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Energy Efficient Engine

Control System Component Performance Report

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1.0 SUMMARY

An Energy Efficient Engine (E^3) Program was established by NASA to develop a technology for improving the energy efficiency of future commercial transport aircraft. As a part of this program, General Electric designed, fabricated, and tested a new turbofan engine. This report describes the design and test of the control and fuel system for the General Electric Energy Efficient Engine.

The control and fuel system for the E^3 was based on many of the proven concepts and component designs used on the GE CF6 engine family. One significant difference was the incorporation of digital electronic computation in place of the hydromechanical computation used on current transport aircraft engines. The timesharing capabilities of the digital computer accommodated the additional control functions required for the E^3 without computer hardware duplication. The improved accuracy and flexibility of digital computation permitted engine control strategies that improved efficiency and reduced deterioration. The digital control also offers improved aircraft/engine integration capability.

For the E^3 ICLS (Integrated Core/Low Spool) turbofan demonstrator, the system performed six control functions. It controlled fuel flow, fuel flow split (to two combustor zones), compressor stators, and three independent clearance control air valves. The system also provided condition monitoring data. For the core engine test that preceded the ICLS, system functions were the same except that the compressor stator control function was deleted (stages are set individually by a test facility control system for experimental flexibility) and all fan/fan turbine related functions were deleted. The system for a production engine would be the same as for the ICLS with the addition of ignition and thrust reverser control.

System components for the demonstrator engines included (1) the digital control (which is a modification of a design produced under the Navy FADEC program, (2) a modified F101 fuel pump and control, (3) modified CF6 stator actuators, (4) modified F101 IGV actuators for air valve actuation, (5) a

number of air valves modified from existing designs, and (6) several custom-designed components including fuel flow split control valves, control mode transfer valves, and a compressor clearance control air valve. An off-engine digital control was used for the core engine, whereas an on-engine design was used for the ICLS. For a production E^3, dual redundant digital controls would be used initially, but it is anticipated that in-service development will produce a digital control with reliability equivalent to current controls so that ultimately a single-channel control will suffice.

2.0 INTRODUCTION

The Energy Efficient Engine (E^3) Program was a program established by NASA to develop a technology that would improve the energy efficiency of propulsion systems for subsonic commercial aircraft of the later 1980's and early 1990's. The specific major objectives of the program were to develop a technology that would provide at least a 12% immprovement in cruise specific fuel consumption and a 5% improvement in direct operating cost relative to a current commercial aircraft engine, the CF6-50C. These improvements were to be achieved within the restraints of strict new noise limits as given in FAR-Part 36 (July 1978 revision) and emissions limits are given in the January 1981 EPA standard for such engines.

Beyond the overall program objectives, design objectives also were established for the various elements of the E^3. For the fuel and control system, the primary objective was to define a system that thoroughly exploited the engine's fuel conservation features, provided operational capability and reliability equal to or better than current transport engine control systems, and to employ digital electronic computation suitable for interfacing with aircraft propulsion and flight control computers. The system thus defined was demonstrated on the full-scale core and ICLS (Integrated Core/Low Spool) test engines which were a part of the E^3 program.

This report describes the control and fuel system design and documents the performance observed as the system was bench tested and subsequently run on the E^3 demonstrator engines.

3.0 CONTROL AND FUEL SYSTEM REQUIREMENTS

The E^3 control and fuel system was designed to meet several contractually specified general design requirements established during the preliminary design phase of the program and to meet functional requirements established by the nature of the engine itself (Figure 1 cross section). These requirements are given below.

3.1 GENERAL DESIGN REQUIREMENTS

Digital Computation - The system employed digital electronic computation rather than the hydromechanical computation used in current transport engine controls. This was done because the digital computer provided more scheduling flexibility of controlled variables; had timesharing capability so that many control functions were performed without computer hardware duplication; could interface directly with aircraft system computers which, by the late 1980's, will also be digital; and offers the promise of lower cost by taking advantage of rapid electronics industry advances in circuit integration and automated manufacture.

Aircraft Interfacing - In conjunction with the previous requirement, the system was designed to interface with a typical aircraft control computation system.

Power Management - The system incorporated power management capability which automatically optimised performance with minimum flight crew input.

Sensor/Actuator Failure Tolerance - Computational techniques were employed to make the system generally insensitive to failures in digital control input sensors and output actuators so that redundancy of these elements was not necessary.

Reliability - System reliability by the time of introduction into service shall be equal to or better than the reliability achieved with current transport engine hydromechanical control system. In a sense, this requires improved reliability because the E^3 system performs more control functions.

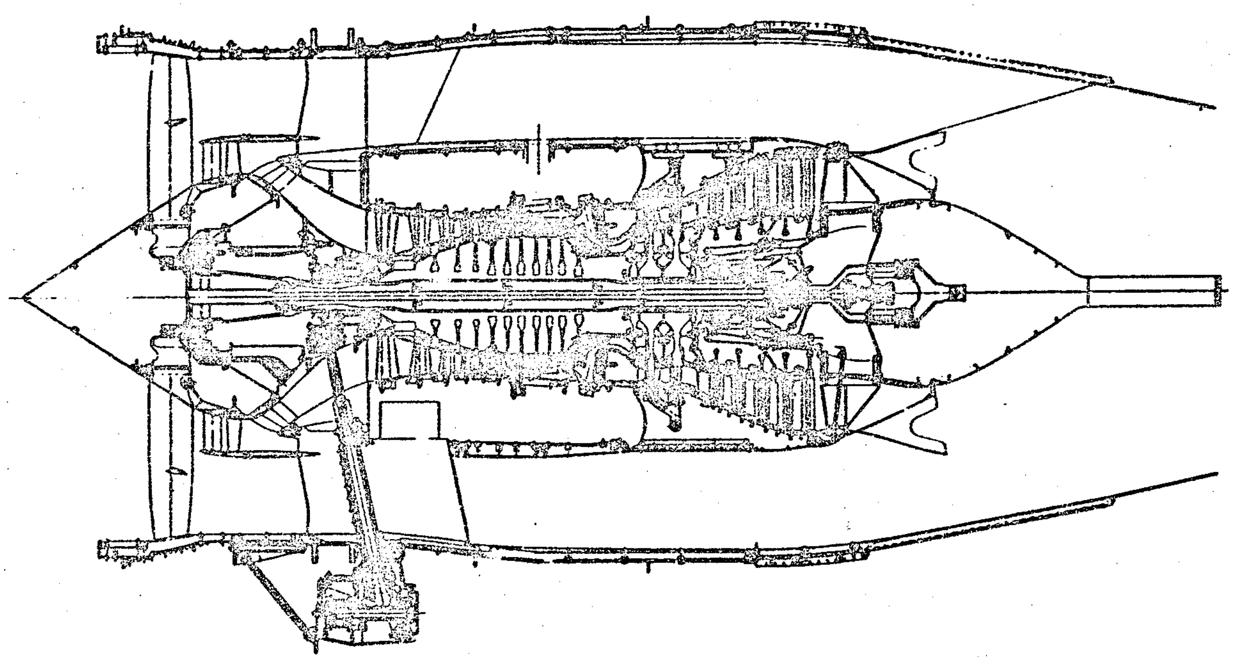

Figure 1. E^3 ICLS Engine Cross Section.

3.2 FUNCTIONAL DESIGN REQUIREMENTS

The design of the E^3 ICLS required that the control system have outputs as shown on Figure 2 and it performed the following functions:

- Modulated fuel flow to control thrust.
- Split fuel flow to the two zones of the double-annular combustor.
- Positioned core compressor variable stators for best compressor performance.
- Positioned air valves for independent active clearance control of the compressor (Stages 6-10) and the HP and LP turbines.
- Provide condition monitoring data to the engine operating crew.

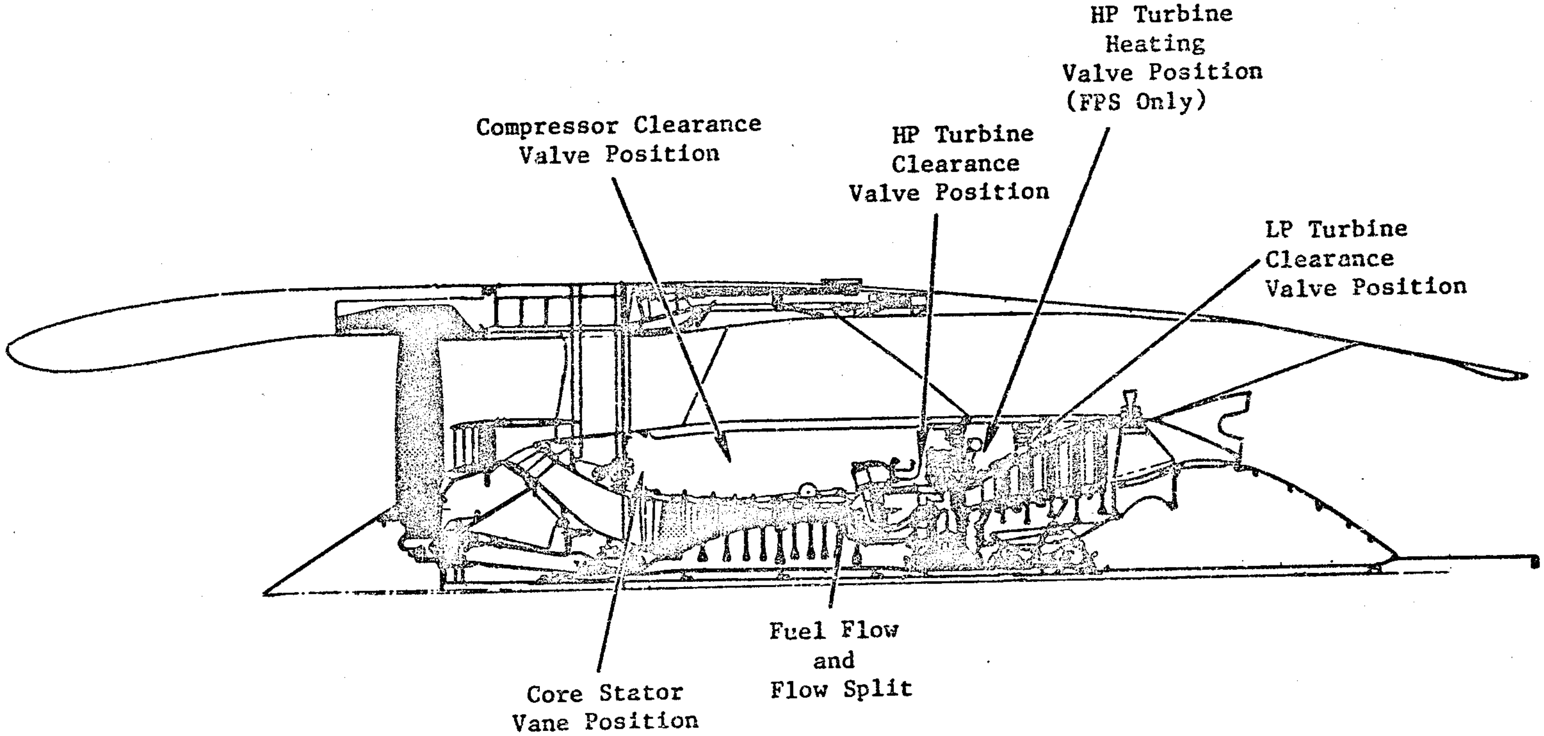

Figure 2. Control System Outputs

4.0 BASIC SYSTEM STRUCTURE

Consideration of design requirements, particularly the one regarding digital electronic computation, led to the definition of a basic system structure as shown in Figure 3. The digital control was the central element in the system. It received input signals from the control room and from various engine sensors, it provided servo signals to control the output devices shown, and it received position feedback signals from the output devices.

Figure 4 shows pictorially the inputs that were received from outside of the control system. Seven temperatures were sensed including fan inlet air, compressor inlet and discharge air, HPT discharge gas, and engine skin temperatures in the three areas where active clearance control was provided.

Air pressure inputs to the system included freestream total pressure which was indicative of the average pressure at the fan inlet and compressor discharge pressure. A pressure sensor was provided for HPT discharge pressure which is a potential thrust control parameter for the FPS design. This was not demonstrated on the core or ICLS test vehicles.

Inputs were also received that were indicative of fan rpm and core rpm, the latter being supplied from a core rotor-driven control alternator which also served as the primary source of electrical power for the digital control. The control also received 28 volt d.c. power from an external source for use during starts and as an alternate power supply in the event of an alternator failure.

Command data was provided to the digital control through a multiplexed digital link which simulated an aircraft interface connection. The primary command input was the position of the engine operator's power lever, but the data link was also used to transmit adjustments and selector switch positions from a control room Operator and Engineering Panel which provided experimental flexibility for demonstrator engine testing.

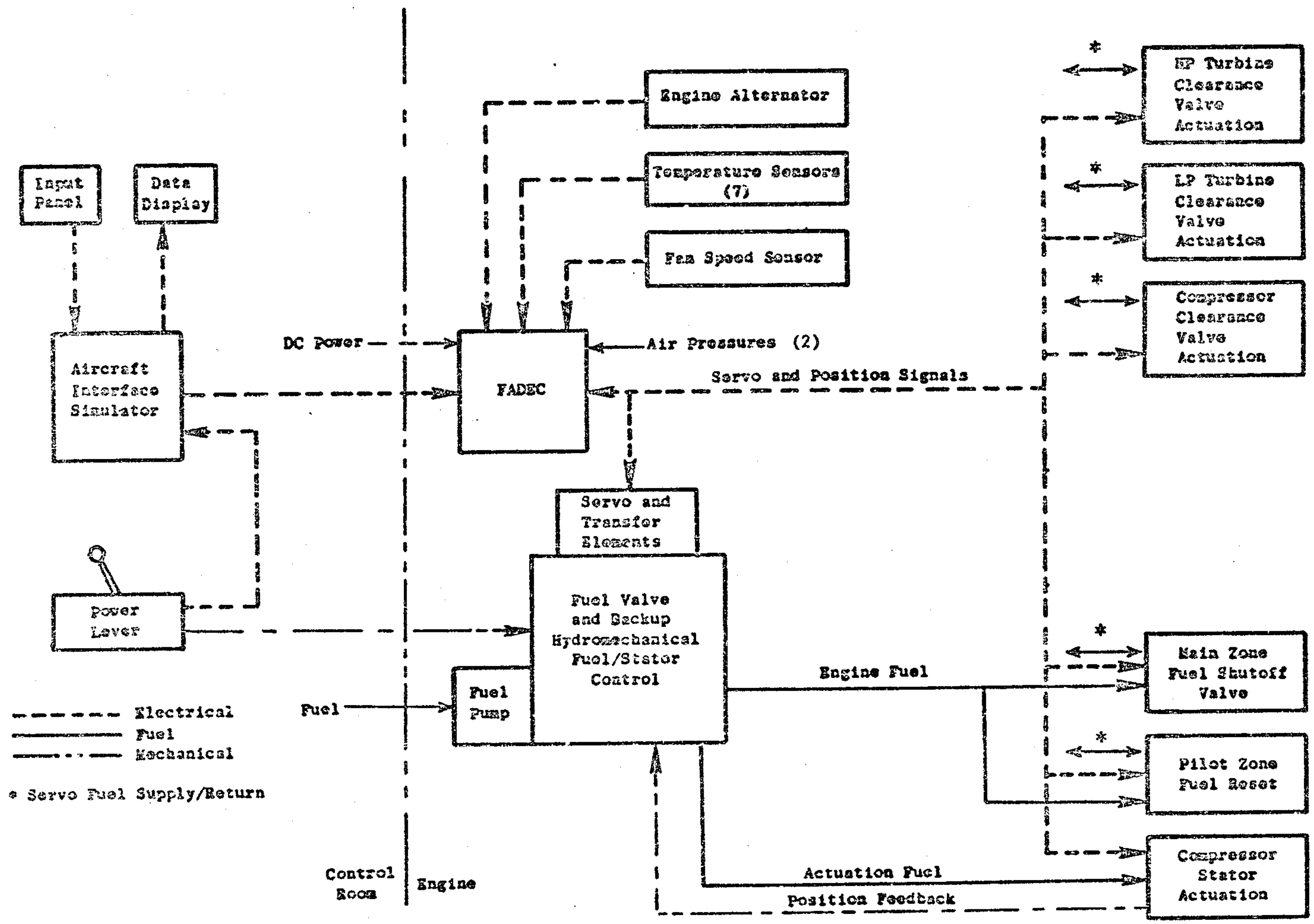

Figure 3. E^3 ICLS Control System.

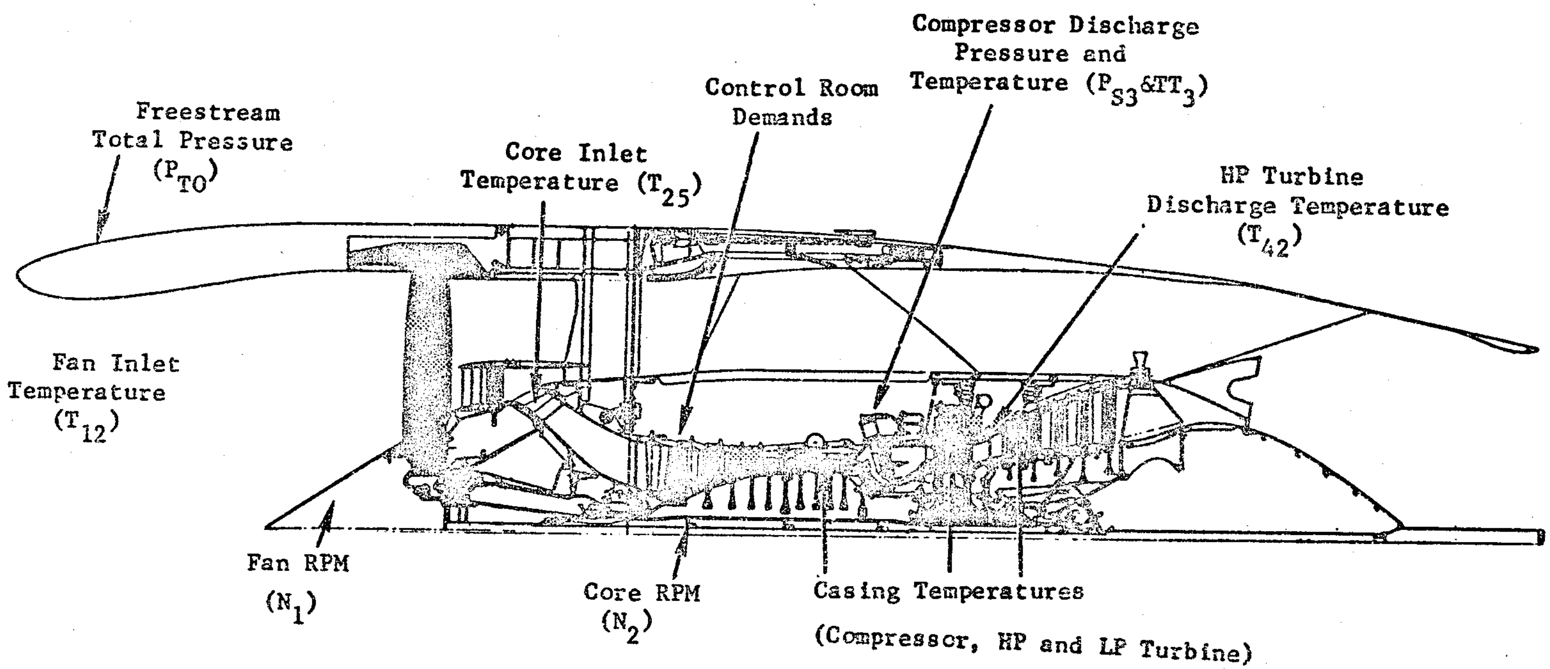

Figure 4. Control System Input.

