on his HUD, along with an indication of the remaining maneuver capability after the reconfiguration. There was also an on-board expert system for maintenance diagnostics, which fed into the ground diagnostics capability. Most of this system was installed in the on-board general-purpose Rolm Hawk research computer. Simulated failures could be introduced into the system through pilot commands.

The SRFCS was flown in a 25 flight program beginning in late 1989. Forty-three hours of data was accumulated, and quality data was excellent. All of the reconfiguration tests were successful. Most of the induced failures were detected, although some of the partial surface failures were not correctly identified. The flying qualities in the reconfigured system were generally good except for fine tracking. Most impressive was the lack of any false alarms.

F-15 Self-Repairing Flight Control System

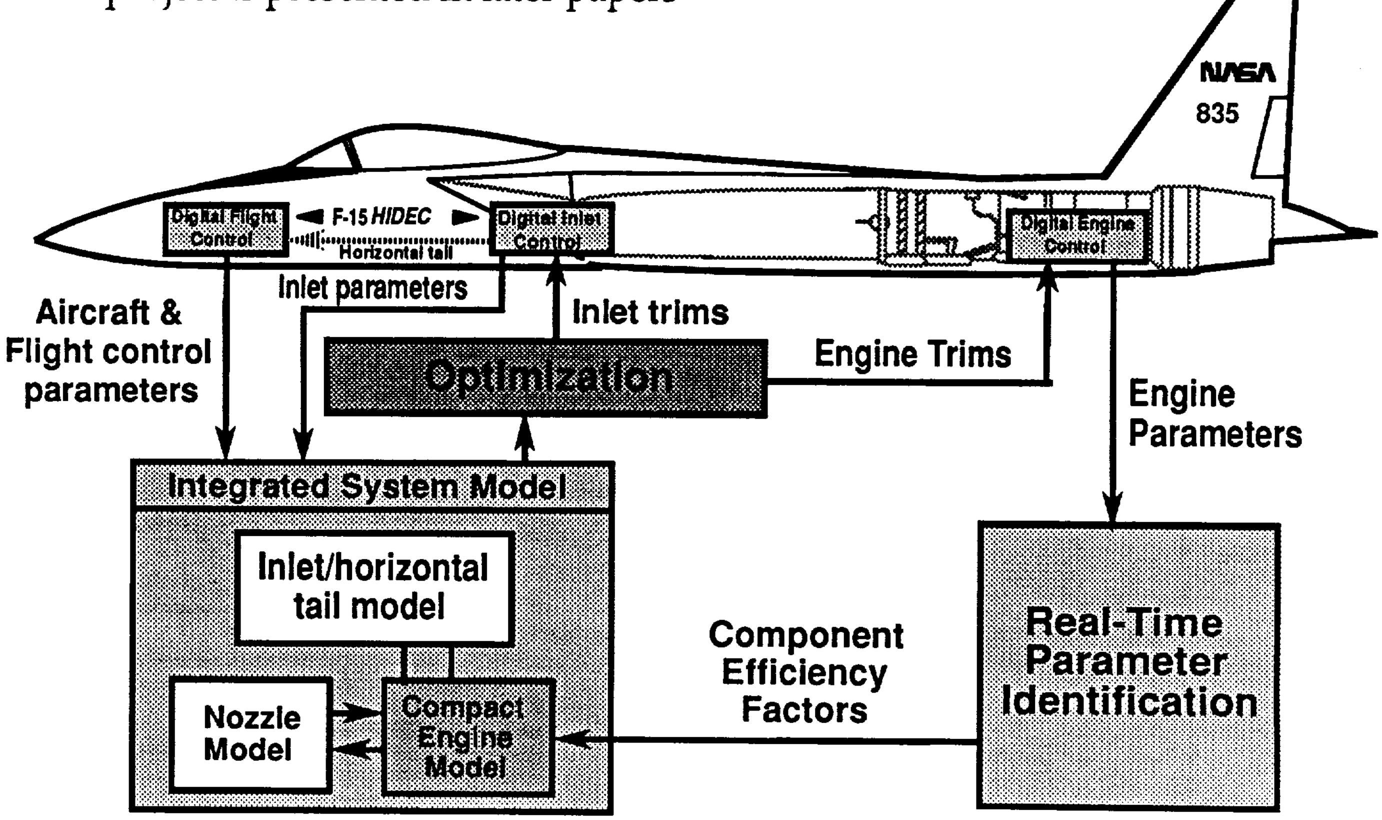


Performance-Seeking Control (PSC)

