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# IPCS IMPLICATIONS FOR FUTURE SUPERSONIC TRANSPORT AIRCRAFT

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## SUMMARY

The Integrated Propulsion Control System (IPCS) will demonstrate control of an entire supersonic propulsion module - inlet, engine afterburner, and nozzle - with an HDC 601 digital computer. The program encompasses the design, build, qualification, and flight testing of control modes, software, and hardware. The flight test vehicle will be an F-111E airplane owned by the government. The L.H. inlet and engine will be operated under control of a digital computer mounted in the weapons bay. A general description and the current status of the IPCS program are given.

## INTRODUCTION

The historical trend of controls development has been toward greater functional integration to maximize aircraft mission capability. This trend will undoubtedly continue as analytical techniques are refined and flightworthy hardware becomes more readily available. The eventual result may be the integration of propulsion and flight control subsystems as diagrammed in figure 1. Until then, integrated control of propulsion system components must stand on its own merits. SST experience convinced Boeing that the classical approach to propulsion control is inadequate, expensive, and even hazardous when applied to high performance aircraft. New engineering techniques must be developed to obtain the required control coordination. New management techniques must be devised to permit simultaneous development by various manufacturers of subsystems that will share and use in an optimum fashion the information available to the total system.

We are confident that the Integrated Propulsion Control System is technically and economically reasonable. The IPCS program will demonstrate this feasibility in flight tests and lay the groundwork for its incorporation into future aircraft.

A discussion of some key aspects of the IPCS Program is given in this paper. Since many forms of technology are represented in the IPCS activity, a complete description would be very lengthy. Discussion of some activities has been deliberately omitted in this paper so that more space and time could be devoted to those features that may be relevant to future supersonic transport aircraft. This is consistent with the goals of the National Aeronautics and Space Administration in conducting the Symposium.

## OVERVIEW

The Integrated Propulsion Control System (IPCS) Program encompasses the design, build, flight qualification, and flight testing of propulsion control modes, software, and hardware. The flight test vehicle will be an F-111E airplane owned by the government. The L-H inlet and TF30-P-9 engine will be modified to operate under control of an HDC-601 digital computer mounted in the aircraft weapons bay. The layout of the IPCS on the aircraft is shown in Figure 2.

The IPCS is one of the Exploratory Research Programs funded by the Air Force Aero Propulsion Laboratory*. Technical support is being provided by NASA; the Flight Research Center (FRC) and the Lewis Research Center (LeRC). Major contractors are Boeing Aerospace Company, Honeywell, Inc., G&AP Division, and Pratt and Whitney Division of United Aircraft (P&WA™). A diagram showing organizational responsibilities is given on figure 3.

The goals of the Air Force in funding the IPCS program are twofold:

1. Improve aircraft systems performance through technological advances.

2. Reduce the cost and risk of future development programs through an expanded technical data base and demonstrated management methodology.

Specific goals established for the IPCS program pursue the goals of the Air Force Exploratory Development Programs. The first of these is to develop, demonstrate, and evaluate in a flight environment, certain advanced technical features that have to date been explored only under very restricted conditions. These are listed in Table 1.

The second major goal is the development of an intercompany management approach applicable to the design and development of integrated systems. The IPCS management methodology addresses three areas of potential concern;

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TABLE 1

IPCS ADVANCED TECHNICAL FEATURES

- Full authority digital propulsion control with hydromechanical backup. This will permit control law changes without hardware modification.
- Closed loop control on turbine-inlet gas temperature (TIGT).
- Use of compressor discharge Mach number for surge protection during engine transients.
- Automatic detection and suppression of inlet buzz so that engine airflow may be reduced during airplane deceleration.
- Continuous monitoring of distortion to extend the operating envelope with the compressor surge bleeds closed.
- Fuel manifold prefill logic to smooth afterburner transients.

TABLE 2

SALIENT FEATURES OF IPCS INTERCOMPANY MANAGEMENT APPROACH

- Horizontal division of responsibility - each organization exercises its own area of expertise over the entire range of the program.
- Direct communication at the working level is stressed.
- Regular (monthly) coordination meetings are attended by representatives of the prime and major subcontractors.
- Periodic working sessions are conducted with attendance by technical personnel of each of the three firms. These meeting sites are rotated.
- Progressive step-by-step hardware test sequence.
- Final decisions impacting program costs or schedule are made by the prime contractor.

division of responsibilities, communication and coordination between geographically remote organizations, and minimization of technical risk and cost through a timely test sequence. The salient features of the IPCS management approach are listed in Table 2.

Achievement of these program goals will identify potential development problem areas. It will generate a body of technical data upon which to base further development work and will provide a basis for estimating the time and cost of development of an operational IPCS.

## IPCS DEVELOPMENT SEQUENCE

Major IPCS activities are shown in figure 4. Contract date was 1 March 1973. The Air Force has determined that a 36 month program is compatible with the scope of the program; hence flight test completion is scheduled for 29 February 1976. (An additional four months are allowed for data reduction and preparation of the final report.) The IPCS schedule was developed to fit these constraints.

It will be noted that about half of the total program period is devoted to an extensive test program. This required careful scheduling of the analysis, design, and fabrication of hardware and software to meet the test dates. This requirement influenced the design procedure to a great extent, as will be discussed later in this paper.

## DATA MANAGEMENT

There are four classes of data involved in a program such as IPCS:

- Design data
- Hardware and software checkout data
- Data for test planning and test monitoring
- Test evaluation data (results)

Activity was initiated immediately after contract to compile all available data on the characteristics of the P&WA TF30-P-9 engine and the F-111E inlet. In addition to published Air Force and NASA data, a substantial amount of unpublished information was obtained under subcontract from P&WA and General Dynamics/Convair Aerospace Division. These data were incorporated into a document that will be updated at 6-month intervals as necessary throughout the program. Much of the design work was based on the data compiled under this task.

The data compilation discussed above is being supplemented by baseline tests of the IPCS engines and aircraft. These tests also serve as development vehicles for the data acquisition/reduction hardware, software, and procedures to be used during the IPCS flight evaluation program. The baseline engine tests were conducted by NASA/LeRC in their altitude facility. This test series was completed in February, 1974. The baseline flight tests, to be conducted by NASA/FRC are scheduled to begin in July, 1974. The baseline test program is described later under the test program heading. The handling of the data is described below. It is anticipated that similar procedures will be used in subsequent system-level tests.

## Instrumentation

The intent in selecting instrumentation for the IPCS program was to measure engine and inlet operating parameters with minimum disturbance to the gas flow. Thus, it was decided that the only rakes to be added to the flow path would be to measure compressor face distortion and new control signals. The remaining instrumentation is either production sensors or measurements which can be made at the wall or in control system lines, etc. To the extent possible the same or similar instrumentation will be used throughout the test program to facilitiate data comparisons from one test to another. Table 3 lists the instrumentation for the baseline and IPCS tests.