The data link also included a separate channel for transmission of multiplexed digital engine and control system data to the control room, thereby simulating an aircraft engine monitoring connection. These data were displayed on a CRT and made available for the demonstrator engine test instrumentation system.

Control strategy for the various E^3 control system functions was contained in the digital control's program memory. Output signals were generated by the control and then transmitted to the various actuation devices in order to control them in accordance with the control strategy. Some of this control was done on an open-loop basis, but most was done closed loop by utilizing electrical position feedback signals from the actuation devices. All of the actuation was done with fuel-powered actuators using excess capacity from the engine fuel pump through electrohydraulic servovalves which respond to the digital control output signals.

Control outputs for the fuel valve and compressor stator actuators were handled differently from all others in that they were transmitted to transfer devices capable of providing switchover to hydromechanical control for these two variables only. In the event of a digital control system malfunction, fuel and stator control shifts to the hydromechanical backup plus all other controlled variables are set at safe positions so that the demonstrator engine would continue to run satisfactorily and could be shut down in a safe manner for correction to the malfunction.

System elements and system operation are discussed in more detail in the sections which follow.

4.1 DELIVERY AND CONTROL OF FUEL FLOW

4.1.1 FUEL SYSTEM DESIGN

In designing the fuel system, it was recognized at the outset that many of the considerations for establishing the highly successful fuel system designs on current transport engines, such as the CF6, are equally applicable. Therefore, the system was patterned after the CF6 system in many ways, with modifications made mainly to reflect the use of a digital control and a significantly different combustor. A diagram of the fuel system design that resulted for the ICLS engine is shown on Figure 5.

An engine-driven, positive displacement vane pump with an integral centrifugal boost element is used in the system for pumping. Pump discharge fuel passes through a pump-mounted filter and into the fuel control mounted on the end of the pump.

In the fuel control, fuel metering is accomplished by the combined operation of the metering valve and a bypass valve that returns excess fuel to the inlet of the vane pump element. The bypass valve maintains a fixed differential pressure across the metering valve so that the metering valve area determines the amount of fuel flow supplied to the engine combustor. In the primary operating mode the metering valve is positioned by the digital control, and in the backup mode (discussed further in Section 4.4..1) it is positioned by the hydromechanical computer. A transducer on the metering valve provides position feedback to the digital control.

Metered fuel passes out of the fuel control through a pressurizing valve which is necessary to maintain sufficient pressure to operate fuel servos at low flow conditions and through a cutoff valve which provides a means for positively shutting off fuel to the engine. The fuel then passes through a flowmeter (which is included to provide experimental test data) and an engine lube oil cooler. Downstream from the cooler the fuel flow is split, part going to the pilot zone and part going to the main zone of the combustor. On/off valves in the main zone and pilot zone lines provide a means for modifying local fuel-air ratios in the combustor under certain conditions as explained below in the discussion on fuel flow split control.

4.1.2 FUEL CONTROL STRATEGY

Fan speed was selected as the basic fuel control parameter. Control strategy for fuel flow is shown in block diagram form in Figure 6.

Fuel flow, for the most part, is modulated to control fan or core rotor speed in accordance with the power lever angle (PLA) schedules shown as blocks

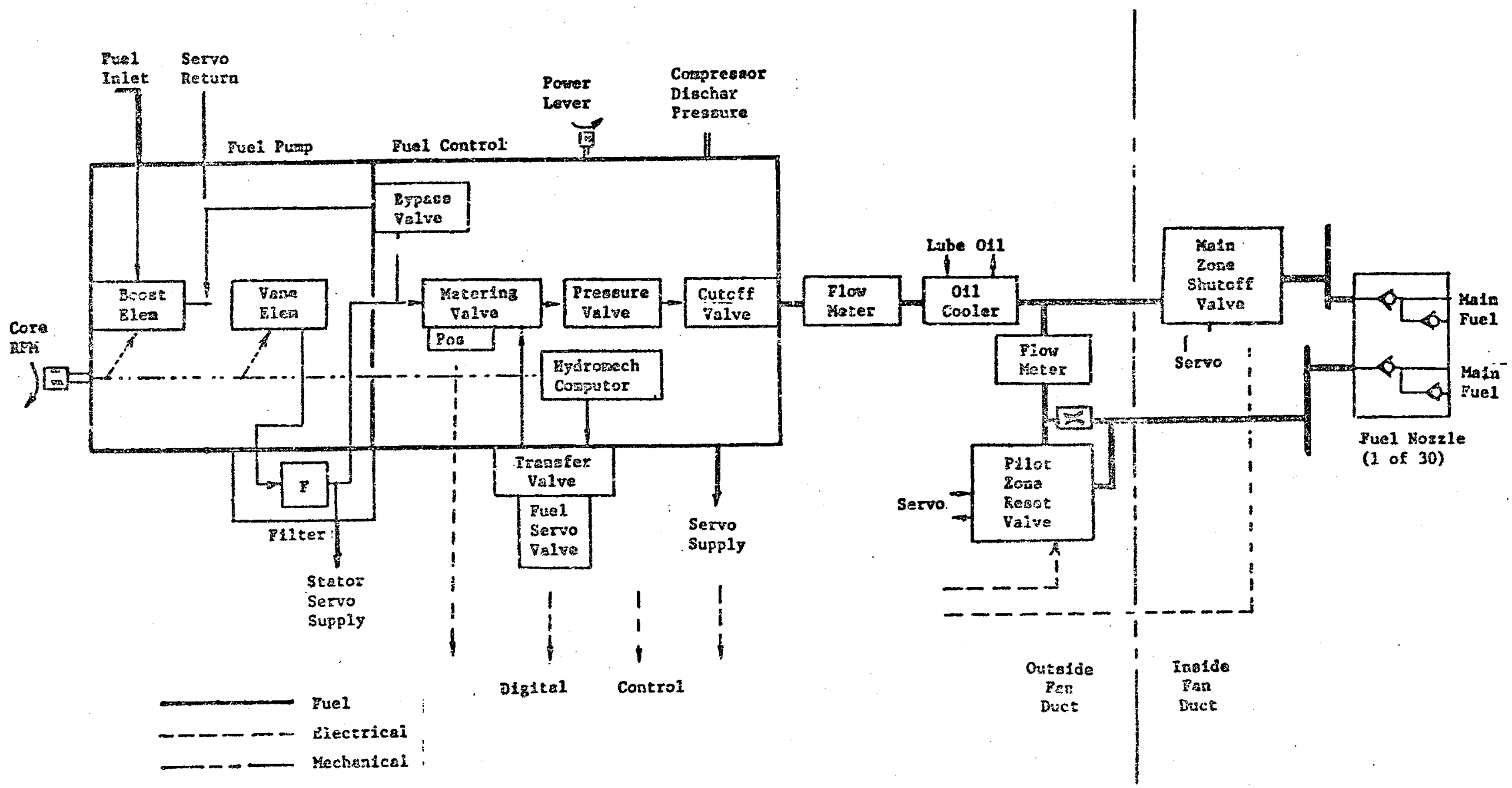

Figure 5. ICLS Fuel System.

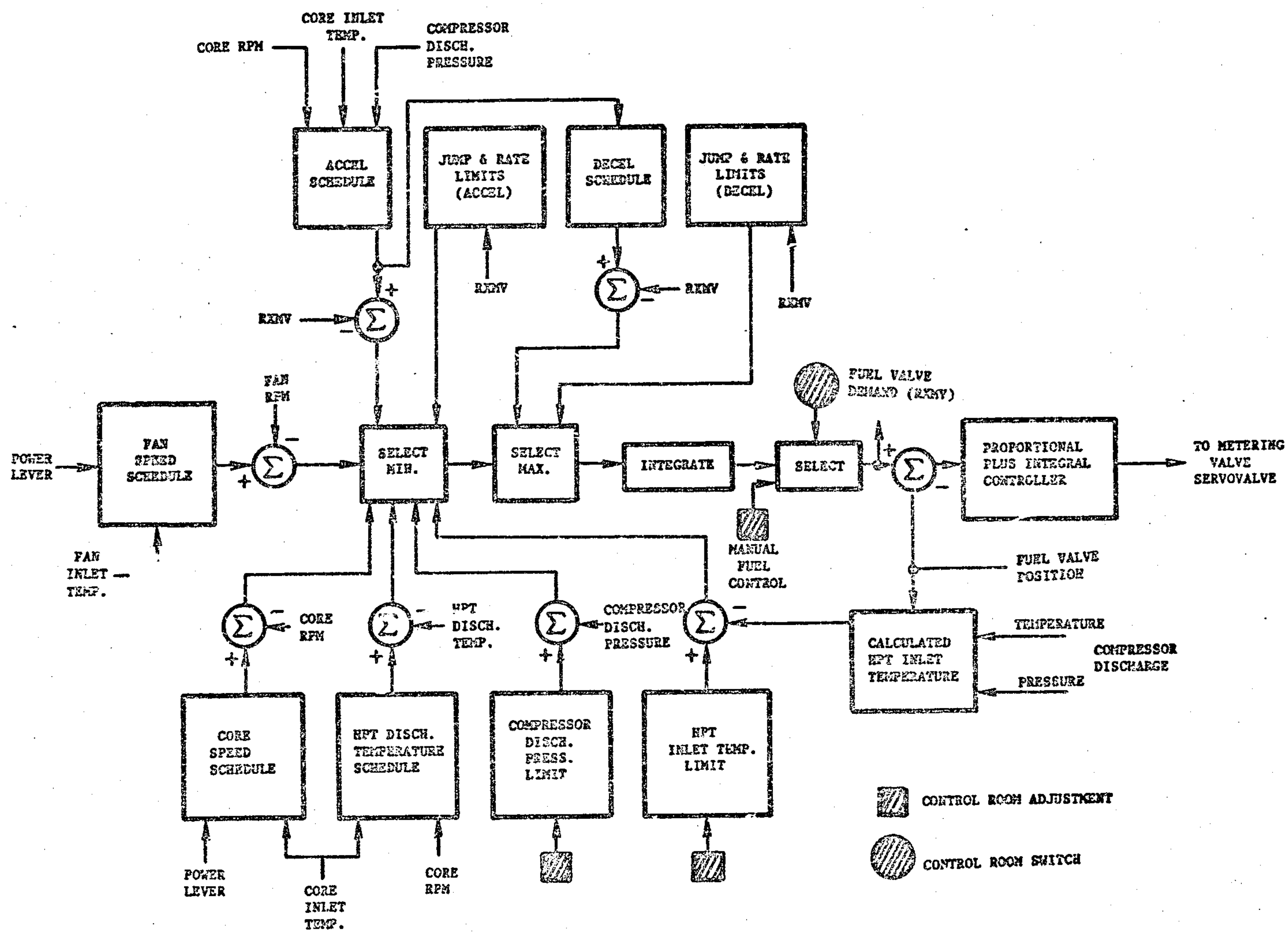

Figure 6. ICLS Fuel Control Strategy.

in the center and lower left portion of the diagram. For ICLS, the schedules are set up so that the core speed schedule is in effect from idle to approximately 30% thrust and the fan speed schedule is in effect above that.

Limits are imposed on the basic schedules to prevent excessive HPT inlet temperature (calculated), excessive LPT inlet temperature (T42), and excessive compressor discharge pressure (PS3). In addition, transient fuel schedules and limits are included to (1) prevent compressor surge during rotor accelerations, (2) prevent loss of combustion during rotor decelerations, and (3) limit thermal shocks (by limiting fuel flow rate-of-change). The schedules and limits are combined in a selection network which establishes priorities and assures smooth transition between control modes. A manual input is included to provide the capability of adjusting fuel flow from a control room potentiometer to explore subidle engine characteristics.

The output of the selection network is a fuel metering valve position demand that operates a position control loop to position the valve, thereby setting the desired fuel flow.

4.1.3 FUEL FLOW-SPLIT CONTROL STRATEGY

The double-annular combustor shown in Figure 7 required that fuel from the main fuel metering valve be split between pilot and main zones. The required flow-split characteristics are listed below.

Start Mode - Full fuel flow was required to the pilot zone to assure ignition and best combustion during acceleration to idle.

Run Mode - Full Fuel flow to the pilot zone was required at idle when not in flight to provide minimum exhaust emissions. Above idle or in flight, fuel is required to both zones.

Decel Mode - Two experimental options are provided if decel blowout problems are encountered:

a. Temporary switchover to enriched main zone
b. Temporary switchover to pilot zone only

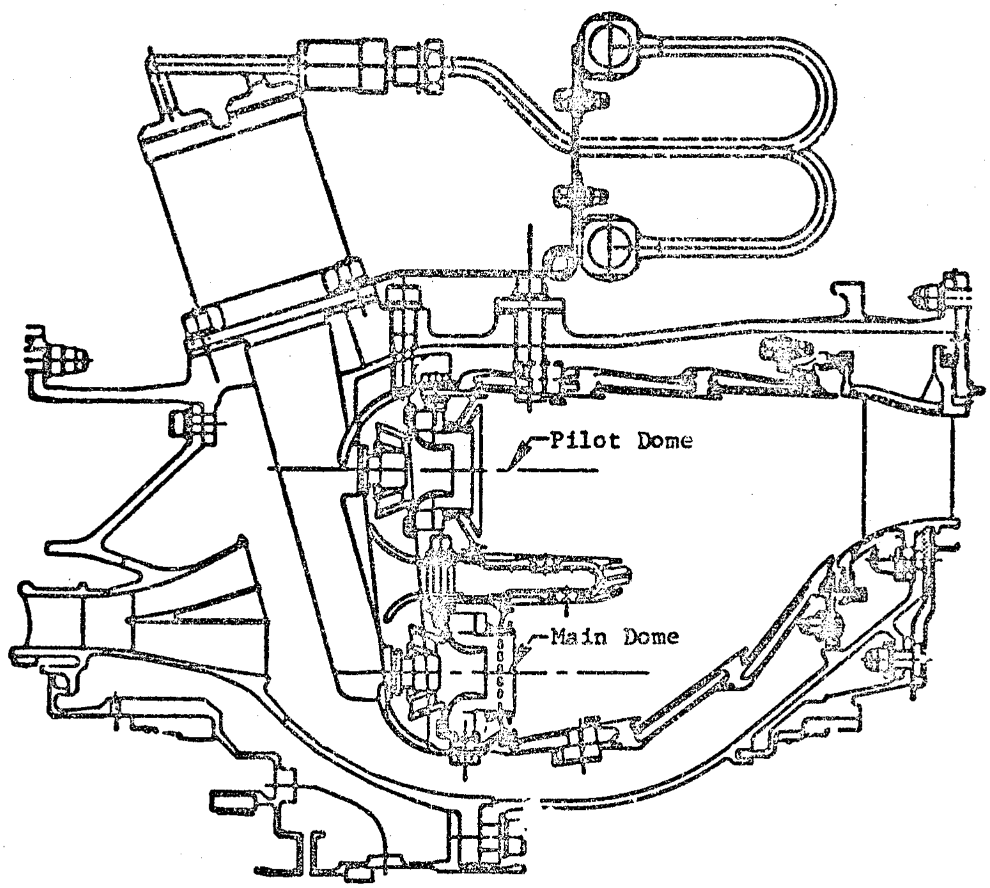

Figure 7. E^3 Double-Annular Combustion.

Transition - For transition to full burning mode, main zone flow must be temporarily held low to prevent pilot starvation as main injectors fill.

The control strategy designed to meet these requirements is shown on Figure 8. The block at the upper left provides the basic on/off logic for the main zone shutoff valve and the blocks at the bottom provide the pilot zone reset that is part of this transition mode. The blocks in the center provide the main zone throttling function to prevent pilot zone starvation during transition to full burning. The duration of throttling is varied as a function of total fuel flow as indicated by main fuel metering valve position and as a function of the time since last main zone operation.

The decel mode logic is shown in the block at left center. Engineering panel adjustments required to trigger this mode are provided so that this function can be modified or deleted altogether from the control room during engine operation.

A manual mode is also provided for both the main zone shutoff valve and the pilot zone reset valve which allows each valve to be independently positioned from the control room during engine operation.

The output of the main zone shutoff logic network operates the main zone valve through a control loop that includes position feedback so that the valve can be set at any position from fully closed to fully open. The pilot zone reset valve servocontrol does not include position feedback so this valve can only be set fully open or fully closed.

4.1.4 FUEL CONTROL LOOP DETAILED DESIGN

Design details of the fuel control strategies just described were defined primarily on the basis of predicted engine cycle characteristics using data from the computer model of the engine at steady state (cycle deck) and data from transient computer models derived from the steady-state model.

The basic fuel control system schedules of core and fan rpm as functions of power lever angle were designed so that the relationship between angle and thrust is nearly linear at ICLS operating conditions. The

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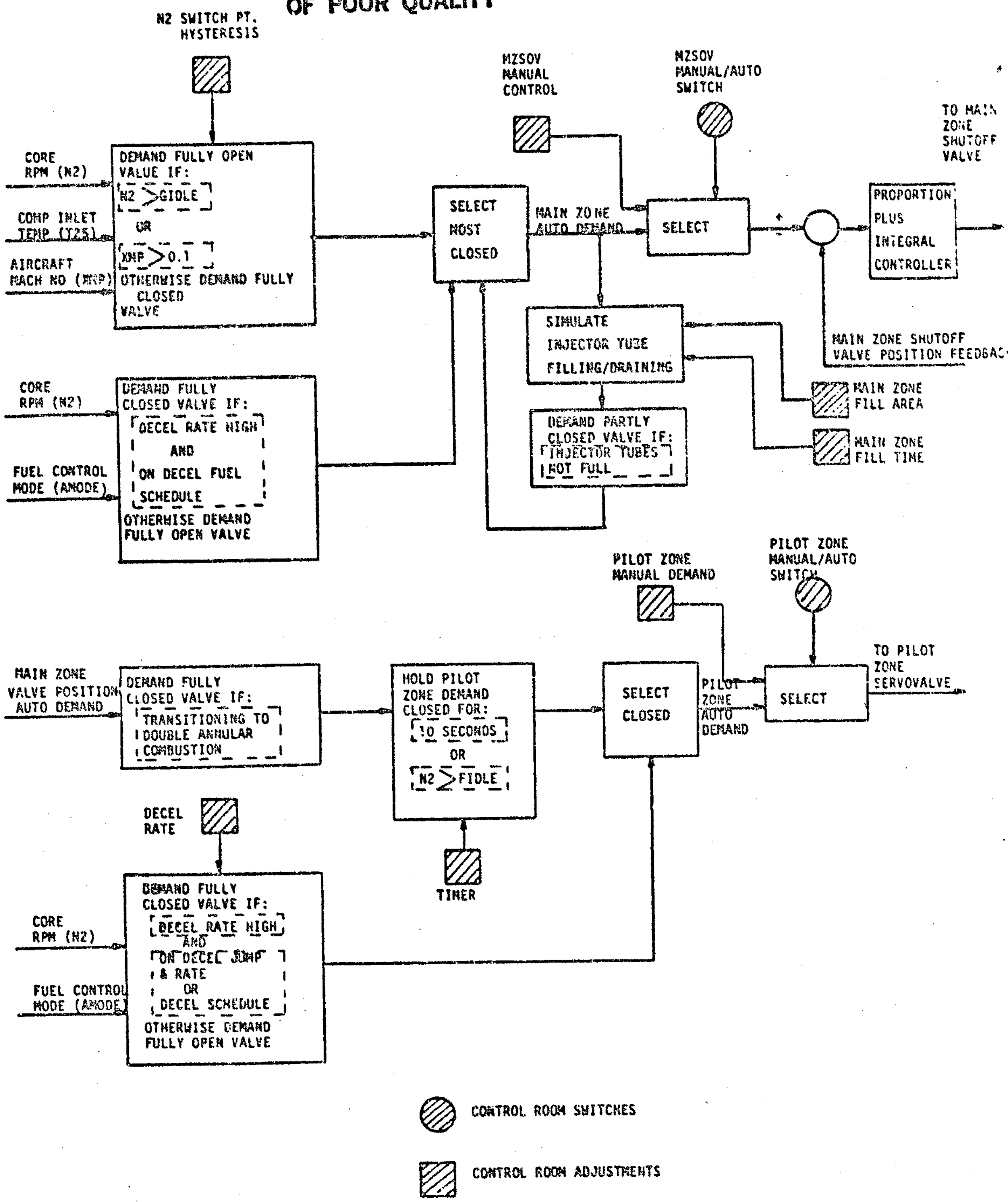

Figure 8. Fuel Flow Split Control Strategy.

schedules, shown on Figure 9 and 10, are designed so that the corrected fan rpm schedule is normally in effect above approximately 70° power lever and the corrected core rpm schedule is in effect below.