After the success of the ADECS tests, which was a schedule-based optimization of a single parameter (EPR) for an average engine, it was desired to perform a more sophisticated optimization. The Performance-Seeking Control (PSC) project selected a model-based approach, and performed an adaptive optimization of the propulsion system parameters on the F-15. McDonnell Douglas and Pratt and Whitney assisted NASA in developing and testing the PSC system. Several modes were implemented in the on-board research computer, including maximum thrust, minimum fuel flow at constant thrust, minimum temperature at constant thrust, and minimum supersonic thrust for rapid supersonic deceleration.

In the flight evaluation, the PSC system was evaluated on the F100 EMD engines on the F-15. Significant performance improvements were demonstrated. Thrust improvements and constant thrust temperature reductions and fuel flow reductions were determined, and compared to predictions. Various levels of engine degradation were also tested. Intentional engine stalls were conducted to validate the stability audit procedures.

Typical results for an altitude of 30,000 ft. showed increases of 10 to 14 percent in thrust at intermediate power. Fuel flow reductions of 7 to 17 percent were obtained in the afterburning range with thrust held constant. These engine performance improvements resulted in airplane performance improvements (rate of climb, specific excess power) of 10 to 25 percent. The PCA project is presented in later papers

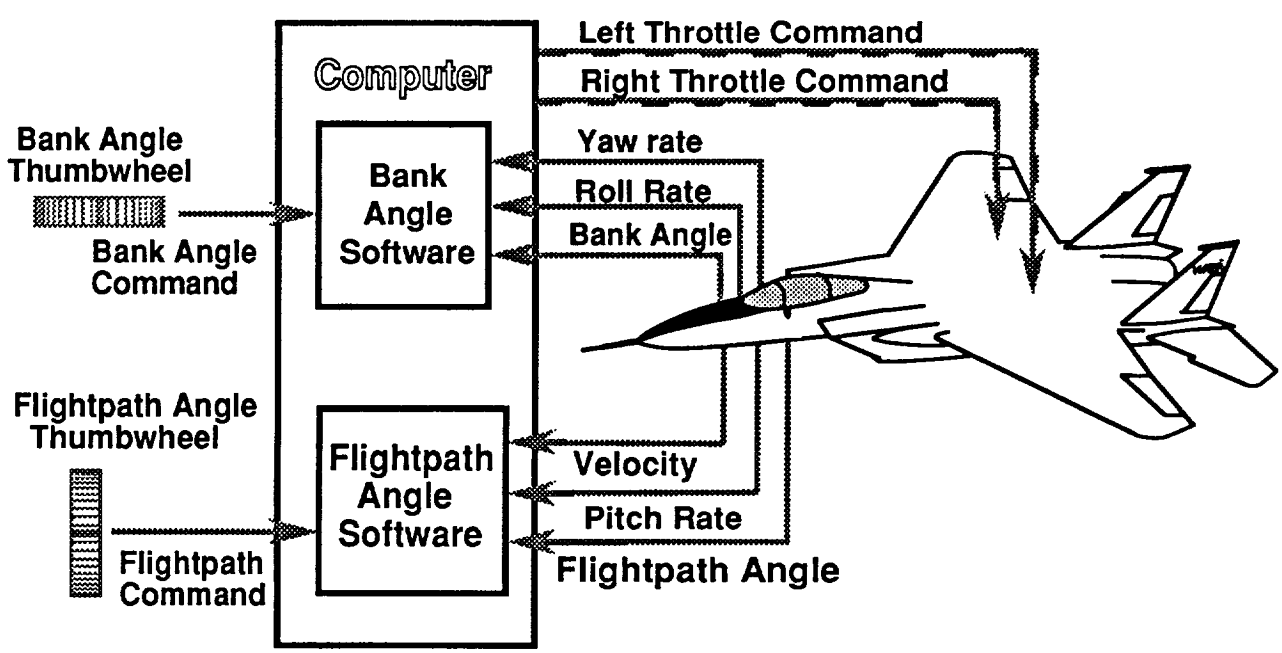


Propulsion Controlled Aircraft (PCA)

As a result of several accidents in which all or major parts of the flight control system was lost, NASA Dryden investigated the capability for a "Propulsion Controlled Aircraft" (PCA), using only engine thrust for flight control.