For the IPCS control mode, total pressure and temperature measurements are required at the exits of the high and low pressure compressors and total temperature is needed at the turbine inlet. Probe designs and the required engine case modifications for these probes were not available prior to the start of the baseline engine test. Total pressure and temperature measurements were made at the low pressure compressor exit using probes similar to the IPCS design that could be inserted through an existing hole in the engine case. These compressor exit measurements will not be made during the baseline flight test since the IPCS engines will not be used.

An unavoidable difference in instrumentation systems exists between LeRC and FRC. In the flight tests there will be no steady-state instrumentation equivalent to the DAMPR system at LeRC during the IPCS flight test, therefore data from the Digital Propulsion Control Unit (DPCU) will be used. Where possible the equivalent test instrumentation will be eliminated to avoid duplication in sensors and data processing. To a degree the same approach can be used during the IPCS altitude test, however, during this test it will be important to retain sufficient instrumentation to demonstrate the validity of the control sensors.

## Recording

Both digital and analog recording systems will be used - digital for low frequency response data (DC-50HZ) and analog for high frequency response data (∿500 HZ). The NASA/LeRC digital system consists of a steady-state system for performance measurement, and a 200 channel low-to-medium frequency system used for recording transients. NASA/FRC uses a PCM digital system for both steady-state and low frequency transient data. At both facilities the high frequency data are recorded on FM analog systems.

TABLE 3

INSTRUMENTATION

| VARIABLE | ENG TEST B/L | ENG TEST IPCS | FLT TEST B/L | FLT TEST IPCS |
|---|---|---|---|---|
| **AIRPLANE/TEST CELL CONDITIONS** | | | | |
| Freestream Total Pressure | X | X | X | X |
| Freestream Static Pressure | X | X | X | X |
| CG Long. Accel. | | | X | X |
| Freestream Total Temperature | X | X | X | X |
| Wing Sweep Angle | | | X | X |
| Angle of Attack | | | X | X |
| Angle of Sideslip | | | X | X |
| **ENGINE VARIABLES** | | | | |
| Total Fuel Flow. Wft | X | X | X | X |
| Engine Fuel Flow, Wfe | X | X | X | X |
| Engine Fuel Temperature | X | X | X | X |
| Throttle Position, (PLA) | X | $X^1$ | X | $X^1$ |
| RPM (N1) | X | $X^1$ | X | $X^1$ |
| RPM (N2) | X | $X^1$ | X | $X^1$ |
| Engine Hub Total Pressure, Pt2n | | | X | $X^1$ |
| Fan Exit Static Pressure, PS13 | X | X | X | X |
| LPC Exit Static Pressure, PS22 | X | $X^1$ | X | $X^1$ |
| LPC Exit Total Pressure, P22 | X | $X^1$ | | $X^1$ |
| LPC Exit Pressure Differential (P-PS)22 | X | $X^1$ | | $X^1$ |
| HPC Exit Static Pressure, PS3 | X | $X^1$ | X | $X^1$ |
| HPC Exit Total Pressure, P3 | | $X^1$ | | $X^1$ |
| HPC Exit Pressure Differential, (P-PS)3 | | $X^1$ | | $X^1$ |
| LP Turbine Exhaust Pressure (P6M) | X | $X^1$ | X | $X^1$ |
| Engine Pressure Ratio (EP2) | | | X | X |
| Compressor Face Temperature (T2) | X | $X^1$ | X | $X^1$ |
| HPC Inlet Temperature (T22) | | $X^1$ | | $X^1$ |
| HPC Exit Temperature (T3) | X | $X^1$ | X | $X^1$ |
| Turbine Inlet Temperature-measured (T4) | | $X^1$ | | $X^1$ |
| Turbine Inlet Temperature-harness (T4H) | X | $X^1$ | X | $X^1$ |
| Turbine Discharge Temperature (T5) | X | $X^1$ | X | $X^1$ |
| Nozzle Area (AJ) | X | $X^1$ | X | $X^1$ |
| Compressor Bleed Switch Positions | X | $X^1$ | X | $X^1$ |
| Engine Fuel Pressure (2) | X | X | X | X |
| A/B Fuel Pressure (5) | X | X | X | X |
| Main Fuel Valve Position | | $X^1$ | | $X^1$ |
| A/B Metering Valve Position (5) | | $X^1$ | | $X^1$ |
| Computer Calculated Parameters | | $X^1$ | | $X^1$ |

1 Available from the DPCU

TABLE 3 (Continued)

| VARIABLE | ENG TEST B/L | ENG TEST IPCS | FLT TEST B/L | FLT TEST IPCS |
|---|---|---|---|---|
| **INLET VARIABLES** | | | | |
| 40-Probe Compressor Face Rake | X | X | X | X |
| Rake Zero Switch | X | X | X | X |
| Reference Pressure | X | X | X | X |
| Distortion Computer Output | X | X | X | X |
| Nulling Rake Pressure | | | X | X |
| Spike Position | | | X | X |
| Cone Angle | | | X | X |
| Local Mach Pressure Ratio | | | X | X[1] |
| Duct Mach Pressure Ratio | | | X | X[1] |
| Shock Position Signal | | | X | |
| Distortion Signal | | | | X[1] |
| **MISC.** | | | | |
| Tape Motion Switch | | | X | X |
| Event Marker | X | X | X | X |

1 Available from the DPCU

During flight tests the PCM data will be telemetered to the ground for use in monitoring the progress of the test flight. Approximately 80 digital-to-analog converters and Sanborn recorders are available to convert the data into time histories during the flight. There is no requirement to telemeter any of the analog data during the flight.

## Data Processing

NASA/LeRC provided on-line capability to process much of the steady-state data during baseline engine tests. The on-line program, which uses a remote terminal on the IBM 360, had the capability of calculating any of several separate sets of variables. A complete run of the program was made overnight to provide the remainder of the data by early the morning after the run. In addition, selected data were recorded on oscillograph for use in running the test.

The PCM data will be telemetered during the flight tests. These data will be demultiplexed and up to 80 channels will be displayed on Sanborn recorders on-line, in real time. Digital tapes of the data from the PCM system will be prepared by NASA. These data will be calibrated and will be in engineering units. Printouts of these tapes will be available within a week of the flight for use at FRC.