The dynamic characteristics of the fuel control loop were designed by the use of linear stability analysis techniques and by the use of a transient model of the engine and control on a hybrid computer.

The transient engine model was based on the steady-state cycle deck with component subroutines programmed directly from the cycle deck source. The block diagram in Figure 11 shows the information flow through the model. The diagram consists of blocks connected by flowpath techniques. These blocks represent the component subroutines just noted. Each block is identified by the engine-component thermodynamic function represented therein. Inputs to the engine components on each pass include flight conditions, iteration variables from the iteration logic, rotor speeds from the rotor simulations, and control variables from the control simulation. Compressor bleed and horsepower extraction are not shown but are included. Separate blocks represent inputs and outputs for the iteration logic, rotor simulations, and control simulation.

The stability analysis effort and the transient model work resulted in control system dynamic characteristics that produce the engine transient characteristics shown in Figure 12 which is a set of data traces showing a fast deceleration followed by a fast acceleration on the transient model.

The dynamic design work just described was limited to the region above idle because the engine cycle deck and transient model are limited to that region. Therefore, a separate subidle engine model was prepared to aid in designing the transient characteristics in the starting region. This model was patterned after a similar subidle model for an existing engine and adjusted to match predicted characteristics at idle. It was further adjusted when actual subidle data became available from component testing of the compressor and HP turbine.

Figures 13 and 14 show typical subidle model data pertinent to control of fuel flow and to choice of a starter. Design objectives call for a

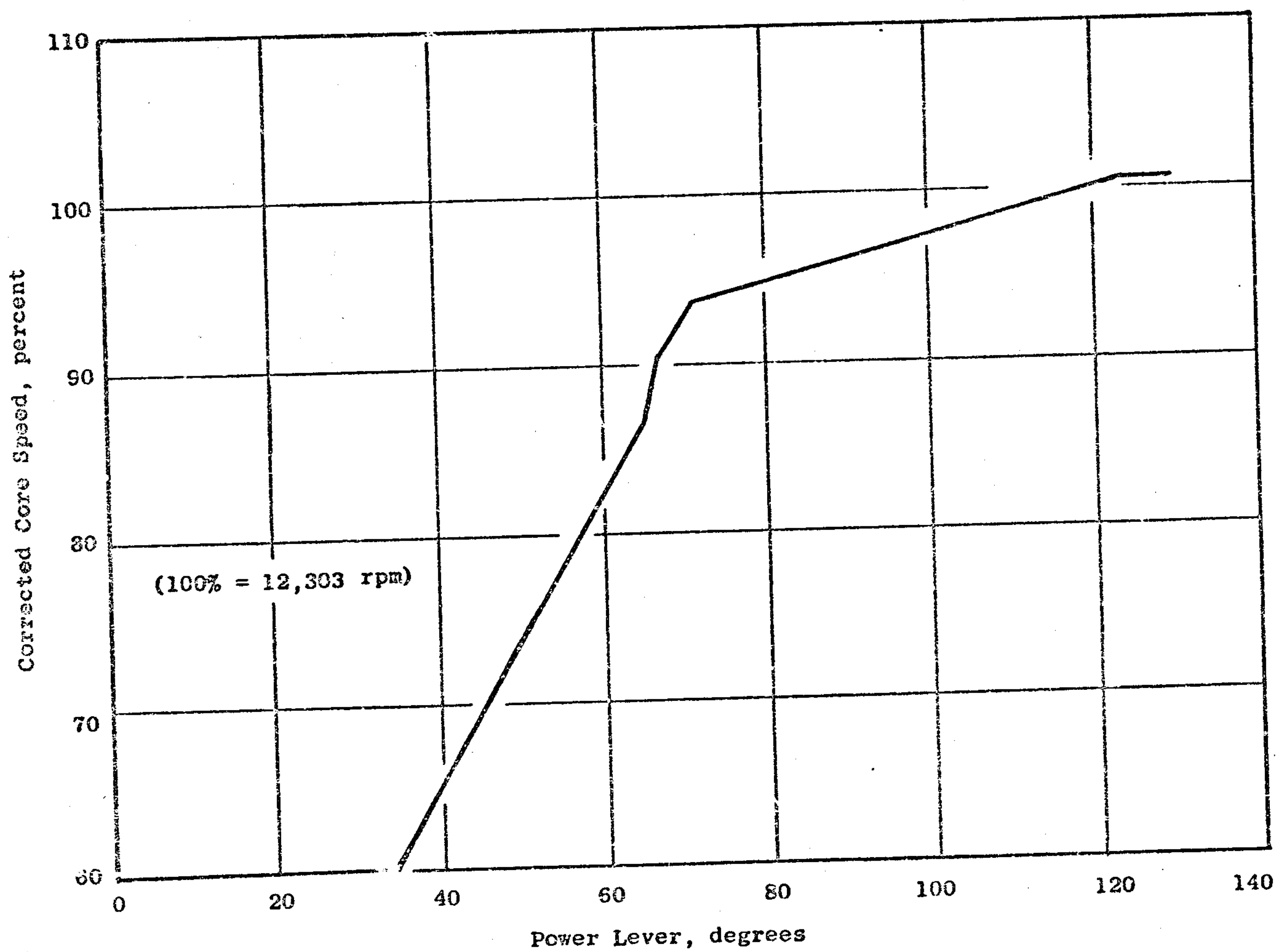

Figure 10. Power Lever Schedule of Corrected Core Speed.

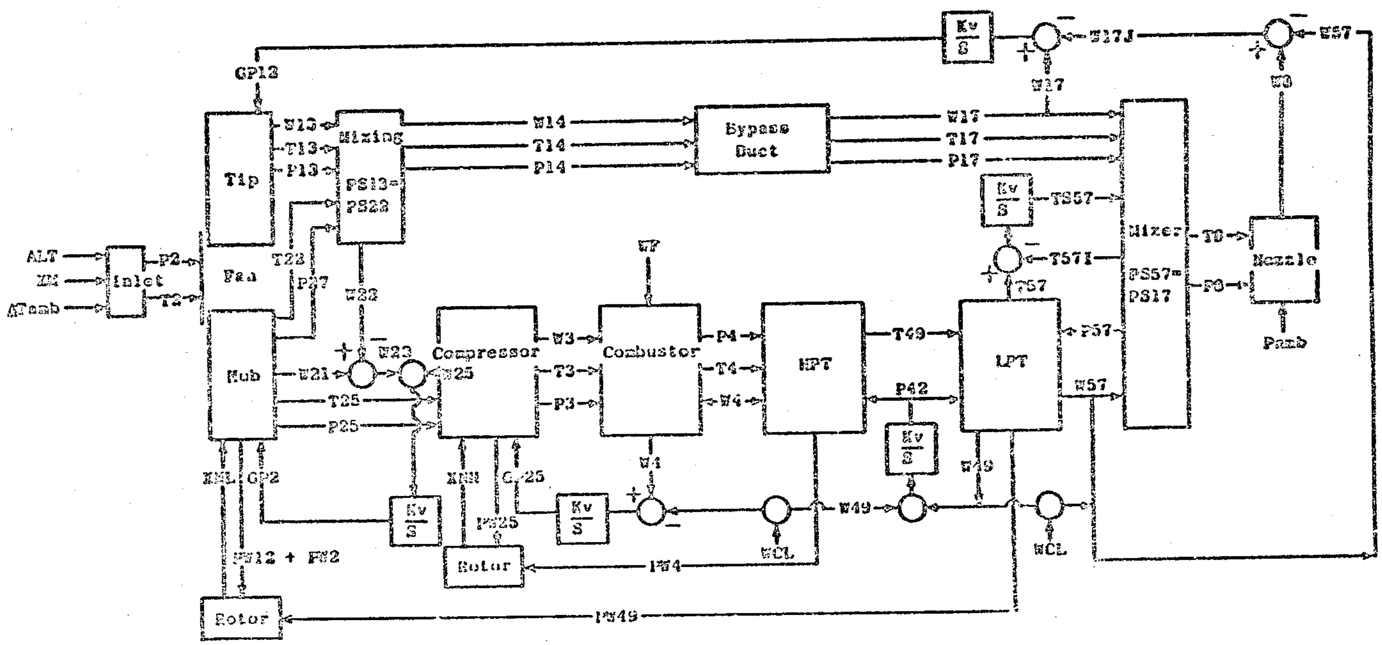

Figure 11. E^3 Hybrid Model Block Diagram.

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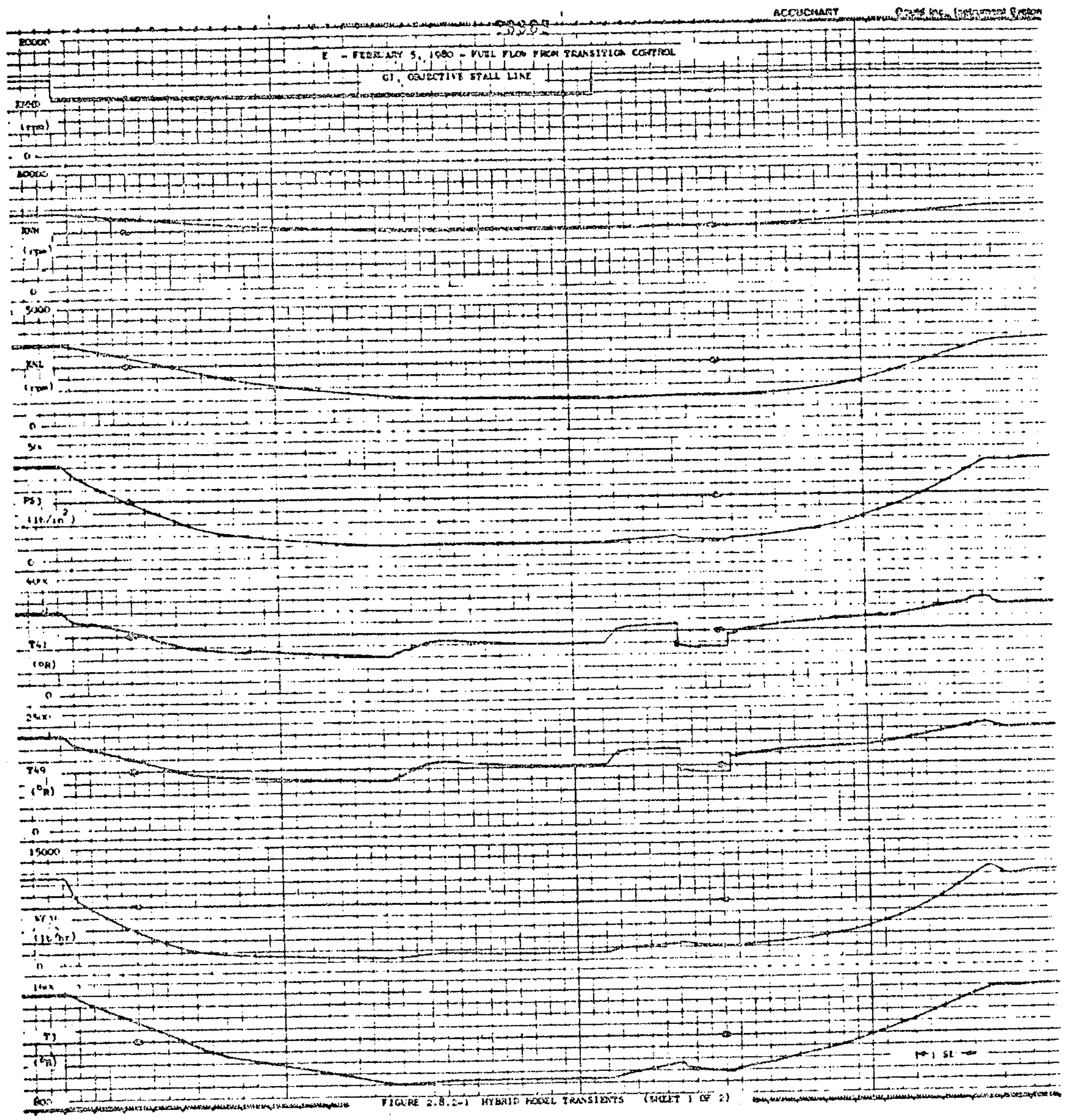


Figure 12. Hybrid Model Transients.

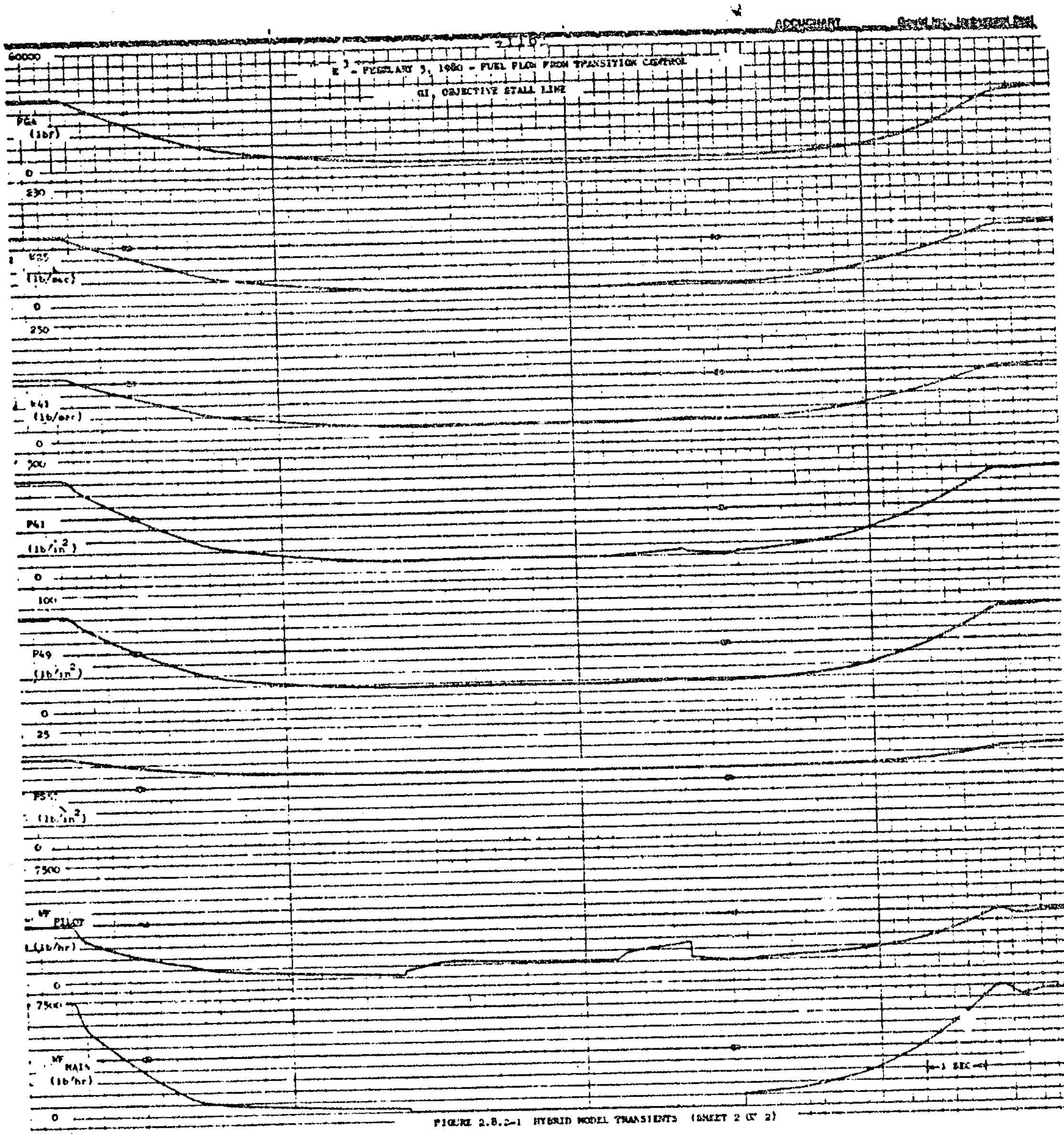


Figure 12. Hybrid Model Transients (Concluded).

60-second start on a standard day, while maintaining at least 10% compressor stall margin and limiting turbine inlet temperature to 1228 K (1750° F) maximum. A preliminary fuel schedule meeting the latter two criteria is plotted on Figure 13 and the resulting core rotor torque characteristic is shown in Figure 14.

4.2 CONTROL OF COMPRESSOR STATOR VANES

4.2.1 COMPRESSOR STATOR ACTUATION AND CONTROL

On the ICLS engine the compressor IGV's and the first four stator stages were variable and ganged. A system of levers and annular rings surround the compressor so that the stages move simultaneously with a stage-to-stage relationship established by linkage characteristics. As shown in Figure 15 the linkage is operated by a pair of fuel-driven ram actuators that are normally controlled by the digital control through an electrohydraulic servovalve. Position feedback to the control is provided by a position transducer connected to the actuation linkage. In the event of a digital control system failure, control of the stator actuators transfers to the hydromechanical control which provides a basis schedule similar to that in the digital control. This is described further in Section 4.4.

On the core engine the compressor IGV's and the first six stages were variable and were individually controlled by Test Facilities provided equipment.

4.2.2 COMPRESSOR STATOR CONTROL STRATEGY

The conventional practice of scheduling compressor stator angles as a function of rpm and inlet temperature is used for the E^3, but the added computational capability offered by the digital control is utilized to supplement the basic schedule and to further exploit the potential of variable stators to improve engine operation and performance.

Figure 16 is a block diagram of the stator control strategy. The basic schedule is shown in the next-to-top block on the left with the modifiers applied to it through downstream summations. The modifiers are described below.