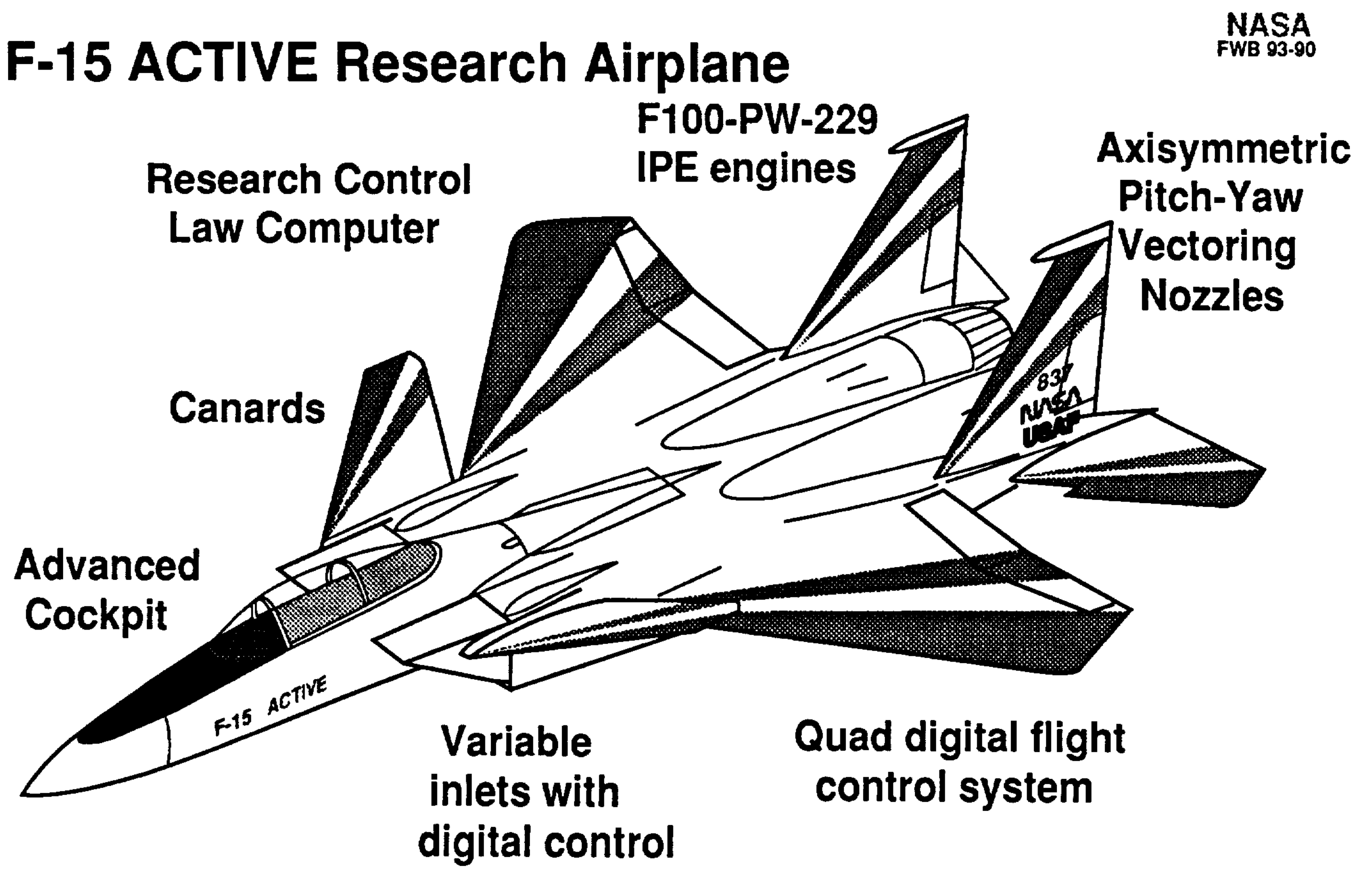
Initial flight studies with the pilot manually controlling the throttles and all flight controls locked in the NASA F-15 showed that it was possible to maintain gross control. For instance, a climb could be initiated by adding an equal amount of power to both engines. Bank control could be achieved by adding power to one engine and reducing power to the opposite engine. Using these techniques, altitude could be maintained within a few hundred feet and heading to within a few degrees. These same flights showed that it was extremely difficult to land on a runway. This was due to the small control forces and moments of engine thrust, difficulty in controlling the phugoid oscillations, and difficulty in compensating for the slow engine response. Studies in flight simulators at Dryden and at McDonnell Douglas were able to duplicate the flight results. These simulators also established the feasibility of a PCA mode, shown below, using feedback of parameters such as flight path angle and bank angle to augment the throttle control capability and to stabilize the airplane.