The FM data are demultiplexed and digitized by the Boeing Test Data Processing Center. The typical data sample consists of a 200 millisecond interval centered about an event such as a period of high distortion or compressor surge. The pressure signals are low-pass filtered (-3Db at 160 Hz) to retain only the frequency range of significance to the engine. Data are digitized at a rate of 1,000 samples per second per channel. The output digital data tape is converted to a format compatible with the CDC 6600 for the remainder of the processing. The digitized data are then processed through the distortion routine used with the steady-state data. Figure 5 presents a typical distortion time history for a stall event from the baseline test.

The major differences between the engine and flight test data processing programs are in the input and output routines due to the different data systems and variables being recorded, absence in the flight programs of some engine calculations, and the addition of inlet and airplane computations in the flight data program. Data from steady flight conditions will be averaged to produce steady-state data.

# DYNAMIC SIMULATIONS

Dynamic simulations of the F-111 propulsion systems have formed the foundation for the IPCS control system development and software validation. Two types of simulations have been generated. The first is an entirely digital simulation developed for use on a large digital computer such as a

CDC 6600. The second is a comprehensive hybrid simulation, based on the digital simulation, that was developed by Honeywell. They incorporate much of the system definition data and hence form a compact and convenient repository for masses of detailed information. Linear state models extracted from the digital simulation have been used to study control system stability and response. The digital simulation has been the principal test bed for evaluating new control modes. The hybrid simulation is being used to evaluate the response of the system to selected failures and will be used to check out both the digital propulsion control unit (DPCU) and its software prior to shipment.

## Digital Simulation

The digital simulation employs the SOAPP system developed by P&WA. With this modular system, most of the simulation is created from routines drawn from the SOAPP library. This library is a major reason for the development of SOAPP. It forms a repository for up-to-date versions of those utility routines that determine the speed and accuracy of the simulation.

The SOAPP program generates both steady-state and transient engine performance data. This feature is made possible by the application of a technique called SMITE, originally conceived by the Air Force AeroPropulsion Laboratory. It uses the solution to a set of linearized adjunct equations to obtain an iterative solution to the complex nonlinear equations in the simulation. Steady-state solutions are obtained merely by setting all the temporal derivatives to zero. Figure 6 illustrates the simulation adjustment. Data generated by the digital program are compared to corresponding baseline engine test data obtained at NASA/LeRC. Adjustment improved the fidelity of the simulation significantly.

## Hybrid Simulation

The hybrid simulation of the propulsion system has been prepared using two 781 EAI analog computers, two 231R EAI analog computers, a PACER 16k digital computer, and a SIGMA 5 40k digital computer. The PACER is used solely for generating bivariate functions, for on-line analysis, and for problem setup. The Σ5 computer is used to generate the control functions and to drive a scope display. The system has been designed to run ten times slower than real time when under control of the Σ5.

Check-out of the DPCU hardware and software will be accomplished by replacing the Σ5 by the HDC 601 flight computer with its interface unit (IFU). A custom built simulation interface adapter (SIA) will condition signals from the analog computers to simulate the outputs from the flight transducers. In this service, the simulation will run in real time. All time-dependent functions are performed in the EAI 781 computers to facilitate time scale switching.

## CONTROL MODE IDENTIFICATION

The DPCU will exercise control over six variables:

- Gas generator fuel flow
- Compressor bleeds - 7th and 12th stage
- Afterburner fuel flow
- Exhaust nozzle area
- Inlet spike position
- Inlet cone position

These variables must be adjusted and coordinated to provide engine thrust in response to power level setting while maintaining safe, stall free operation. Development of appropriate control modes was a major IPCS activity.

### Gas Generator Fuel Flow

Isochronous governing of N2 is the primary gas generator fuel control mode. Steady state high rotor speed is a function of power level angle (PLA) and fan face conditions; total pressure (P2) and total temperature (T2). Isochronous control holds thrust more nearly constant during bleed and shaft power extraction than does droop control. It also provides better thrust response during part power excursions. Limiting loops are provided to override the N2 loop when required to protect engine integrity or operating stability. Direct measurements are used for limiting where available; otherwise correlations are used. The limiting loops are listed in Table 4.

TABLE 4

IPCS GAS GENERATOR LIMITING LOOPS

| Limited Variable | Signal Source | Purpose |
|---|---|---|
| Low rotor speed | Tachometer | Structural Limitation |
| High rotor speed | Tachometer | Structural Limitation |
| Burner Pressure | Pressure transducer | Structural Limitation |
| Compressor exit Mach No. | $\Delta P/P$ | Stall Prevention |
| Airflow | $f(N1/\sqrt{\theta 2}, EPR)$ | Engine/Inlet Compatibility |
| Turbine Inlet Temp. | Fluidic transducer | Turbine Overtemp Protection |

## Compressor Bleed Control

The distortion tolerance of the TF30-P-9 engine is a strong function of low rotor speed and compressor bleed position as shown by figure 7. The IPCS test aircraft will be equipped with four pressure probes in the inlet duct. Distortion will be inferred from the output of these four probes plus the output of a high-response (Kulite) transducer installed in the NASA test instrumentation rake. The distortion correlation is shown in figure 8.

In operation the engine distortion tolerance will be compared to the sensed distortion. Bleed positions will be selected as required to protect the engine. The compressor bleeds are also opened under certain conditions at low power settings and during engine deceleration to provide greater stall margin.

## Afterburner Fuel Control

The IPCS modulates afterburner fuel flow in the afterburning region as limited by engine requirements and the need to maintain engine/inlet compatibility. The design approach was to use direct (or synthesized) measurements to schedule fuel flow and maintain fan suppression limits. The IPCS schedules engine stream and duct stream afterburner fuel-air (f/a) ratio as a function of a rate limited PLA. This signal is also used to schedule base exhaust nozzle area. Engine stream airflow is calculated as a function of HPC discharge pressures and temperature (P3, PS3, and T3). Duct stream airflow is obtained from the difference between total calculated airflow and engine stream airflow.

Calculation of the zone fill valve timing to permit prefill of manifolds is performed as a function of a rate limited power lever angle signal. Zone fill time, using flow rates and manifold volumes, determines the rate limited PLA signal at which the zone fill valve is opened. Transient performance improvement obtained through use of the A/B prefill logic is shown in figure 9. The IPCS will consistently achieve maximum thrust in the period of time shown in figure 9.

The normal mode for maintaining fan suppression is with the exhaust nozzle area. This mode is discussed under Exhaust Nozzle Area Control. There are, however, certain regions in the flight envelope where the exhaust nozzle area cannot be opened further. In this case control is transferred to the afterburner fuel control loop to permit fuel cutback to maintain the fan match.

## Exhaust Nozzle Area Control

The rate limited PLA that schedules after burner fuel-air ratio is also used to schedule a nominal exhaust nozzle area. This schedule is set to minimize airflow trim requirements. The schedule is also designed to force the area open faster when fuel is added, and close slower when the fuel is decreased. This provides a fan operating point during A/B transients that is farther away from the stall line, resulting in a slight undersuppression.