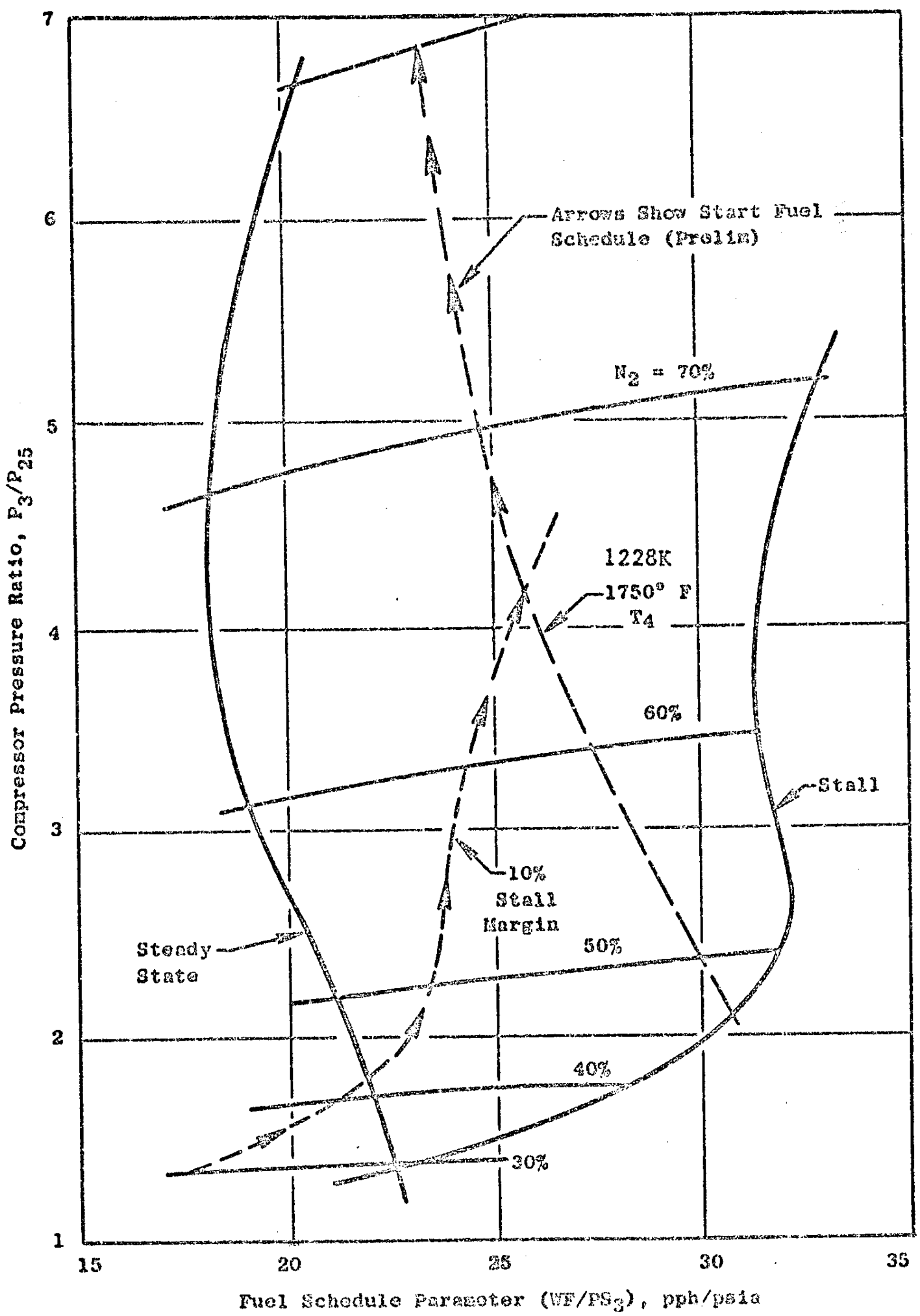


Figure 13. Subidle Model Data.

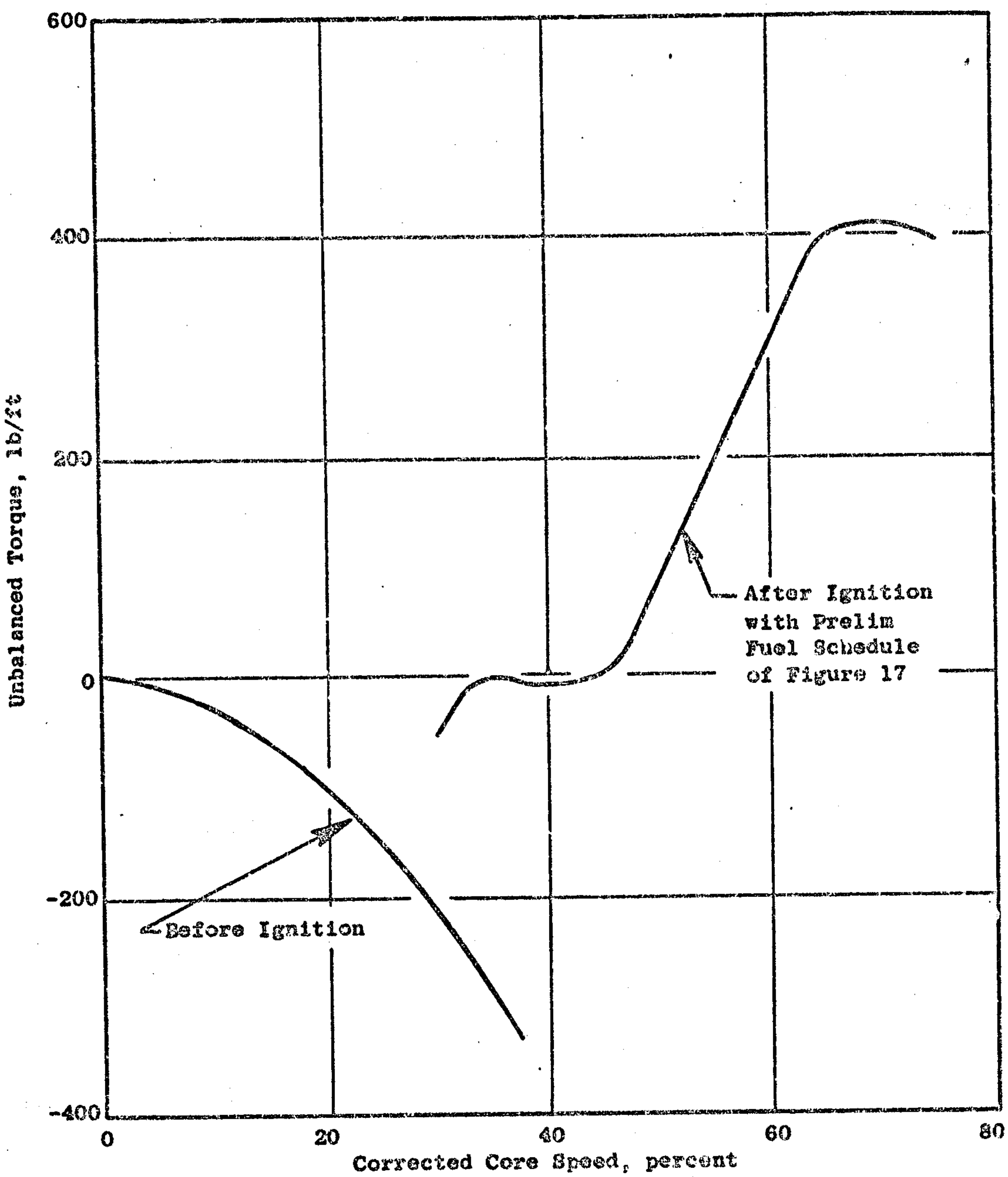


Figure 14. Torque Data from Subidle Model.

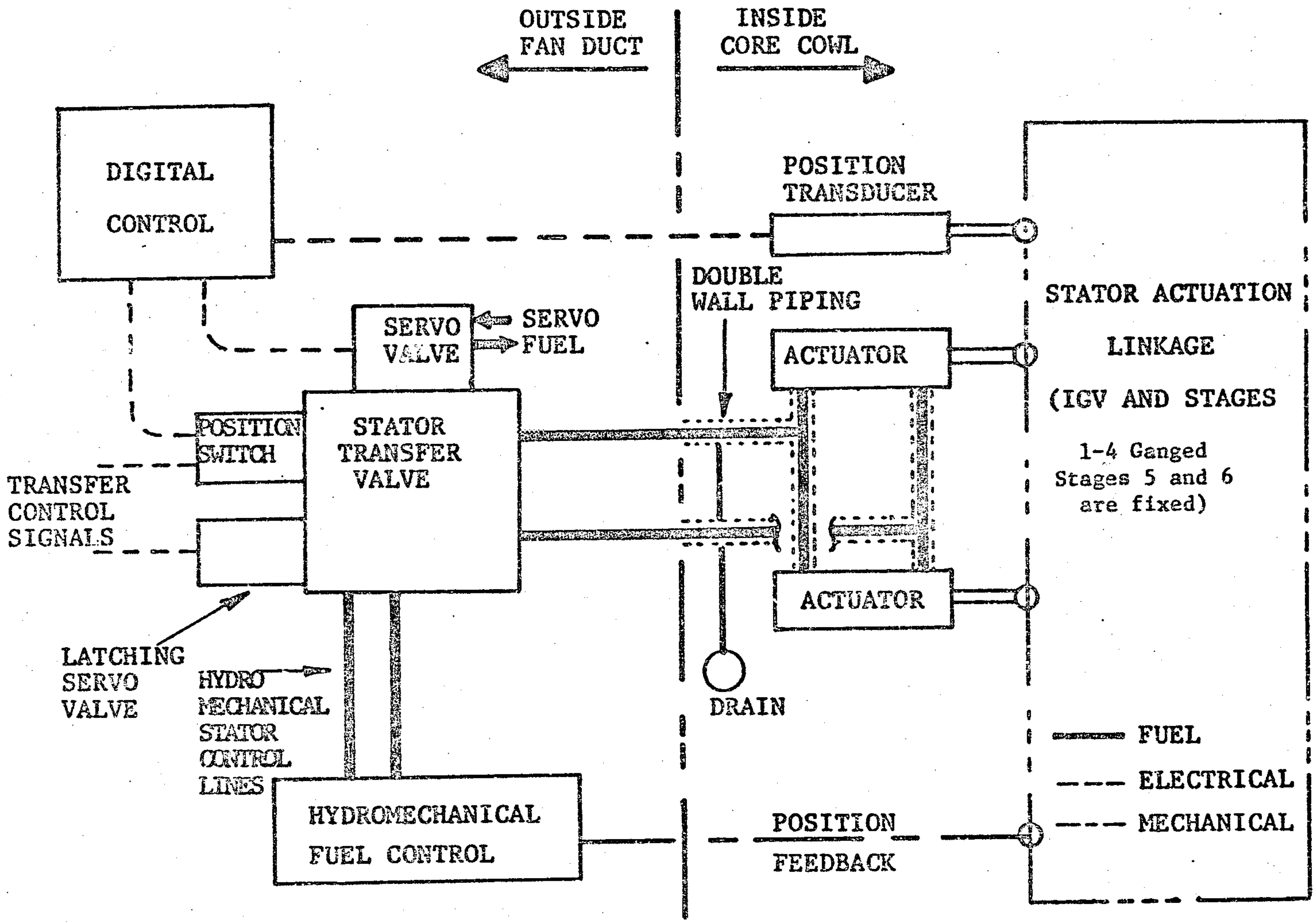


Figure 15. Compressor Stator Actuation and Control.

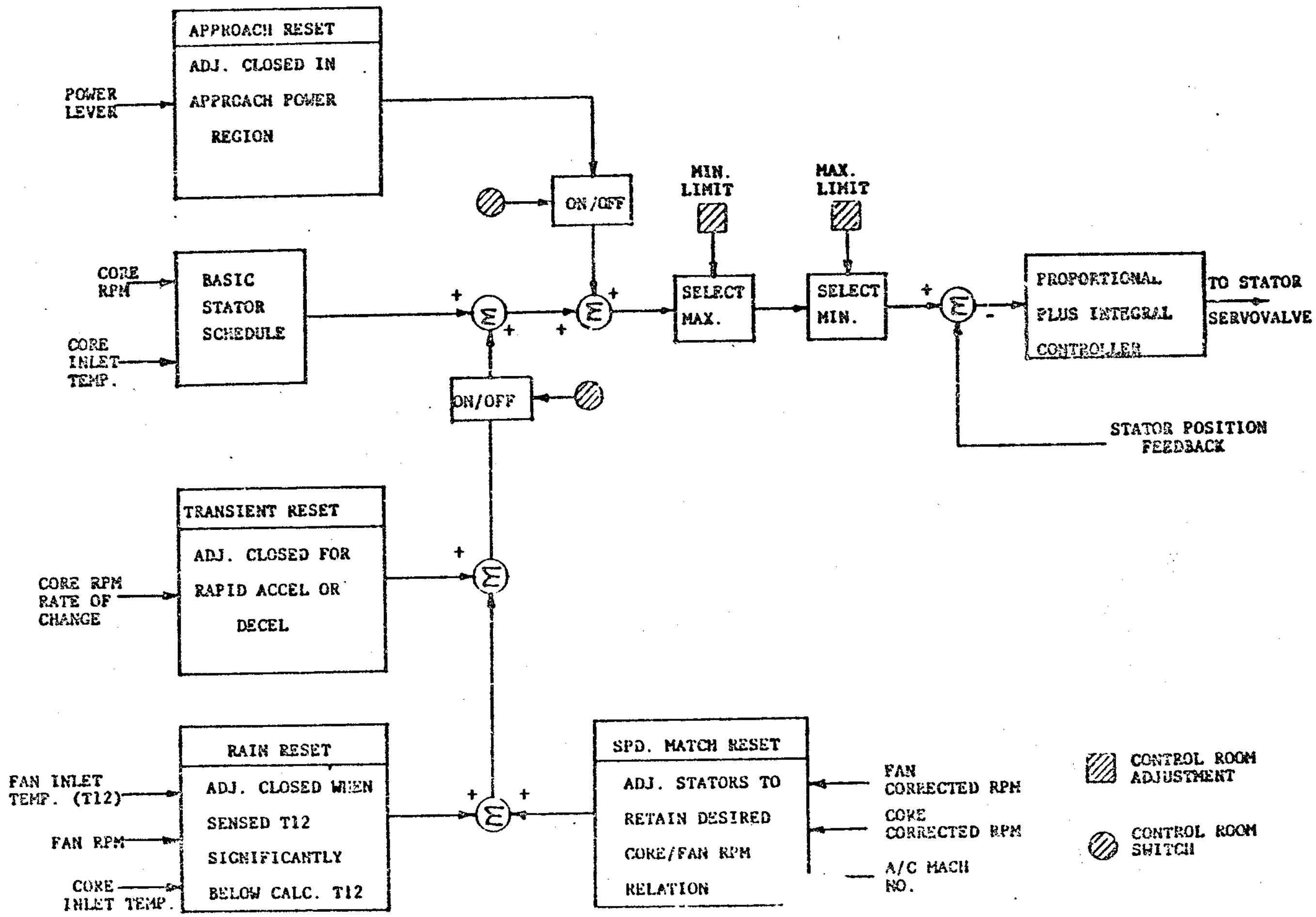


Figure 16. Compressor Stator Control Strategy.

Approach Reset - This feature in effect provides an alternate schedule that closes the vanes much further than normal in the approach thrust range. This results in higher core rpm during approach, thus making it possible to regain high thrust more quickly in the event of an aborted landing. This concept, tried biefly during the NASA/GE QCSEE program, is included in the E^3 program so that it can be explored further.

Rain Reset - Experience with CF6 engines has shown that heavy rain causes a reduction in compressor inlet temperature (T25); rapid termination of rain, combined with T25 sensing lag, can cause compressor stalls. This reset causes a small stator vane closure when sensed T25 is less than calculated T25 (as it will be in heavy rain), thereby increasing stall margin.

Speed Match Reset - Experience has shown that engine deterioration often results in a reduction of core rpm relative to fan rpm and a corresponding reduction in core efficiency at cruise thrust settings. This function detects a deviation from the normal core rpm/fan rpm relationship and adjusts the stator vanes to restore the original relationship.

Transient Reset - The basic stator schedule is designed to provide optimum steady-state compressor performance. But it is not necessarily the best schedule for rotor speed transients. For this reason, a transient schedule reset was included to provide potentially improved transient characteristics. Based on past experience, it is expected that a stator reset in the closed direction will provide additional transient surge margin and better transient characteristics. A reset proportional to the rate of change of speed is incorporated for empirical evaluation.

Switches are provided as shown on the block diagram (Figure 16) to allow the above modifiers to be disabled during the test program so that they cannot interfere with normal stator scheduling. Also, adjustments are included (not shown on diagram) to eliminate the effects of individual modifiers.

4.3 ACTIVE CLEARANCE CONTROL

4.3.1 ACTIVE CLEARANCE CONTROL MECHANIZATION

There are three separate active clearance control systems on the E^3: one for the aft stages of the compressor, one for the HP turbine, and one for the LP turbine. They are shown schematically on Figure 17.

Clearance control in compressor Stages 6 through 10 is achieved by passing a variable flow of Stage 5 bleed air over the compressor casing in this region to provide a thermal adjustment of casing dimensions. The Stage 5 air extracted for LPT purge is ported so that it can flow through the compressor clearance control chamber and through an external bypass pipe. Air from these two flowpaths is ported to a rotary three-way valve which is designed to provide virtually constant total flow but a flow split between the two flowpaths that varies with valve rotor position. The valve is positioned by a fuel-operated servoactuator controlled by the digital control. An electrical transducer within the actuator provides position feedback to the control.

Turbine clearance control is achieved by impinging variable amounts of air, independently, onto the HP and LP turbine casings to provide thermal control of casing dimensions. Both systems utilize fan discharge air picked up by scoops in the fan duct pylon wall and passed through variable area butterfly valves. These valves are independently positioned by fuel-operated servoactuators similar to the one used for compressor clearance control. The HPT clearance control system also includes a provision for introducing compressor discharge air onto the casing. Studies, using the clearance model described below, revealed the desirability of using this air for a brief period immediately after engine start in order to establish proper clearances quickly and, thereby, eliminate the possibility of a rub if the engine is accelerated before the casing can heat up naturally. The studies showed a similar feature which was not needed for the LP turbine. This feature was not demonstrated on the core or ICLS test vehicles.

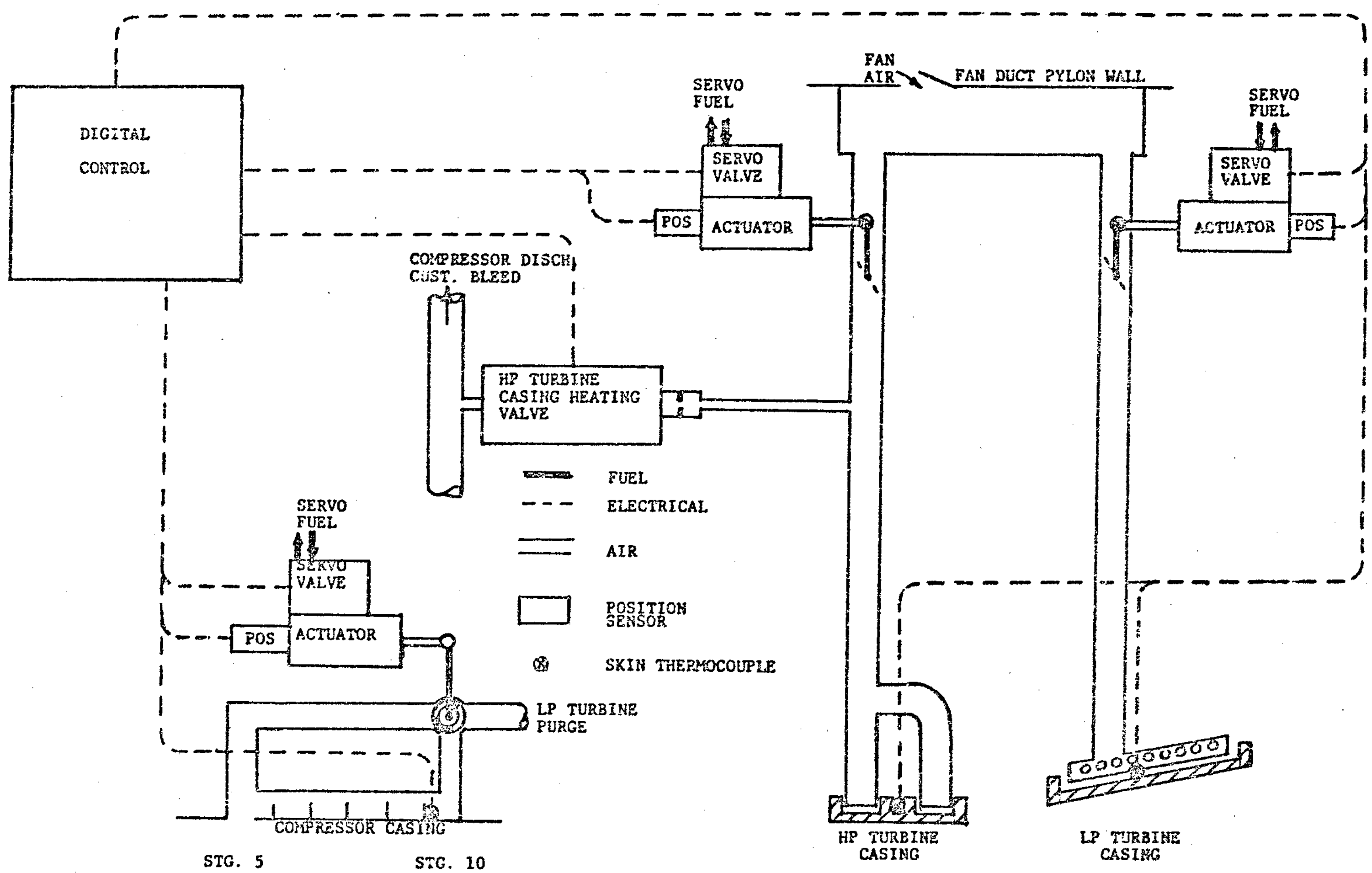


Figure 17. Clearance Control System.