The NASA F-15 was an ideal testbed airplane for this research. It incorporated digital engine controls, digital flight controls, had a general-purpose computer and data bus architecture that permitted these digital systems to communicate with each other. The only equipment added to the airplane was a control panel containing 2 thumbwheels, one for flightpath command, and the other for bank angle command. Later papers will describe the design, development, and flight test results.



F-15 ACTIVE Research Airplane

The integrated controls flight research program from the HIDEC airplane will be continued on the F-15 ACTIVE (Advanced Control Technology for Integrated VEhicles) airplane. This F-15 airplane was transferred to NASA following the USAF STOL/Maneuver Technology Demonstrator program. Features are shown below. The airplane has independently actuated canards, a quad redundant digital flight control system, an advanced (F-15E) cockpit, F100-PW-229 engines with improved DEECs, and will be equipped with Pratt and Whitney axisymmetric thrust vectoring nozzles. The research computer will be transferred from the HIDEC airplane, as will the digital inlet control system. This program is discussed in the ACTIVE Plans paper.



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PSC Session Information

A model-based, adaptive control algorithm called Performance Seeking Control (PSC) has been flight tested on an F-15 aircraft. The PSC was developed to optimize aircraft propulsion system performance during steady-state engine operation. The multimode algorithm minimizes fuel consumption at cruise conditions; maximizes excess thrust (thrust minus drag) during aircraft accelerations; extends engine life by decreasing Fan Turbine Inlet Temperature (FTIT) during cruise or accelerations; and reduces supersonic deceleration time by minimizing excess thrust. On-board models of the inlet, engine, and nozzle are optimized to compute a set of control trims, which are then applied as increments to the nominal engine and inlet control schedules. The on-board engine model is continuously updated to match the operating characteristics of the actual engine cycle through the use of a Kalman filter, which accounts for unmodeled effects. The PSC algorithm has been flight demonstrated on the NASA F-15 HIDEC test aircraft. This session includes papers which present the key elements of the PSC algorithm, its implementation and integration with the aircraft, and summarizes the flight test results.

Agenda

John S. Orme, "Performance Seeking Control Program Overview"

Mark Bushman, Steven G. Nobbs, "F-15 Propulsion System"

Steven G. Nobbs, "PSC Algorithm Description"

Steven G. Nobbs, "PSC Implementation and Integration"

John S. Orme, Steven G. Nobbs, "Minimum Fuel Mode Evaluation"

John S. Orme, Steven G. Nobbs, "Minimum Fan Turbine Inlet Temperature Mode Evaluation"

John S. Orme, Steven G. Nobbs, "Maximum Thrust Mode Evaluation"

Timothy R. Conners, Steven G. Nobbs, John S. Orme, "Rapid Deceleration Mode Evaluation"

Timothy R. Conners, Steven G. Nobbs, "Thrust Stand Test"

Gerard Schkolnik, "Performance Seeking Control Excitation Mode"

Timothy R. Conners, "PSC Asymmetric Thrust Alleviation Mode"

PSC Session Information (Concluded)

Agenda (Concluded)

John S. Orme, "Summary"

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