The IPCS fan suppression control for the TF30-P-9 engine uses the fan match line as a reference schedule for trimming about the base area setting. An airflow reference is balanced against the airflow correlation measurement to trim area until the fan match is satisfied. If the fan match cannot be satisfied due to area being at the maximum limit, trim authority is transferred to the afterburner fuel module. The main fuel module is also biased with a trim signal received from the inlet module, to improve the off design engine/inlet airflow match.

### Inlet Control

A sketch of the F-111 inlet installation is shown in figure 10. The controllable aerodynamic surface is the spike, which translates fore and aft. The spike surface consists of two cones; the second cone may be expanded or contracted over the range of 8.5° to 26° included angle.

In the bill-of-materials (BOM) inlet control, both the spike and cone positions are scheduled as functions of local Mach number and duct exit Mach number. The BOM inlet control schedules have been retained for the IPCS. They are supplemented by an anticipation function that momentarily resets the surfaces for smoothing the afterburner light-off or shut-down transient. A buzz detector, based on that developed for the SST, is provided. It repositions the surfaces for more efficient supersonic air spillage when buzz is sensed. Engine/inlet compatibility is enhanced by an airflow loop that shifts both engine and inlet operating points slightly to control the inlet throat Mach number.

## PERFORMANCE/STABILITY TRADES

There is usually a stability penalty associated with each performance improvement. The standard procedure during a development program is to establish a formal trade study to determine the optimum balance between performance and stability. A system such as IPCS, with the flexibility to change software schedules and set points well into the development cycle, lends confidence to the trade results since it can be based on actual, rather than projected system performance. For example, protection of compressor stability by sensing compressor exit Mach number has been discussed earlier. The program timing does not permit a test series to develop pressure probes to sense internal Mach number. Hence, a tentative compressor exit Mach schedule will be programmed into the software; the schedule will be modified as necessary during the engine test program.

One of the major IPCS goals is the sensing of incipient instability or conditions indicative of instability so that operating points may be shifted as required for duration of the disturbance. Three disturbances in particular are thus addressed for the first time in a flight test program:

Inlet buzz
Inlet flow distortion
Afterburner rumble

Steady-state inlet distortion was discussed in the previous section. The unsteady component of distortion, inlet buzz, and afterburner rumble are each sensed by circuits tuned to respond to pressure fluctions in the frequency ranges of interest. The circuit output increases gradually (with, e.g., a 0.5-second time constant) when pressure fluctions are sensed and decays to zero when the distribution disappears. This approach is based on the buzz detector/suppressor, developed for the SST, which was very successful in closed-loop wind tunnel tests.

## STABILITY ANALYTICAL MODELS

This section describes in broad terms the methods used in the analytical design process. The fundamental procedure uses small-perturbation methods to design to a series of operating points in the flight envelope. The designs thus developed will be programmed for computer simulation. The simulation will then be subjected to gross transients over the entire flight placard to verify the design.

The procedure is diagrammed in Figure 11. It was designed to make maximum use of existing computer programs and has been developed to provide the greatest feasible degree of automation, both to save time and expense and to assure consistency in the application of design criteria. The procedure is as follows:

- Small-perturbation methods are applied to the digital simulation of the propulsion system to linearize about the desired operating points.
  State models of the form

  $$\underline{x} = A\underline{x} + B\underline{u}; \; \underline{Y} = C\underline{x} + D\underline{u}$$

  are generated.

- Transfer functions required for loop-by-loop analysis are calculated from the state-matrix model.

- Classical linear, constant coefficient design methods are used to develop compensation on a loop-by-loop basis.

- The above steps are performed for a series of operating points to obtain the relationships between compensation parameters and engine burner pressure. Polynominals are generated to describe the relationships.

- The compensation polynominals are programmed into the nonlinear (SOAPP) simulation and subjected to standard disturbances over the flight envelope.

- Adjustment is made and the process is repeated if necessary.

In lieu of classical design specs, the following criteria have been established as golas to be used in controller compensation design:

- Phase margin of all loops shall be at least 65°.

- Gain margin of all loops shall be at least 6db.

- Loops designated as limiting (maximum or minimum) shall have no overshoot when subjected to a step input.

- Where overshoot is permitted, overshoot shall not exceed the value attained under BOM control as predicted by the SOAPP simulation.

- Rise time of each loop shall be as fast as the value attained under BOM control.

- Settling times of variables shall not exceed settling times attained by the SOAPP simulation under BOM control.

For some of the IPCS control loops there are no analogous loops in the BOM controller. Time domain specs for these loops are based on engineering judgement of what is required to attain good servo response. All loop compensations designed by linear single input/single output methods are verified using the non-linear SOAPP simulation.

## SOFTWARE DEVELOPMENT

Efficient software is crucial to the success of a program, such as IPCS, that employs a digital computer as the central element of a control system. Furthermore, it is a large-budget, long-lead-time item. Esoteric by nature and unspectacular compared to high-technology hardware, software has been a source of much grief to the unwary. In view of these factors, a significant portion of the IPCS effort has been devoted to software development.

Two sets of software are being developed for the IPCS program; a digital representation of the bill-of-material hydromechanical control (BØMDIG) and the computer implementation of the control modes discussed earlier in this paper (IPCS). The software is organized in modular form, which is consistent with the requirements of this program; since both sets of software will drive the same engine hardware. Since most of the sensors are common, many of the subroutines are common to the two programs. The software is being programmed for the Honeywell HDC 601 computer, which is a 16-bit machine with a 16k military core. Characteristics of this machine may be found in the literature.

Memory and timing estimates for the two programs are listed in Table 5. The factor that may appear unique to the engine control is the large number of functional relationships that are stored as tables. Table 5 indicates that 42% of the BØMDIG memory requirement is devoted to data storage. Deleting that portion of the data base that deals with initialization, input, output, etc., it is found that BOMDIG requires about 3600 locations for tables while the IPCS algorithm requires about 6700 locations.