4.3.2 CLEARANCE CONTROL STUDIES AND CONTROL STRATEGY DEFINITION

The control strategy for the clearance control systems was established to meet a set of general objectives as listed below.

- Provide minimum practical clearance at cruise power settings.
- Provide extra clearance for takeoff/climb maneuver deflections.
- Prevent hot rotor reburst rubs.
- Fail-safe (i.e., to maximum clearance).
- Provide manual remote control of clearance air valves for core/ICLS experimental flexibility.

In proceeding with the task of defining a control strategy for the clearance control systems, consideration was given to the use of direct clearance sensing to provide feedback information to the digital control and thus allow direct control of clearances. Clearance sensing on an operating engine has been demonstrated on an experimental basis, but the methods are not far enough along in development to make them feasible for use on initial FPS engines. Thus, it was necessary to develop a control strategy that does not depend on clearance sensing.

To assist in the definition of clearance control strategy mathematical modes of the engine and control elements involved in active clearance control were utilized. These are discussed in some detail in Reference 1. Typical data from the E^3 clearance model is shown in Figure 18. This happens to be for the HPT, but it is typical of all three systems. It shows that the system is capable of modulating the steady-state clearance at takeoff conditions from 0.279 to 1.346 mm (0.011 to 0.053 in.) with the fan air bleed flow within the range established by engine cycle considerations (0.3% of core airflow, maximum). This figure also shows that clearance during and immediately after a rapid rotor acceleration with a given amount of cooling is much less than the steady-state clearance with that same amount of cooling. The maximum

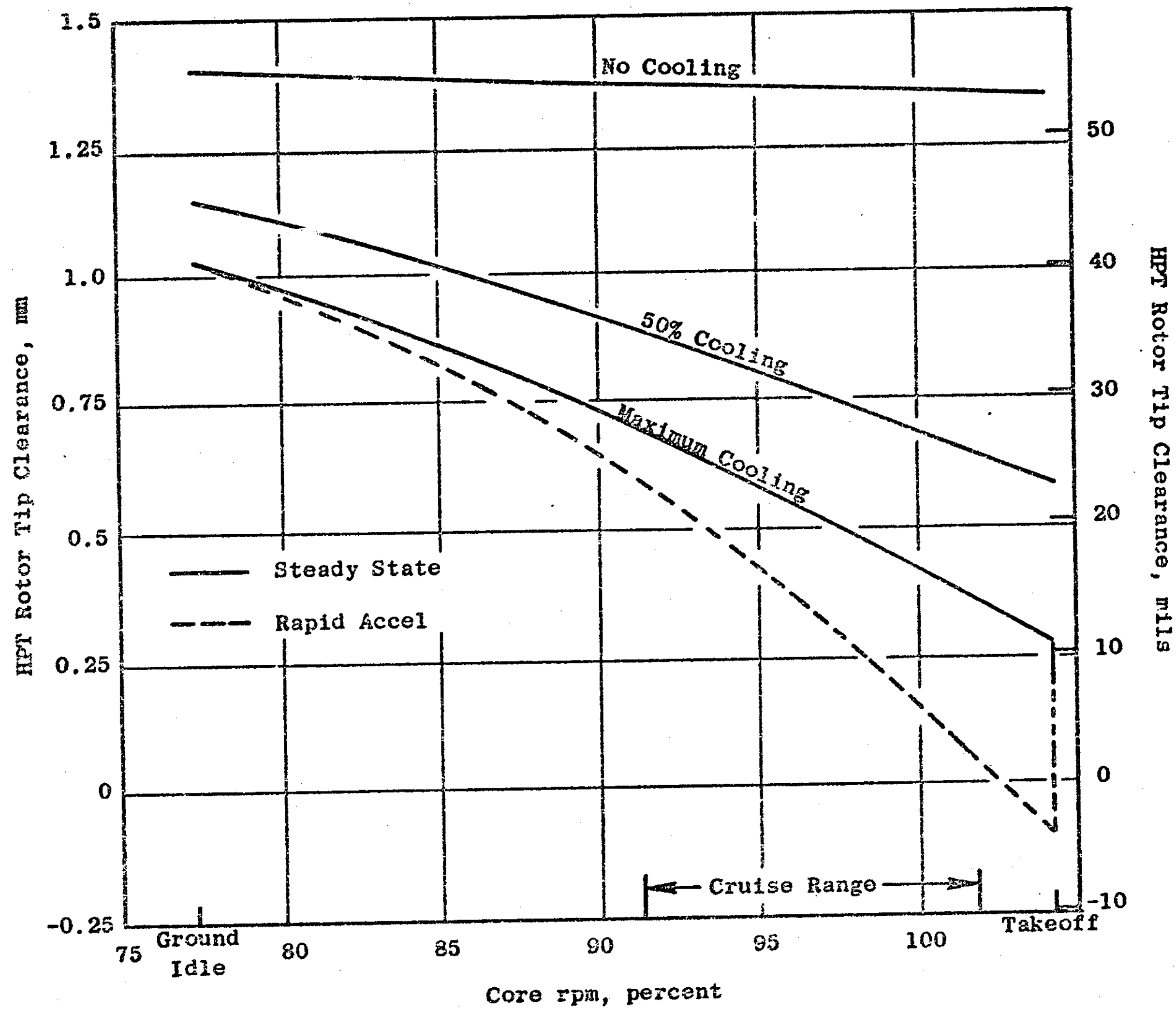


Figure 18. Preliminary HP Turbine Clearance Control Characteristics.

cooling condition shown actually results in an interference at the end of the acceleration. In order to eliminate the potential for such interference, the model data suggests that a limit must be imposed on cooling as a function of rpm. Figure 19 shows just such a limit.

As might be expected, the model also revealed that an orderly relationship exists between steady-state clearance, casing temperature, and rotor rpm (shown by the solid lines in Figure 20). The characteristics shown here suggest that a schedule of casing temperature as a function of rotor rpm could serve as an indirect method of controlling clearance. A trajectory for such a schedule is shown on Figure 20. The trajectory was established on the basis of the following criteria:

- Set the desired minimum running clearance of 0.406 cm (0.016 in.) at maximum cruise conditions.

- Provide additional clearance up to 0.635 mm (0.025 in.) at takeoff and climb conditions to accomodate maneuver deflections.

- Set additional clearance at lower cruise power settings to prevent inadequate clearance transiently after an acceleration.

- Provide maximum clearance at power settings below cruise to provide ample margin for accelerations. (Very little of the total engine fuel consumption during normal flights occurs in this power setting region; thus, the extra clearance margin has negligible effect on fuel use.)

The initial schedule derived in this manner is shown in Figure 21. Note that the schedules are defined in terms of parameters corrected to core engine inlet temperature. Similar schedules were derived in the same manner for compressor and LPT clearance control.

In order to assess the transient effects of scheduling casing temperature (and thus steady-state clearance) in the manner just described, the schedules were incorporated into the clearance model and transients were run. Figure 22 shows typical data from the HPT clearance model during an

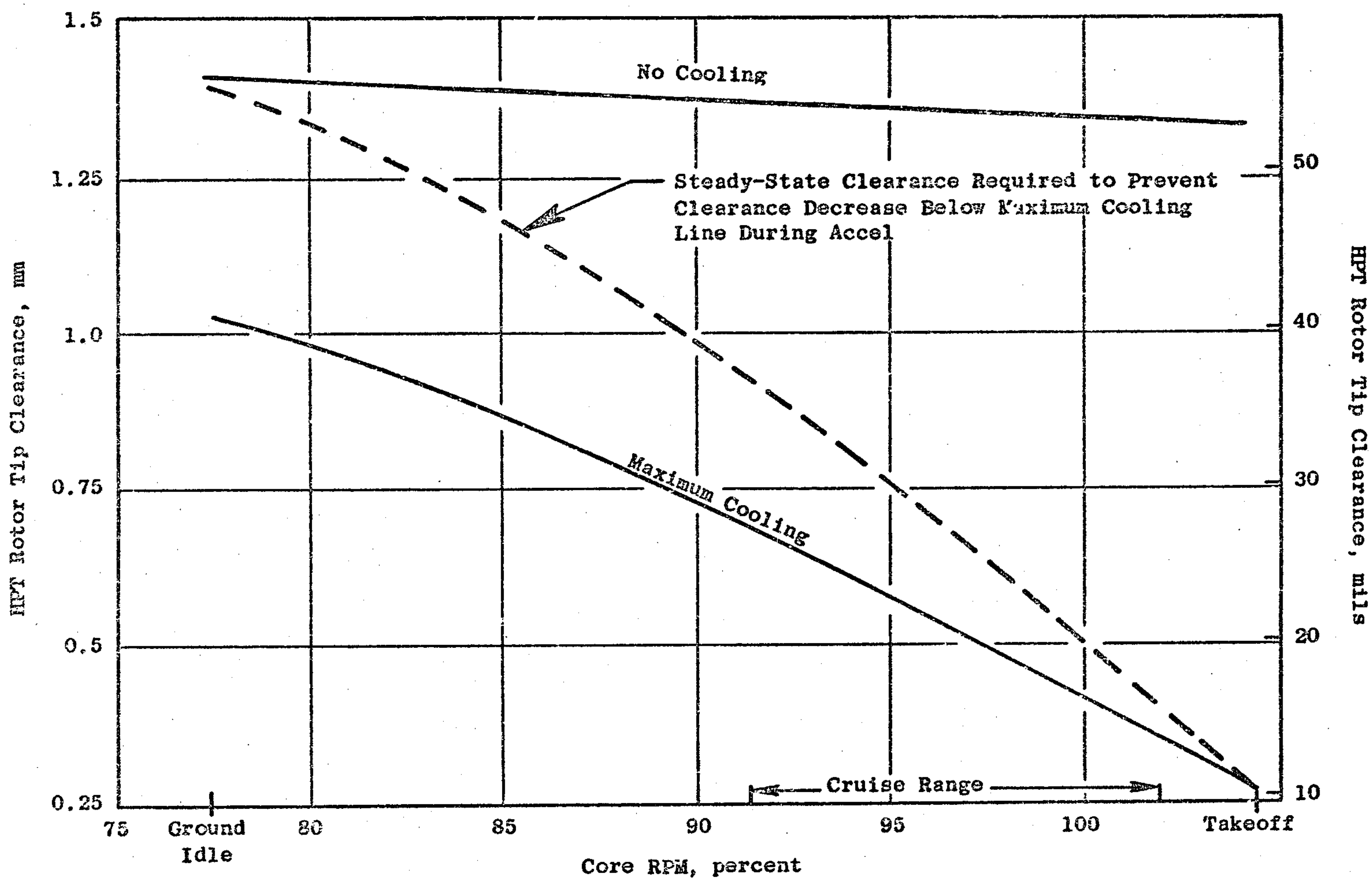


Figure 19. Preliminary HP Turbine Accel Clearance Margin Curve.

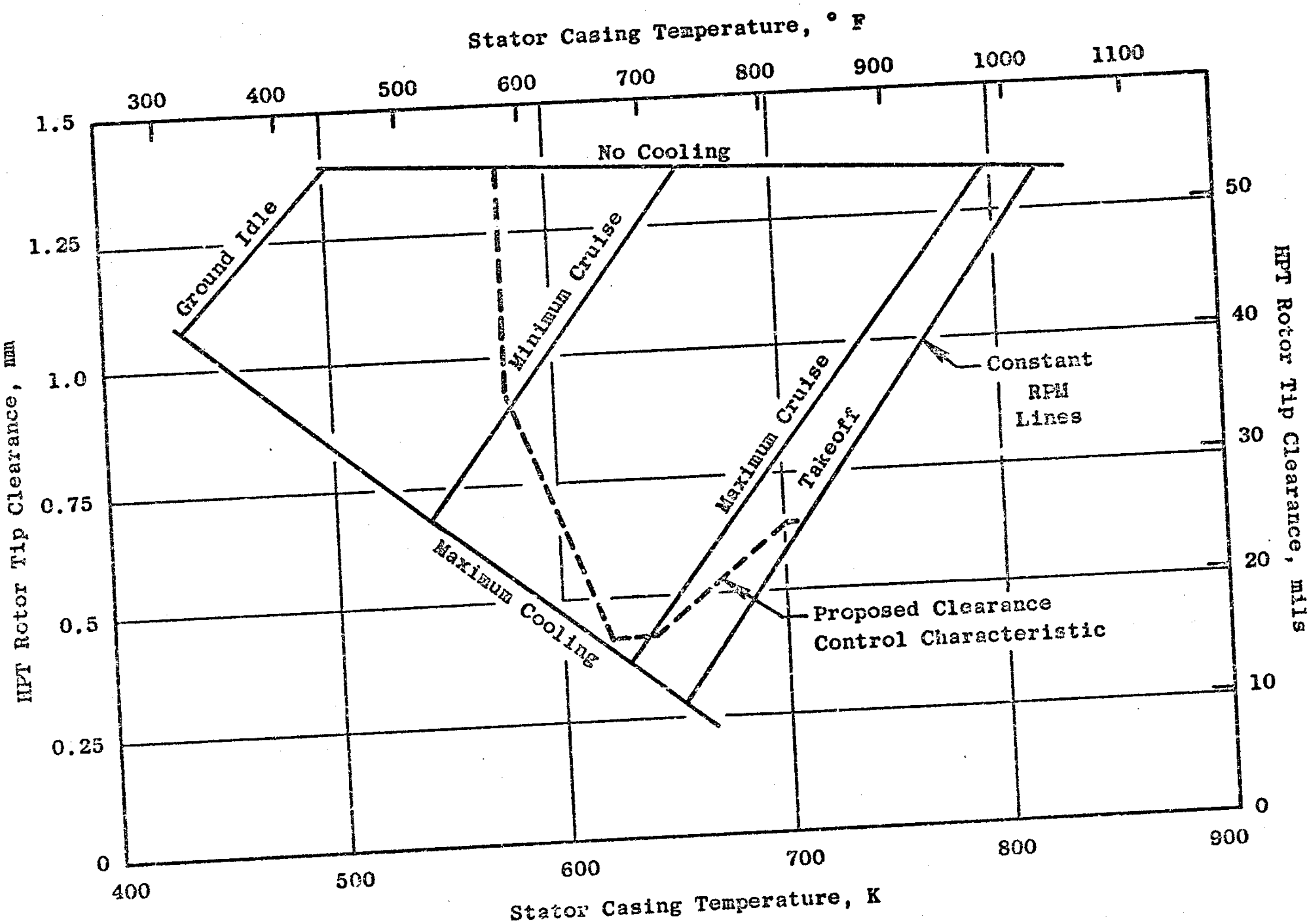


Figure 20. Preliminary HP Turbine Clearance Control Characteristic.

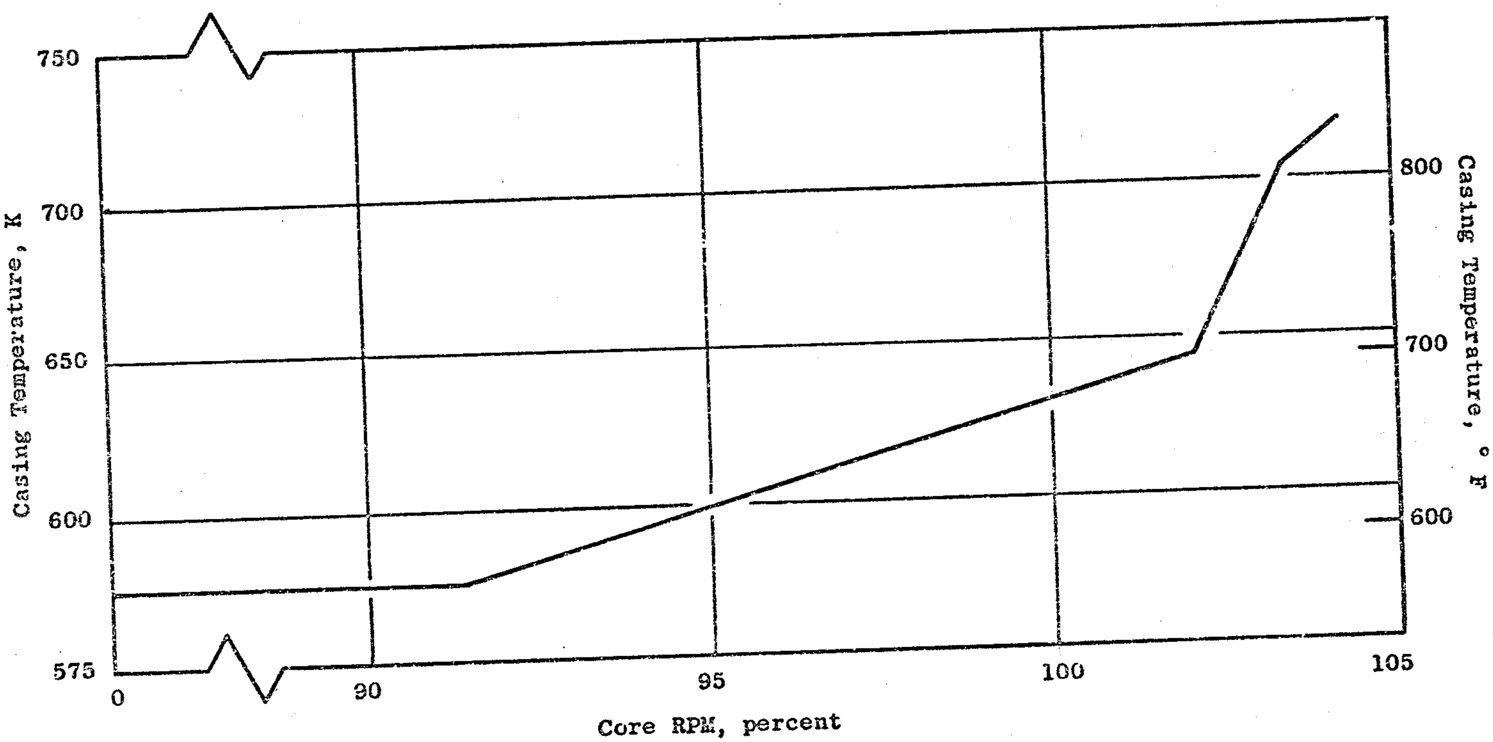


Figure 21. Preliminary HP Turbine Clearance Control Schedule.