TABLE 5

MEMORY & TIMING ESTIMATE OF CONTROLLERS FOR THE IPCS PROGRAM

| | BOMDIG | | IPCS | |
|---|---|---|---|---|
| SUBROUTINE | MEMORY (WORDS) | TIME (MSEC) | MEMORY (WORDS) | TIME (MSEC) |
| EXECUTIVE | 1400 | 2.84 | 1400 | 2.84 |
| SENSOR PROCESSING | 1300 | 4.74 | 1300 | 4.74 |
| CONTROL SUBROUTINE | 6500 | 8.25 | 8300 | 14.66 |
| OUTPUT PROCESSING | 450 | 1.48 | 450 | 1.48 |
| COMPUTER PROGRAM DATA BASE | 750 | - | 750 | - |
| | 10400 | 17.31 | 12200 | 23.72 |
| | ±550 | ±0.86 | ±600 | ±1.17 |
| | (42% Data) | | (61% Data) | |

Since the IPCS is an R&D effort, tasks such as BITE and redundancy do not comprise a large portion of the computing effort. There is a sample problem within the executive subroutine to check the computer function. The outputs of sensors critical to flight safety are tested to determine whether the signals are within the normal operating range. If a failure that might result in damage to the engine is sensed in this manner, control is transferred to the hydromechanical fuel control, which is retained as a backup in this program. Figure 12 diagrams the IPCS Fail Safe provisions. There are in addition some synthesized signals that will be used as replacements if the input goes out of the normal operating range.

Sampling periods of 20 milliseconds and 30 milliseconds for the BOMDIG and IPCS algorithms, respectively, are based upon the timing estimates shown in Table 5. Because program schedule limitations, no particular effort has been made to simplify the IPCS control functions. Neither has any effort been devoted to determining which functions could be sampled at intervals longer than the basic sampling period. In view of this, it is estimated that an optimized IPCS control of the future, without BITE and engine health monitoring added, would require about 11,300 words of memory and have a computational time requirement of 20.6 milliseconds.

In other digitally controlled systems where reliability is a major consideration (Space Shuttle Engine Control and some flight control systems), a rule of thumb has been that the control subroutine time requirement should be increased by a factor of three to include reliability needs. Under this assumption, the control subroutine computational time would be 44 milliseconds. This number suggests that additional computer capability is required to cope with the expanded work load.

The most attractive solution appears to be to apportion the control tasks to a number of parallel processors that are essentially identical to achieve reduced production costs through higher volume. This option can be exercised only if care is taken to provide adequate communication between subcontrollers so that true control integration can be achieved.

## TEST PROGRAM

A sequence of hardware tests will be conducted to evaluate the IPCS. This series is progressing from baseline evaluation of the existing system in a low risk, step-by-step manner through flight evaluation of the IPCS. The test flow is diagrammed in figure 13. This test program provides high confidence of success at each phase due to the gradually increasing complexity of the tests.

## Baseline Tests

Baseline engine and flight tests are designed to document the performance of the F-111E/TF30-P-9 system prior to the IPCS modifications. The baseline engine test has been completed. During this test the two engines to be modified for IPCS were tested over a range of flight conditions to establish steady-state and transient performance and distortion tolerance. Data from the test have been analyzed and used to update the dynamic simulation. The baseline flight test will provide similar data for the airplane and inlet.

## Subsystem Tests

Individual component performance and physical integrity will be demonstrated, where necessary, through component and subsystem tests. Individual components will be subjected environmental tests, temperature cycling and vibration in particular, as required by the NASA specifications. The DPCC hardware and software will be thoroughly checked out prior to shipment from the Honeywell facility as indicated earlier under "Hybrid Simulation." The control software will be loaded into the HDC flight computer and tested in real time with the loop closed by the hybrid simulation. The flight conditions to be explored are sea level static and three Mach numbers at 45,000 feet: 0.9, 1.6, and 2.1. A full complement of power transients will be executed. Typical flight disturbances will be presented to the system. The effect of transducer failure will be evaluated by disconnecting the signal lines to simulate failure. This extensive in-house test program will drastically reduce the number of "bugs" encountered during subsequent system-level testing and will thereby effect significant savings in both cost and calendar time.

## Closed-Loop Bench Test

A comprehensive closed-loop bench test will follow the component tests. The TF30 fuel controls, modified to incorporate electrical interfaces, will be installed in the P&WA fuel bench test facility. A schematic of the test set-up is shown in figure 14. The flight DPCU will be connected to the fuel controls through electrical cables of length chosen to simulate the aircraft installation. The inlet actuators, with their position feedback transducers will be installed in a jig, supplied with hydraulic power, and connected to the DPCU. Analog simulations of the engine and the inlet aerodynamics will be provided to close the loops and generate the signals that would be sensed by transducers in the aircraft. In some cases, simulation interface adapters will be provided to simulate the transducer output format. This test will provide a functional check out of the modified fuel control unit and will establish compatibility between the DPCU and its software and the engine and inlet control hardware.

### Sea Level Static Test

The second test of the series will be a sea level static (SLS) engine test, also conducted at the P&WA facility. The modified fuel controls will be installed on the modified TF-30 engines which will be mounted on a test stand. This test will provide the first opportunity to demonstrate IPCS operation with the engine and will permit the necessary fine tuning prior to the altitude test. The SLS test will also serve as the acceptance test for the IPCS and the modified engines.

### Altitude Facility Test

The altitude test at NASA/LeRC will duplicate most of the operating conditions scheduled for investigation during the IPCS flight tests. Operation of the IPCS will be refined at points throughout the flight envelope, again using an analog inlet simulation. The NASA/LeRC "puff-jet" distortion generator will be used to create disturbances to check operation of the IPCS buzz suppression and distortion loops. Following the altitude test, the modified engine and DPCU will be installed in the airplane for a flight evaluation of the IPCS operation.

The installation of the IPCS on the flight-test aircraft will be performed by NASA/FRC. All electrical cables on the aircraft will be fabricated by FRC to drawings supplied by the contractor. Following installation, a thorough check-out and ground test will be conducted.

### Flight Test

A six-month Flight test evaluation of the IPCS is scheduled. The tentative flight test points are shown figure 15. Test planning has not been completed at this writing. It is anticipated, however, that the projected 26 flights (approximately 50 flight hours) will provide sufficient time to evaluate all of the IPCS features under a variety of conditions.

## CONCLUSIONS AND RECOMMENDATIONS

Since the IPCS program is not quite half completed as this is written, firm conclusions are premature. It is possible, however, to submit tentative conclusions based on experience to date. These are offered below subject to the qualification that they may be modified as further experience is gained.

1. Basing the bulk of the controls analysis on a detailed digital simulation of the propulsion system was a sound approach. A digital computer tape is a convenient and compact way to transmit masses of technical detail. This approach also assured consistency between analytical work performed by each of the three major contractors.

2. Many delays were experienced during baseline engine testing due to shortages of electrical power to operate the facility. If energy shortages prove to be persistent, new approaches to test operation may be necessary. In particular, more rapid methods of establishing test conditions, instrumentation that minimizes time spent on condition, and data reduction methods that correlate data collected under slightly different test conditions would alleviate the problem significantly.

3. Computer software is an item whose importance can scarcely be overstated. There appears to be a tendency in the industry to underestimate lead time and overestimate the flexibility of software. Once constructed and checked out, software is almost as difficult to change as hardware. The principal difference is that software does not have to be vibrated to demonstrate mechanical integrity.