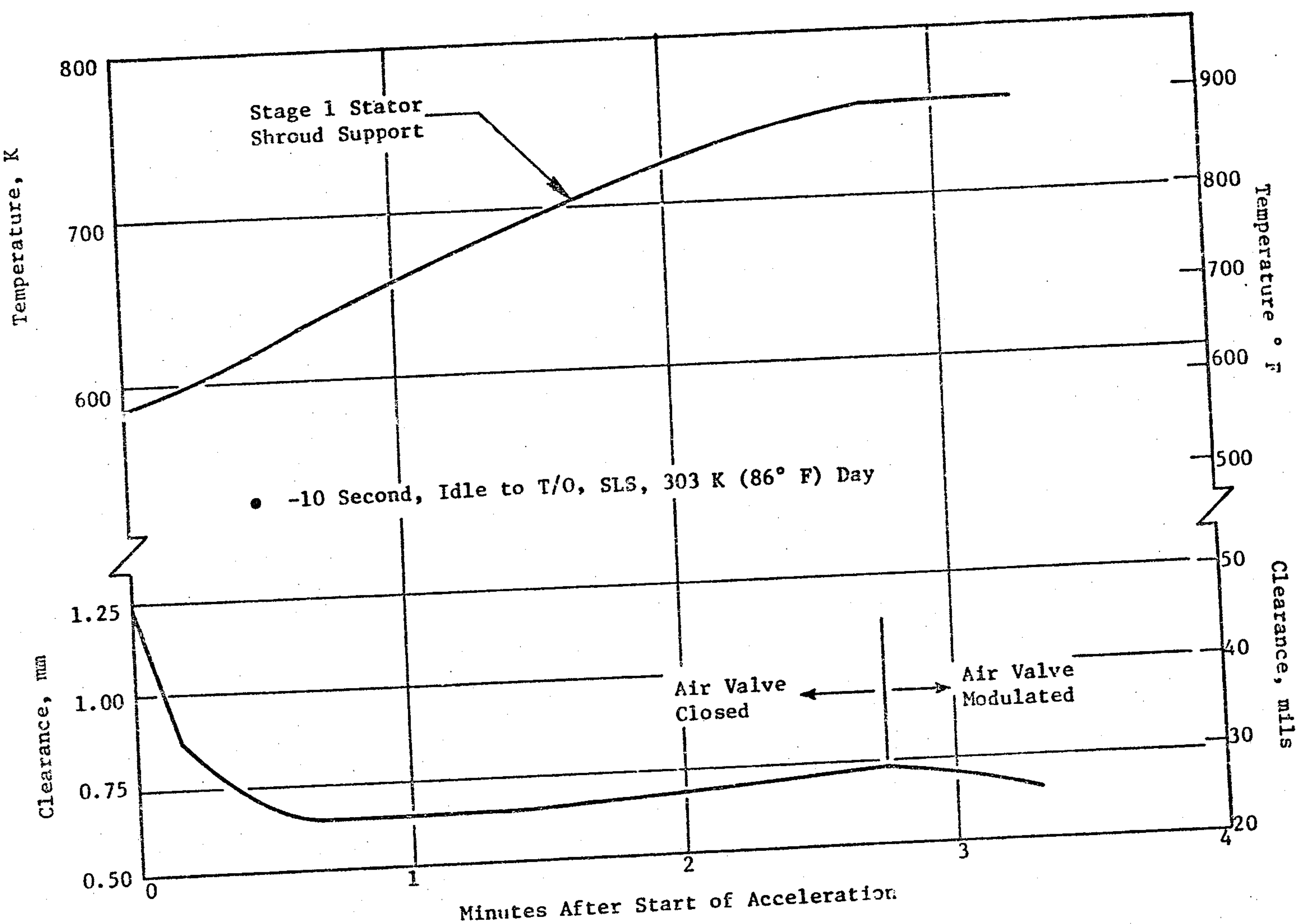


Figure 22. Transient HP Turbine Clearance and Temperature.

acceleration. This data reveals another desirable characteristic of the casing temperature scheduling concept. For nearly three minutes after an acceleration from idle to takeoff power, the casing temperature is below schedule and the clearance control valve is closed. The thermal characteristics without casing cooling are such that clearance remains in the0.635 to 0.762 cm (0.025 to 0.030 in.) range, thereby providing the additional margin desired for the engine deflections that occur during takeoff and initial climb.

Accel transient runs on the compressor clearance model also revealed an interesting characteristic. As shown in Figure 23, the temperature of the Stage 5 clearance control air is higher than casing temperature for about a minute after an acceleration from idle to takeoff power. By rotating the clearance control valve to the maximum casing flow position during this period, casing growth can be accelerated to help provide the extra clearance margin desired for takeoff and initial climb. A model run showing the effect of this feature is shown in Figure 24.

With the casing temperature scheduling concept successfully demonstrated on the clearance model, detailed clearance control strategy definition proceeded. Figure 25 is a block diagram of the strategy for the HPT clearance control systems. The basic casing temperature scheduling function is shown in the upper left part of the diagram. The decel override shown below this was added to prevent rubs in the event of hot rotor reburst (that is, a deceleration followed by an acceleration before the rotor, which cools slower than the casing, has reached steady-state temperature). A rapid deceleration causes the clearance control valve to close and remain closed until the casing temperature reaches the normal steady-state level. If the engine is reaccelerated before steady-state temperatures are established, the decel override is deactivated and the casing temperature schedule functions normally.

A manual control mode is also provided. When the manual mode is selected, the air valve is positioned as a function of a potentiometer on the digital control operator panel in the control room so that clearance control system characteristics can be experimentally evaluated. A decel override is

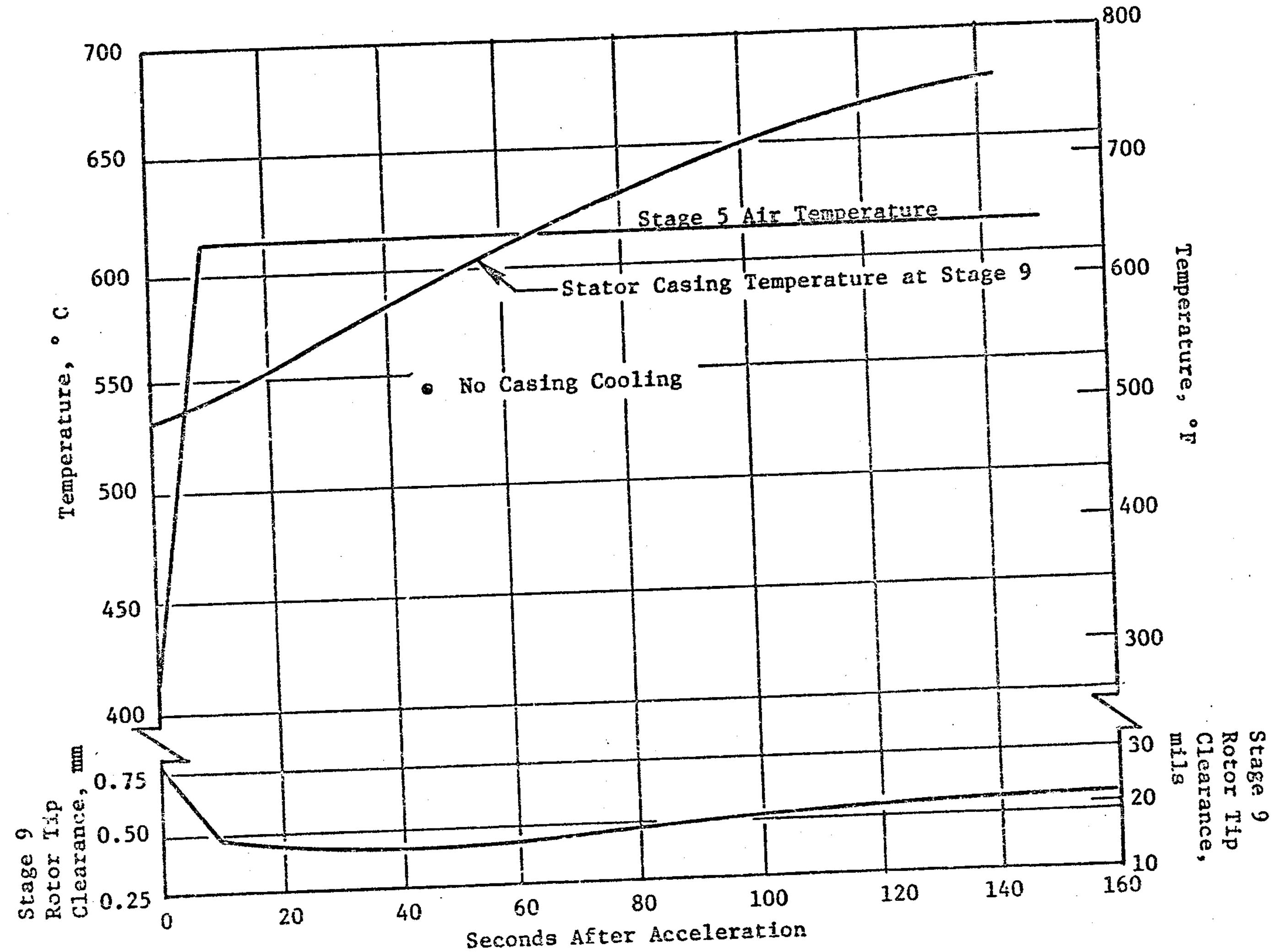


Figure 23. Compressor Clearance Characteristics.

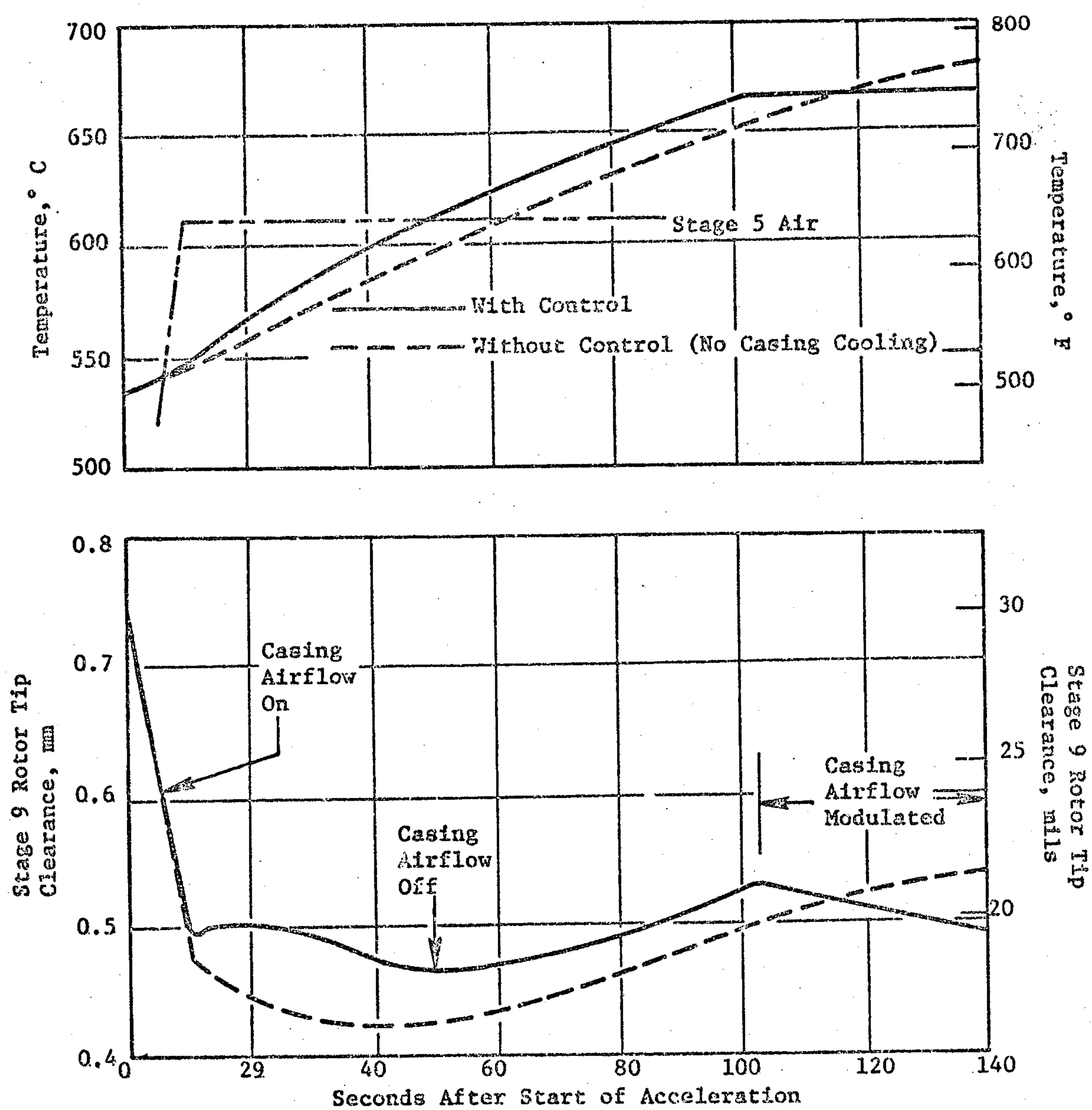


Figure 24. Transient Compressor Clearance With and Without Control.

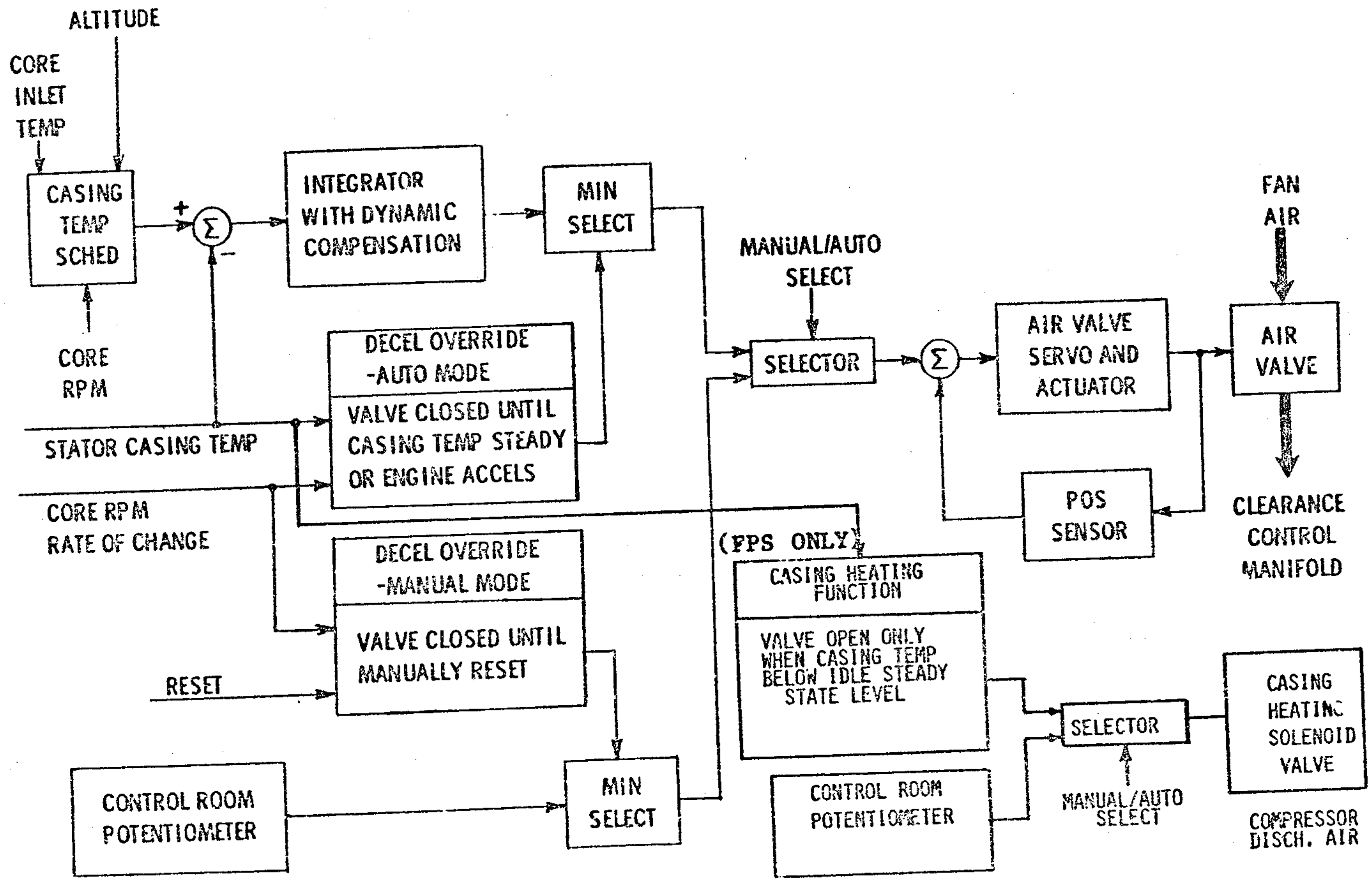


Figure 25. Turbine Clearance Control.

included in the manual mode to preclude a hot rotor reburst with the air valve inadvertently left open after a decel. This override, once activated, remains in effect until manually reset.

In addition, the block diagram of Figure 25 shows the casing heating features that provides quick warmup after an engine start so that an immediate acceleration to high speed can be made without encountering a rub. In theautomatic control mode, this on-off function is triggered as a function of casing temperature with the valve open below steady-state idle temperature and closed above. A manual mode is also provided. The casing heating feature was not included on the test engines but would be part of a production engine design.

The control strategy for the LP turbine is functionally the same as for the HP turbine, except that no casing heating feature is included. Clearance model runs showed this rapid poststart warmup is not necessary for the LP turbine.

Figure 26 shows the control strategy for the compressor clearance control. It includes a basic casing temperature regulator, a decel override, and a manual mode that all function the same as those in the turbine clearance control systems. In addition, it includes an air temperature override which positions the valve to cause clearance control air to flow over the casing when the air temperature exceeds the casing temperature. This is the extra acceleration margin feature described earlier. To eliminate the need for a clearance control air temperature sensor, this temperature is calculated from compressor discharge pressure and compressor inlet temperature, both of which are already sensed by the control system for other reasons.