4. Standardized methods for transmitting information between airborne digital machines are essential if the full potential of digital electronics is to be realized. The centralized super computer that performs all calculations aboard the aircraft appears to be unfeasible throughout the foreseeable future. Sets of small machines operating in parallel are practical and economical, provided the communication problem is solved.

Although IPCS hardware has not been discussed in depth, some comments are in order:

1. Electromechanical and electrohydraulic interface devices must be selected very carefully to minimize electrical and electronic problems. From an electronics standpoint, for example, torque motors are preferable to stepper motors, linear variable differential transformers (LVDTs) are preferable to resolvers for position sensing.

2. Transducers will continue to present problems throughout the foreseeable future. Controls engineers must make a determined effort to design out of the system the requirement for high accuracy and/or high response.

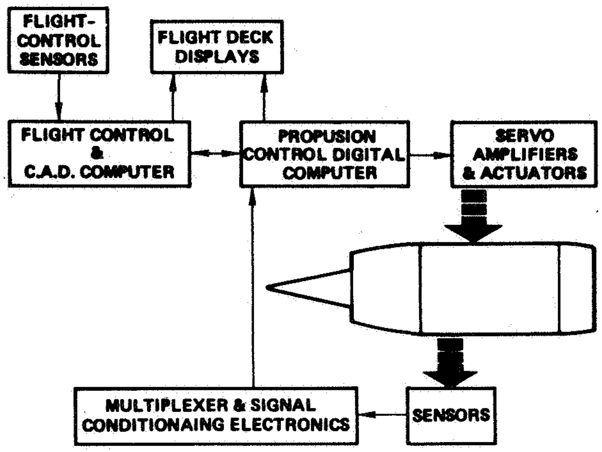


*Figure 1: Integrated Flight/Propulsion Control Concept*

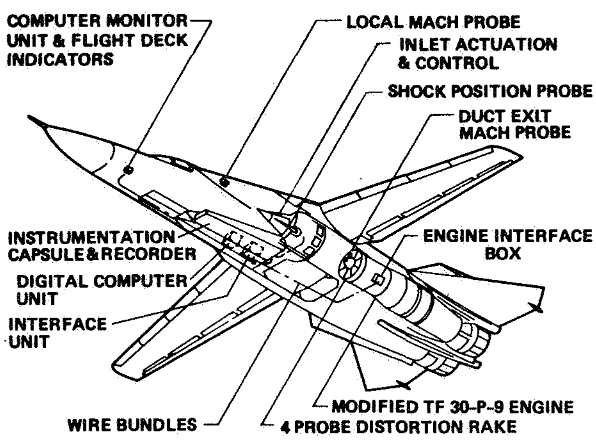


*Figure 2: Integrated Propulsion Control System*

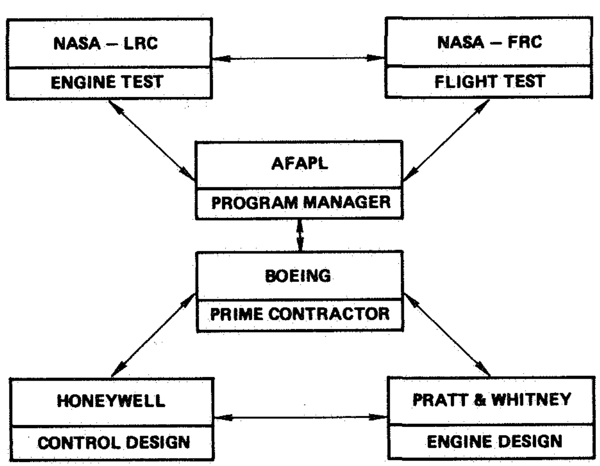


*Figure 3: IPCS Organization*

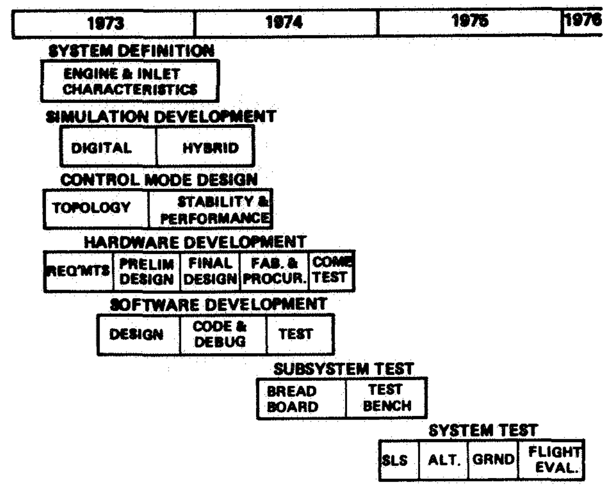


*Figure 4: IPCS Development Sequence*

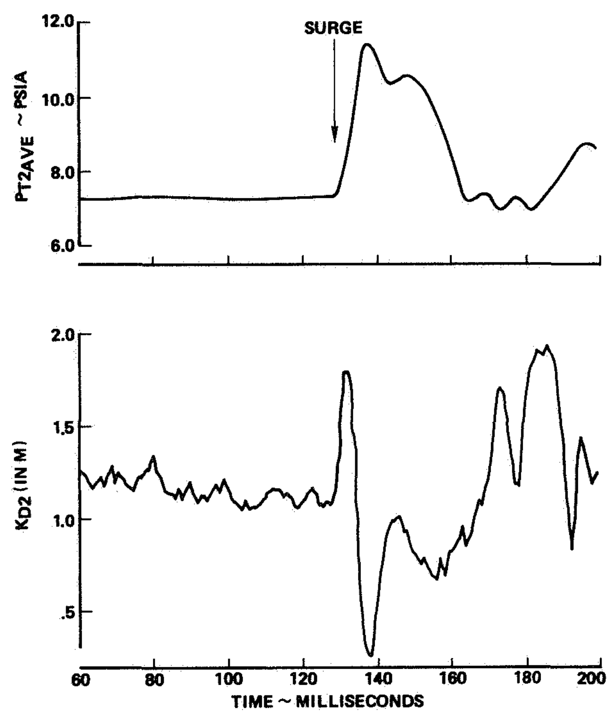


*Figure 5: Distortion Time History, Baseline Engine Test*

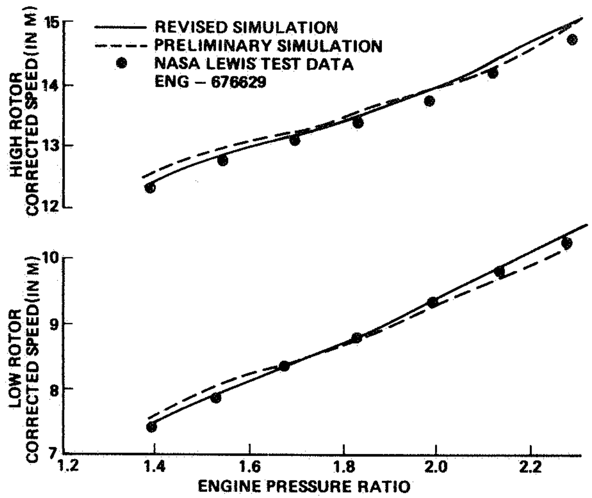


*Figure 6: Comparison of Baseline Engine Data with Simulation at 30,000 Ft. Mach 0.8.*

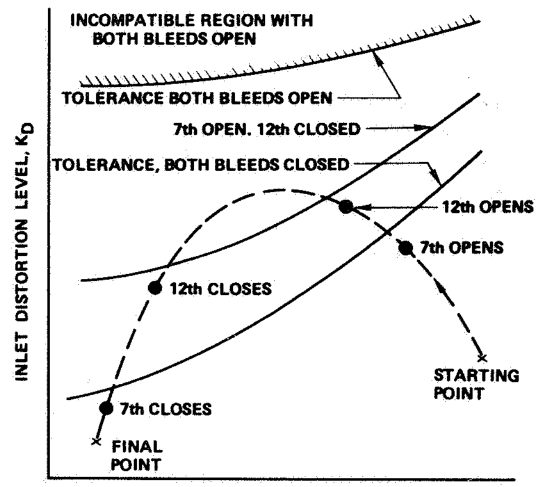


*Figure 7: Compressor Bleed Operation*

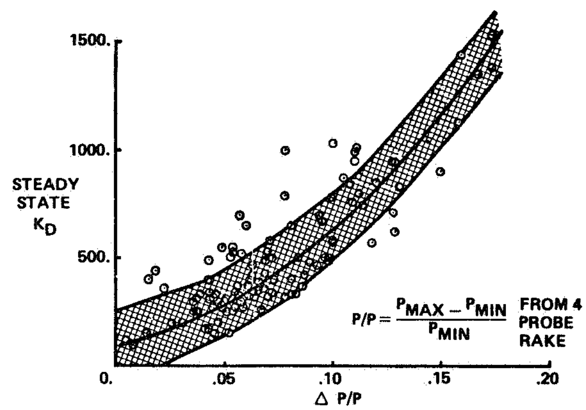


*Figure 8: Steady State Distortion Correlation*

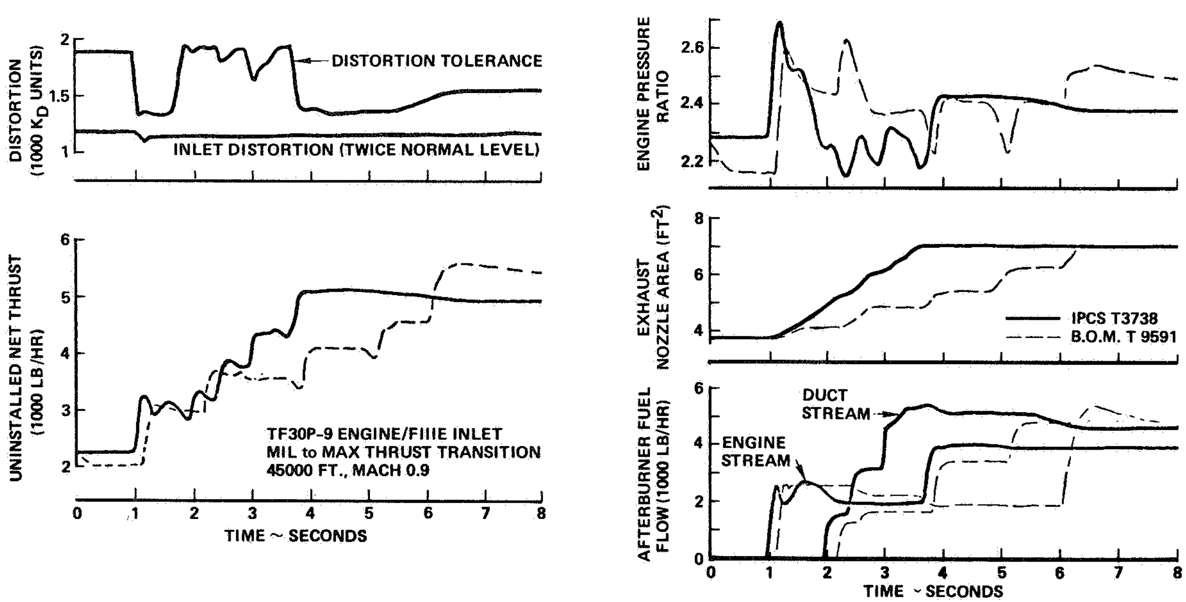


*Figure 9: Military to Maximum Afterburner Transient*

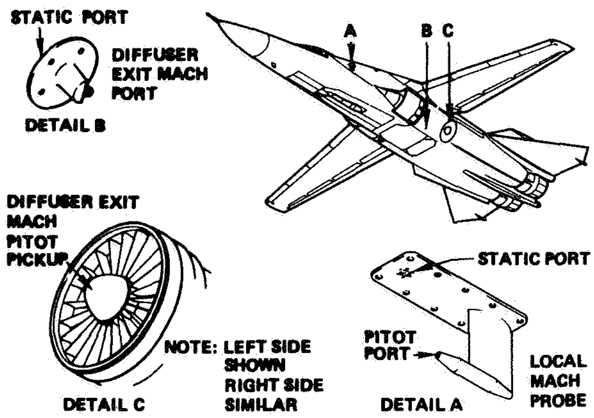


*Figure 10: F-111 Inlet Installation*

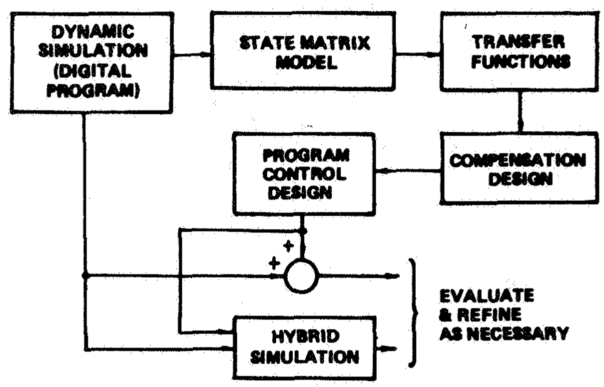