4.4 FAILURE PROTECTION

Protection against failures that can cause control or engine operational problems is an improtant aspect of any control system design. For the E^3 system this is particularly important because the digital control and associated elements are in a relatively early stage of development. Control redundancy is one conventional means of providing such protection; hence, dual

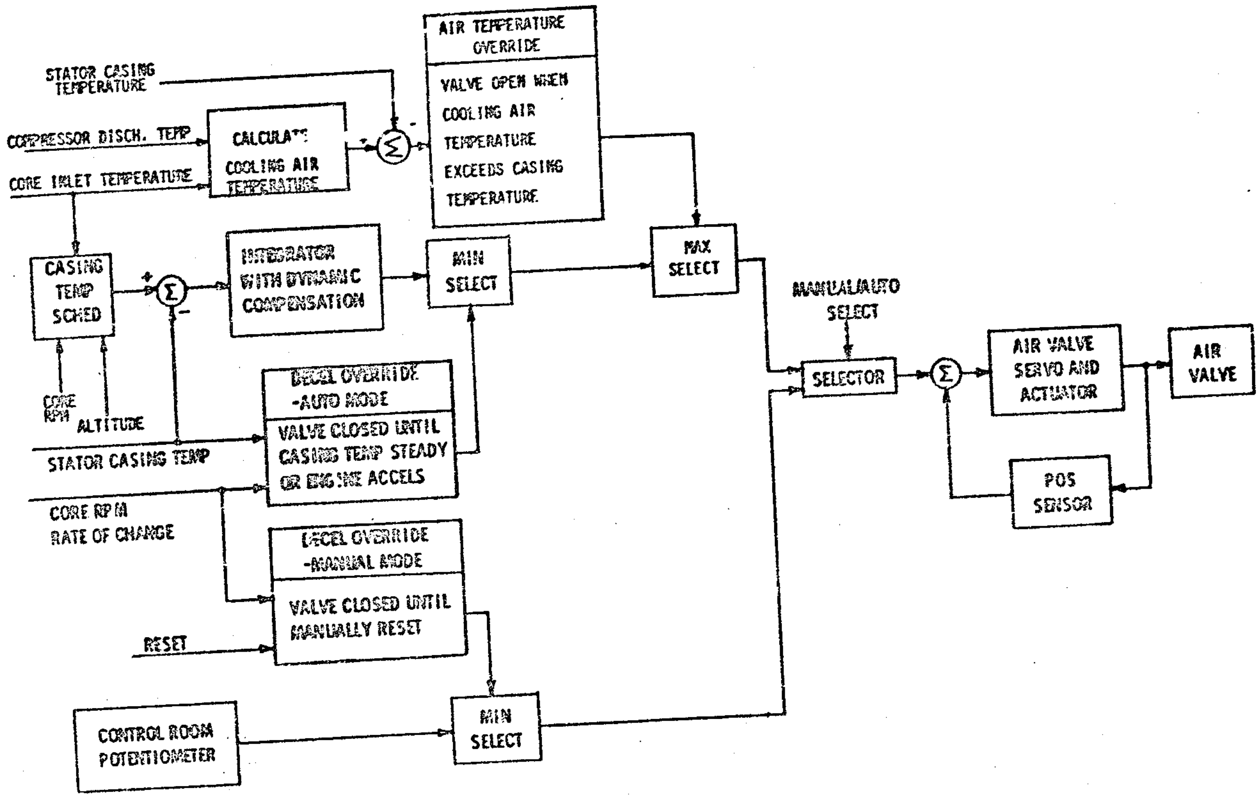


Figure 26. Compressor Clearance Control.

redundant digital controls are proposed for the production engine system. Because the definition and implementation of redundancy was considered beyond the scope of the present program, less costly failure protection features were incorporated for the core and ICLS engines. These are described in the paragraphs below.

4.4.1 HYDROMECHANICAL BACKUP CONTROL

The test engine control system includes an F101 hydromechanical main engine control which is used primarily for its fuel metering section, controlling fuel flow in response to a signal from the digital control. The control also includes a hydromechanical computing section. This section is employed to provide backup control of fuel flow and core stator actuator position. Figure 27 is a general schematic of the backup system. Figures 28 and 29 show additional functional details.

In the primary mode, the latching solenoid valve positions the transfer valves so that the fuel metering valve and the core stator actuators are controlled by the digital control through the electrohydraulic fuel and stator servovalves. When the latching solenoid is energized to the backup position, the transfer valves move to their backup position. Here the fuel metering valve and core stator actuators are both controlled hydromechanically by the fuel control. In this condition a position switch on the stator transfer valve signals the digital control to deenergize all outputs so that built-in offsets in the output devices cause all other controlled variables to go to safe positions. The valves controlling fuel flow split go to the full burning condition, the start bleed and start range turbine cooling valves close, and the clearance control valves go to the maximum clearance position. The latch feature in the solenoid valve assures that the existing condition, either primary or secondary, is retained until a definite signal is received calling for a mode change.

A selector switch in the control room sets the basic system operating mode (Figure 29). With the selector in the normal position the system will normally be in the primary mode, but it will switch to backup position if (1) the digital control power supply voltage is low, (2) if the digital control self-test computation shows a fault, or (3) if a core rotor overspeed occurs

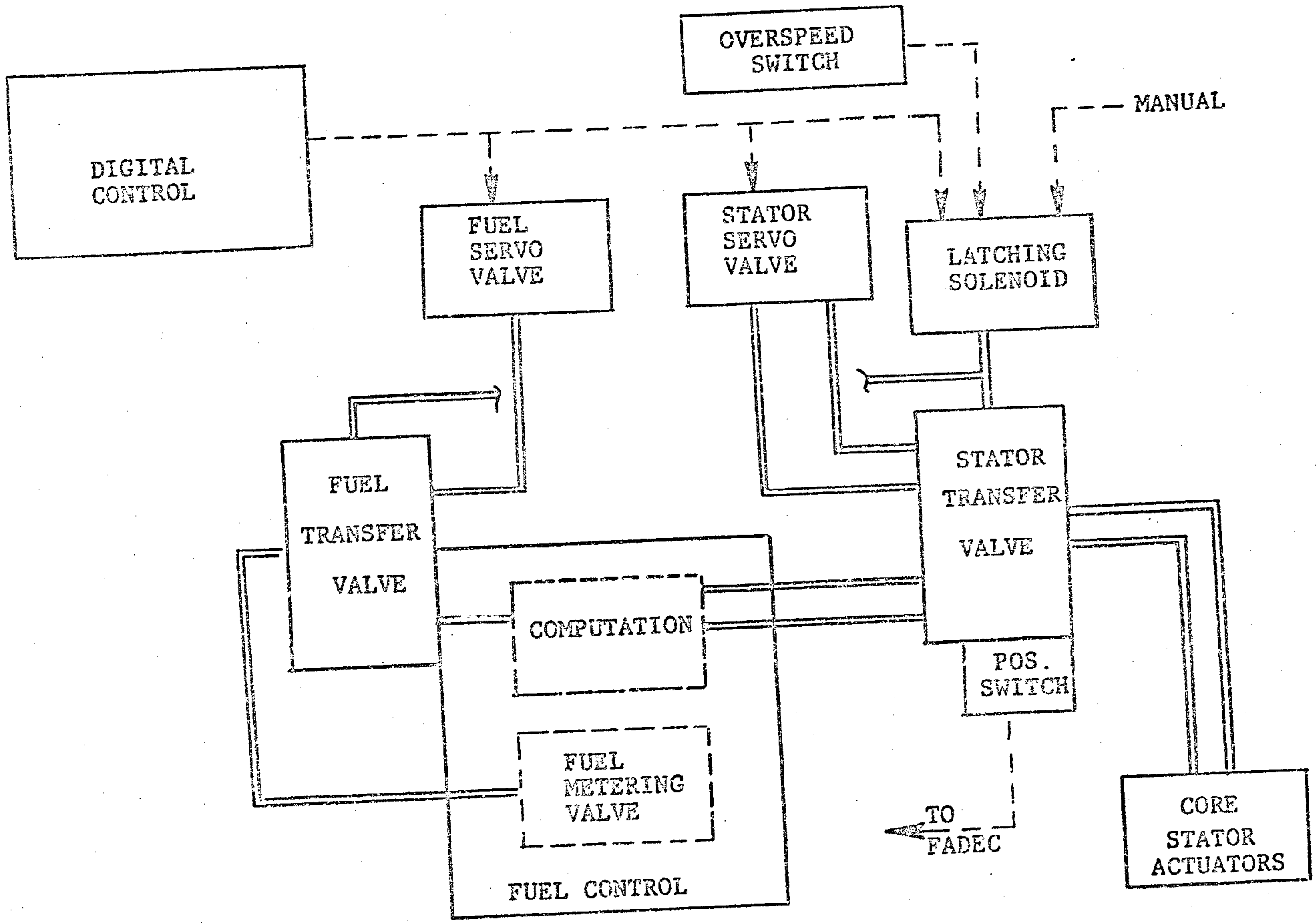
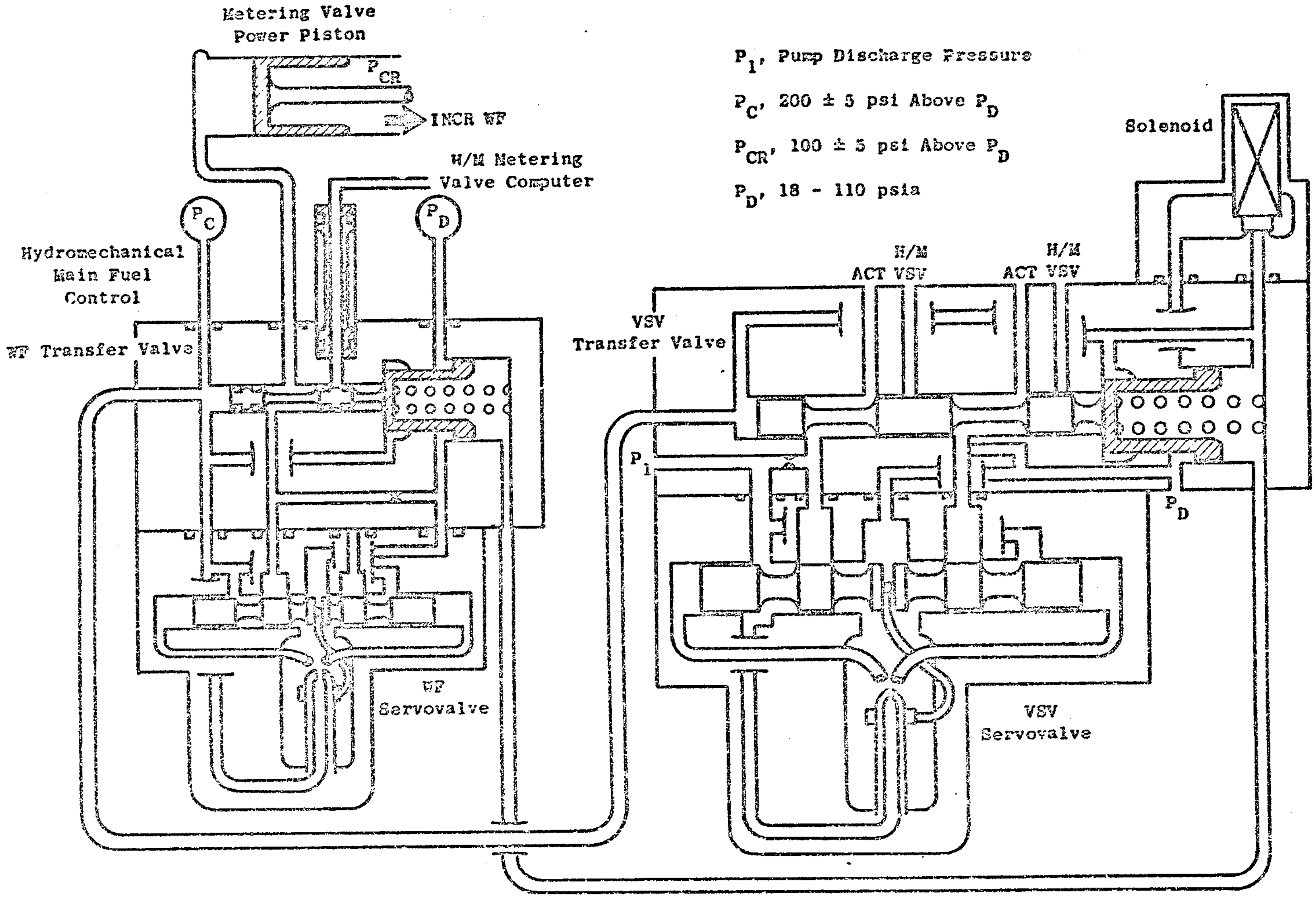


Figure 27. Hydromechanical Backup Control System.



⊙ Valves Shown in Primary Mode

Figure 28. Transfer Valves.

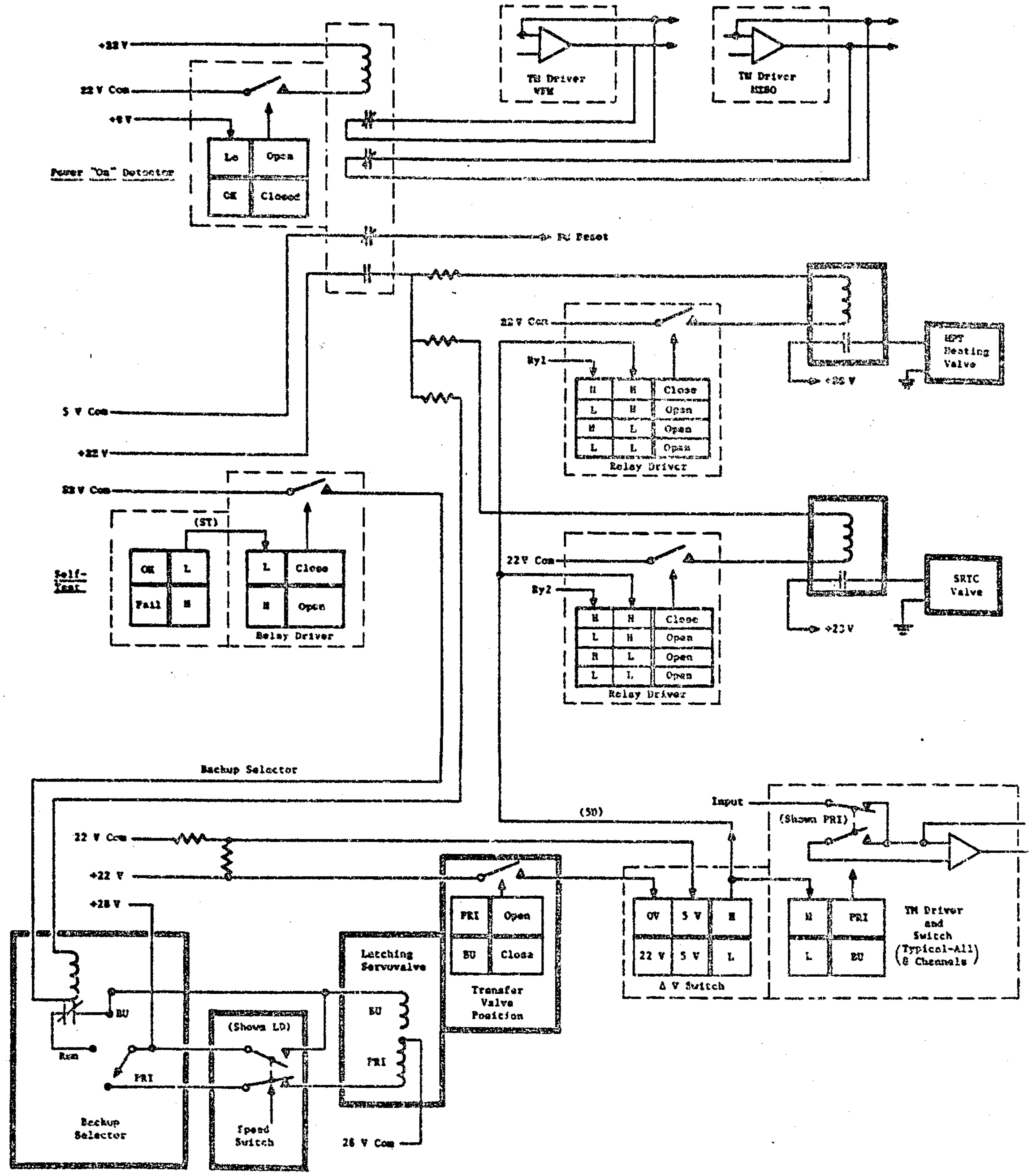


Figure 29. Fail-Safe and Backup Functions.

which sends a fuel pressure signal from the fuel control to an overspeed pressure switch. Selector switch positions are also provided that set manual mode only, primary mode only, or existing mode only operation.

4.4.2 SENSOR FAILURE PROTECTION

The digital control system incorporates a number of electrical sensors that are necessary for proper system and engine operation. Provisions must be made to accommodate occasional sensor failures without significant operational effect. This could be done with sensor redundancy, but this adds cost, increases maintenance activity, and requires additional mounting provisions on the engine. Instead, the computational capability of the digital control is utilized to provide the equivalent of sensor redundancy without multiple sensors by employing a failure indication and corrective action (FICA) concept.

The basic FICA concept involves the incorporation of a simplified engine model in the digital control software, along with sensor failure detection logic which monitors sensor signals and replaces failed signals with model-generated substitutes. A mathematical filter technique (extended Kalman filter) is used to continuously update the engine model using data from all nonfailed sensors.

Figure 30 is a diagram of the FICA. The engine model, outlined in the center of the diagram, is initialized with sensed inputs. It then continues to compute the state-of-engine variables based on inputs from (1) environmental sensors, (2) the fuel control loop (fuel flow rate of change), and (3) the model/sensor signal commparison through the update matrix. If any of the sensor signals deviate from the equivalent computed state variable by more than a predetermined acceptable amount, the computed value is substituted in the control strategy. The error for that variable is eliminated from the update process, and the model continues to compute all state variables with suitable accuracy.

In the demonstrator engine program the FICA concept was demonstrated on the ICLS engine. The core engine had a less extensive control system (no LPT-related control and slave controls for core stators), employed a simpler,

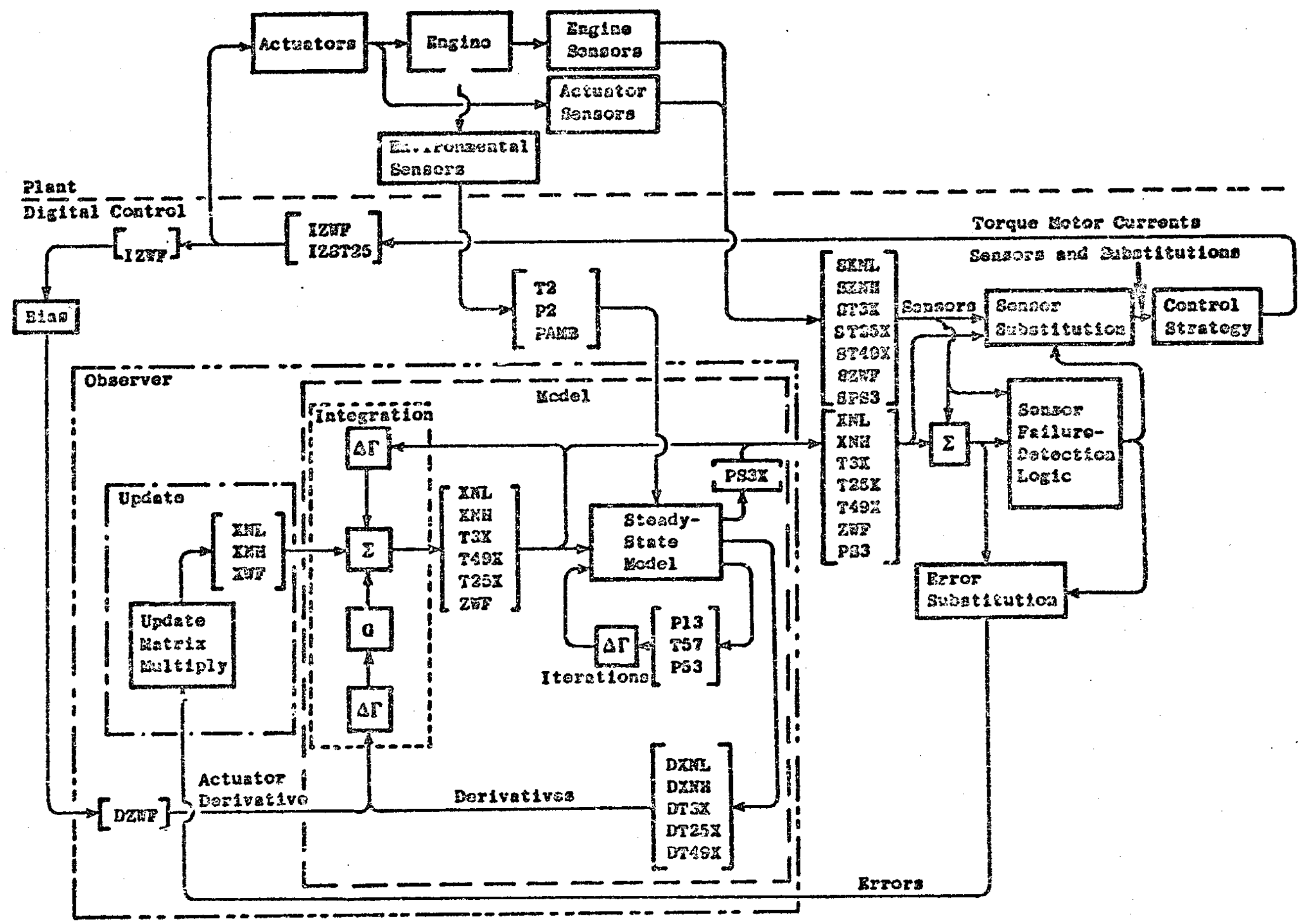


Figure 30. Sensor Failure Indication and Corrective Action.

out-of-limit strategy for sensor failure protection. When any sensed input beyond the normal operating range the digital control takes the following action:

Core Speed	- Indicate self-test failure, switch to backup mode
Core Inlet Temperature	- Substitute valve from manual T25 potentiometer on operator panel
Compressor Discharge Temperature	- Substitute valve calculated from core speed and inlet temperature
Compressor Discharge Pressure	- Substitute value calculated from core speed and ambient pressure (as indicated by potentiometer)
Exhaust Gas Temperature	- Substitute valve calculated from core speed and inlet temperature
Casing Temperature	- Set associated value at maximum clearance position
Compressor Clearance Valve Position	- Set control output to zero, valve goes to maximum clearance position
Turbine Clearance Valve Position	- Set control output to zero, valve goes to maximum clearance position
Main Zone Shutoff Position	- Set control output to zero, valve opens
Fuel Metering Valve Position	- Indicate self-test failure, switch to backup mode.
Power Lever Position	- Switch to backup mode

These out-of-limit functions were also included in the ICLS control system for use when the non-FICA mode is selected and also had final authority when FICA was selected.