*Figure 11: Analytical Design Procedure*

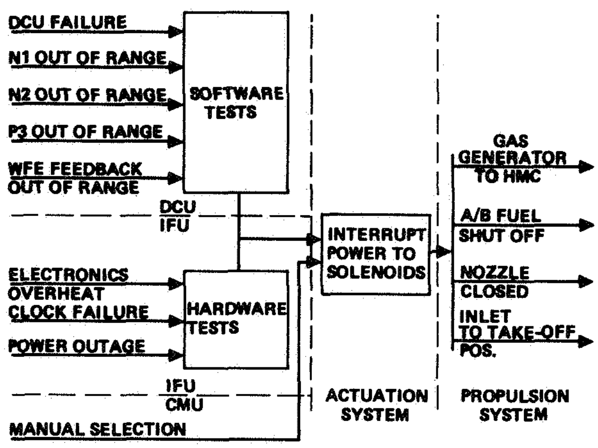


*Figure 12: IPCS Fail-Safe Provisions*

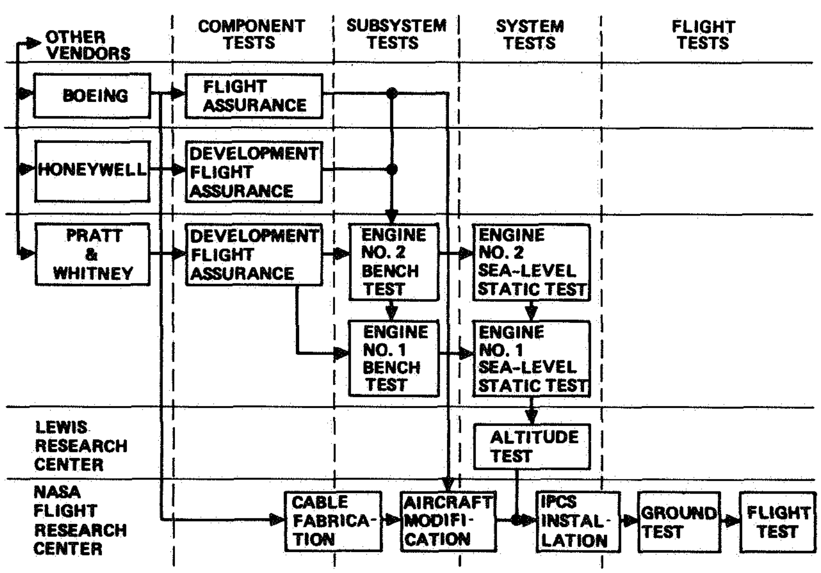


*Figure 13: Test Flow*

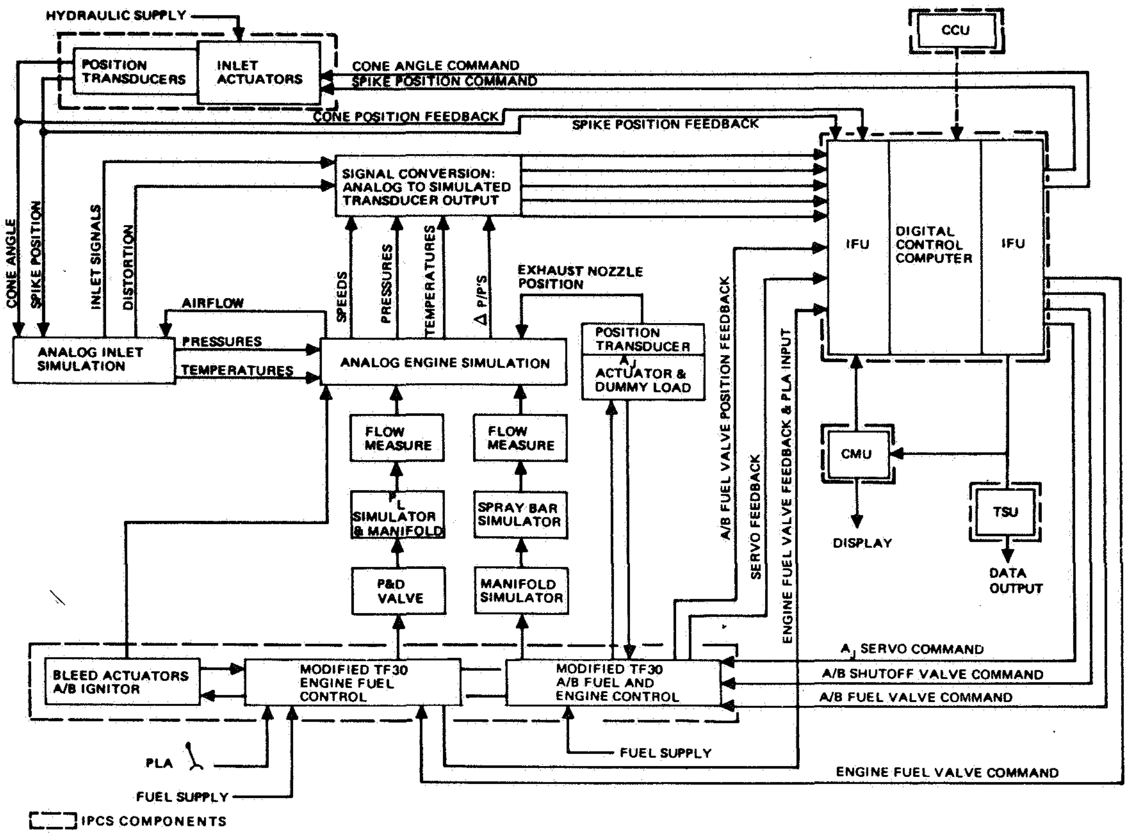


*Figure 14: IPCS Closed-Loop Bench Test Schematic*

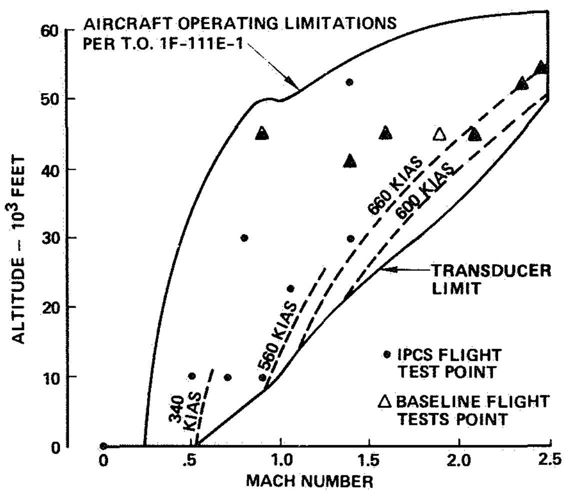


*Figure 15: IPCS Flight Test Envelope*