The digital control also includes provisions for responding in a safe manner to certain fuel valve position sensing failures that result in large errors within the normal operating range. (Loss of certain electrical connections to the fuel valve position transducer can cause such a failure.) The control monitors rate of change of fuel valve position and, when it detects a rate in excess of the normal maximum rate that persists long enough to indicate it is not caused by random electrical noise, it switches to the backup mode. In this way, it protects against a sensor failure that could cause an inadvertent and excessive rise in fuel flow. The stator control system incorporated the same feature for the ICLS vehicle test.

4.5 DIGITAL CONTROL

4.5.1 GENERAL DESCRIPTION

The digital control is a full authority digital electronic control (FADEC) designed for operation of the integrated core/low spool (ICLS) configuration. It is engine mounted and air cooled. For normal operation, electric power is provided by the engine-driven alternator. For engine starting, and in the event of alternator failure, power is provided from the airframe (test cell) 28-volt bus.

The control is housed in a rectangular chassis with four mounting feet, one located at each corner, to support the chassis to the attaching points of the engine frame. A two-sided cold plate separates the chassis into two compartments. The multilayer ceramic modules are mounted on the cold plate in the shallow compartment. The discrete modules are mounted to the cold plate in the deep compartment. Cooling air flows through the finned passage separating the two mounting sides of the cold plate. Electric interface with the control is through seven wall-mounted electrical connectors. Two air pressures are piped to the control and penetrate the chassis wall to the module pressure sensors/transducers. Housed within the control chassis are 4 multilayer ceramic modules, 16 discrete potted modules, 2 wire-wrap circuit boards, 1 relay, and 8 adjustment potentiometers.

A partition wall in the deep compartment metallically shields the power supply functions from the remainder of the control to eliminate electrical noise interference. All wires between the compartments penetrate the shield only through suitable EMI (electromagnetic interference) filters.

The digital control accepts inputs from inside and outside the control system. The outputs control signals to the control system as a function of control system strategy which is programmed into the control. Inputs and outputs are shown on Figure 31.

The simplified schematic (Figure 32) shows the input/output section, the processor section, and the miscellaneous section. The input/output section includes the 16-bit buffered data bus (BD-bus) as its data path to the central processor. Digital information is passed from the inputs onto the BD-bus through the tristate buffer to the data bus (D-bus). Digital information is also passed from the D-bus through the tristate buffer onto the BD-bus and into the output circuits. All data transmission is done under control of the central processor and on a timesharing basis.

The processor section consists of an address bus (AD-bus) and a D-bus. All data information into and out of the control will pass over the D-bus and into the processor. And all destination information will pass over the AD-bus and will determine the source or destination of data present on the D-bus.

The miscellaneous section contains a linear variable phase transducer (LVPT) excitation driver, a crystal control clock oscillator, and an alternator-driver power source with a 28-volt d.c. power source as a backup.

The digital control provides the computational capability for the selected control system. All of the control law programs, signal conditioning, data processing, and input/output capabilities needed to provide the desired engine operation and interface with the sensors and actuation components are included in the control.

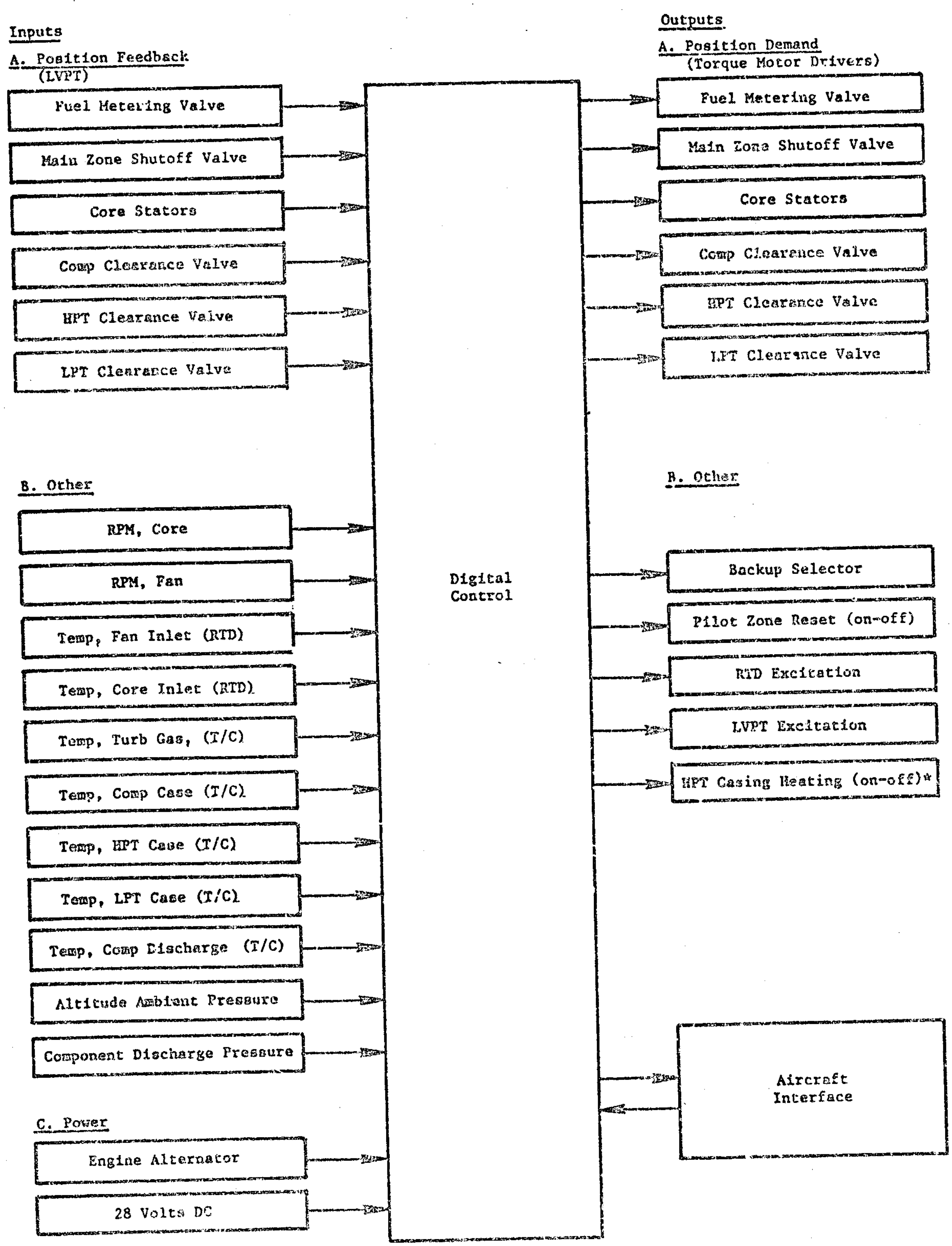


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Figure 31. Digital Control - Inputs and Outputs.

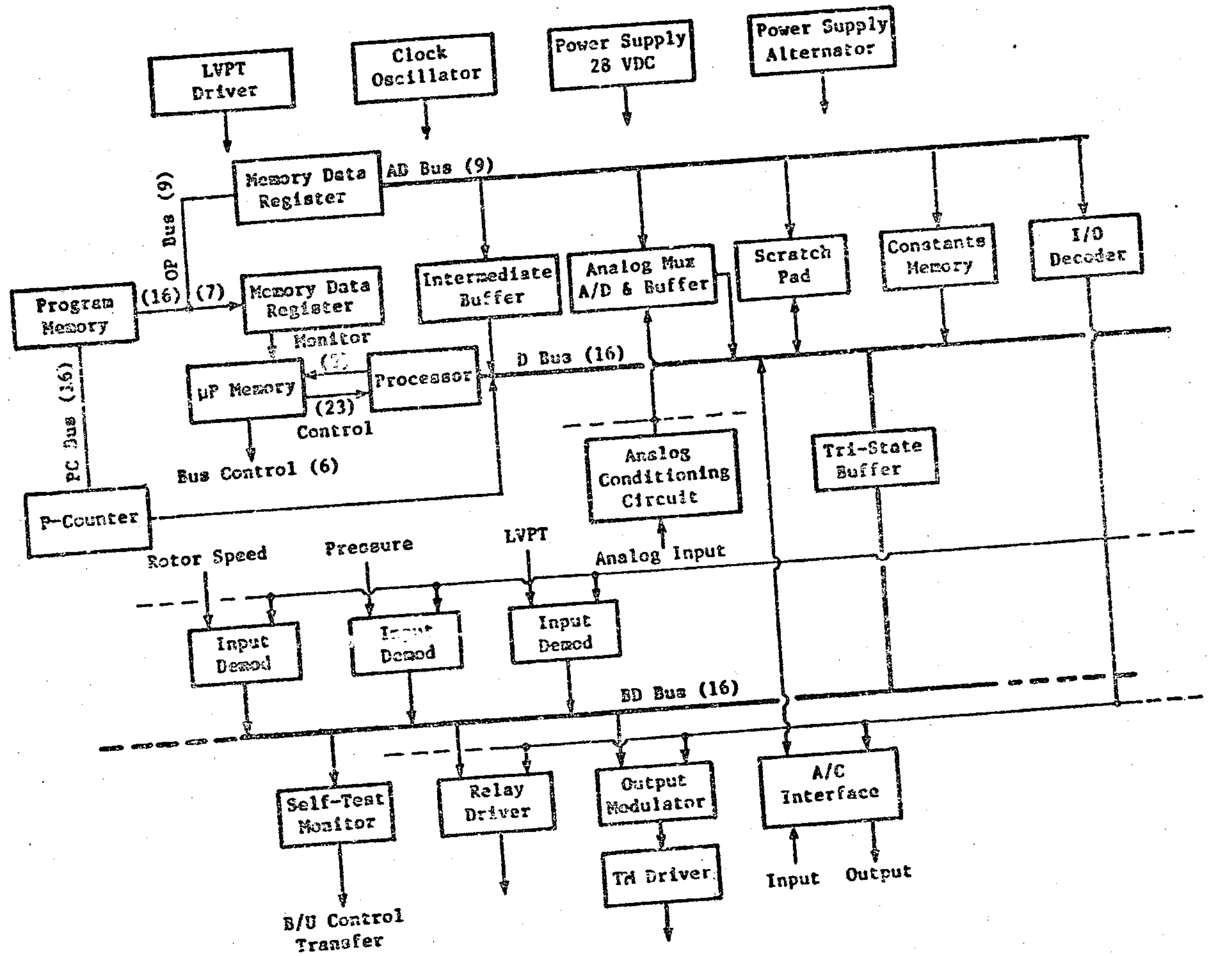


Figure 32. Digital Control Schematic.

4.5.2 MICROPROCESSOR

The central processing unit (CPU) is based on an array of four 4-bit microprocessors cascaded to handle the 16-bit word. This is a fully parallel machine operating at 3.5 MHz clock rate. Figure 33 shows a simplified block diagram of the 4-bit slice AMD 2901 microprocessor used in the control. Features of this processor are (1) special purpose, (2) fractional, (3) two's complement, 4 quadrant, (4) microprogrammed, (5) 3.5 MHz clock rate, (6) 64K word program memory addressing capability, (7) 512-word RAM size, (8) 64-instruction repertoire, (9) 16-bit word size, and (10) low-power Schottky TTL logic family.

This processor is microprogrammable which enabled its design to be tailored for this engine control application. Such tailoring makes it a special-purpose machine. This 16-bit machine computes algorithms using fractional arithmetic in two's complement notation and has 64 microinstructions which include:

- Input, output, and an address strobe instruction
- Load instructions from various sources
- Add and substract instruction of different locations
- A store instruction that places data in a specified location of read/write memory
- A four-quadrant multiply and divide instruction
- Register exchange instructions
- Magnitude with limit instruction
- Various limited instructions to prevent data overflow
- Right- and left-shift instructions

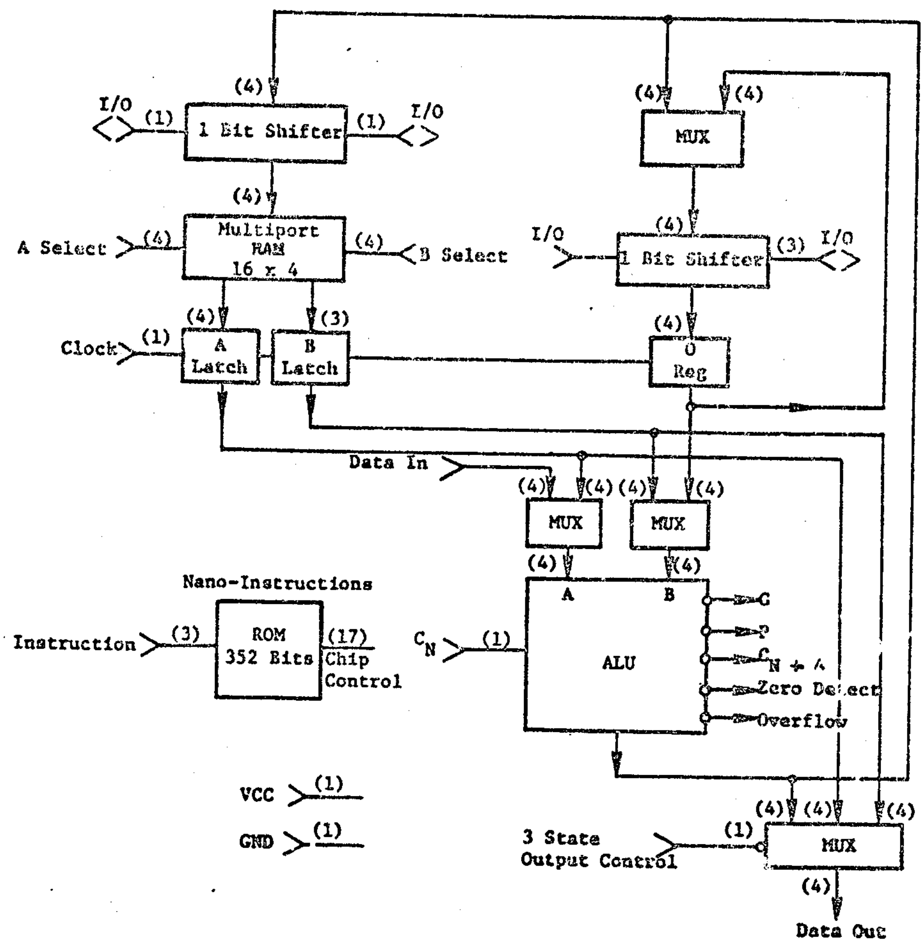


Figure 33. AMD 2901 Microprocessor Block Diagram.

- Selector instructions that select the most positive or negative data from various sources
- Logical instructions including AND, OR, EXCLUSIVE OR, NOT, and COMPLEMENT
- A number of jump instructions including jump to subroutine and return.

The instruction set functions microcycle information. Mnemonics are listed in Reference 1.

4.5.3 MEMORY

4.5.3.1 General

Requirements for the digital control memory resulted in partitioning into four memories: program memory, constants memory, scratch pad memory, and microprocessor memory.

4.5.3.2 Program Memory

The program memory uses programmable read-only memory (PROM) integrated circuits, and includes a list of instructions representing the control laws to be executed by the processor. This control architecture and strategy software is arranged in sequential order of execution. The program memory is located on a wirewrap circuit board (X33 module). The module includes 8K of memory capacity, and the E^3 program used 8K of memory.

4.5.3.3 Constants Memory

The constants memory is a 1K nonvolatile memory (PROM) that is maintained separate from the program memory. It is used to store constant values used in the control calculation. The constants memory is located in the discrete module A9 and is mounted on a wire-wrapped circuit board so that values in the constants memory can be changed without affecting the program memory.

4.5.3.4 Scratch Pad Memory

The scratch pad memory is used for temporary values during the calculation process as the program is executed; it is a 0.5K random access memory (RAM) having read/write capability. Each location is available for input and retrieval of data. The RAM is located in the digital processor MCM HB6 (A16 module).

4.5.3.5 Microprocessor Memory

The microprocessor memory is the repository for the processor instruction set. This is a read-only memory (ROM), accessed by the microprocessor during execution of the control program. The ROM is located in the digital processor module HB2 (A16 module).

5.0 SOFTWARE DEVELOPMENT

5.1 SOFTWARE DEVELOPMENT AND VERIFICATION PROCESS:

Software for the digital control was developed following a six step process as illustrated in Figure 34 and summarized below.

1. Generate the software performance and design requirements: review these two requirements to verify adequate coverage and understanding of the control system requirements.

2. Code software modules and test. The modules are defined in the above software performance and design requirements. Modules for elements such as control laws, schedules, and switching logic are coded in FORTRAN HOL for compatibility with a FORTRAN dynamic engine model (which is used in Step III to perform initial testing against the control system requirements). Modules for elements which require special machine instructions (such as self-test) are coded in assembly language; these assembly language modules are tested with a software emulator.

3. Integrate software modules and test. As shown in Figure 34, a dynamic computer simulation is used to test the integration of the modules coded in the FORTRAN HOL. Such testing is quite effective in finding software errors at an early point in the design process, and it eliminates the expense of many compiles/assemblies to machine code during the de-bug process. Figure 35 describes the dynamic computer simulation used to test the integration of the modules. This closed-loop simulation includes computer models of the HOL control code, sensors, actuation systems, and the engine transient performance. Thus, the code can be conveniently tested over a range of conditions, during both satic and transient operation.

4. Compile and assemble the total source file; test machine code with the Software Transient Simulator. This Simulator tests the final machine code file (which results from the merger of the assembly

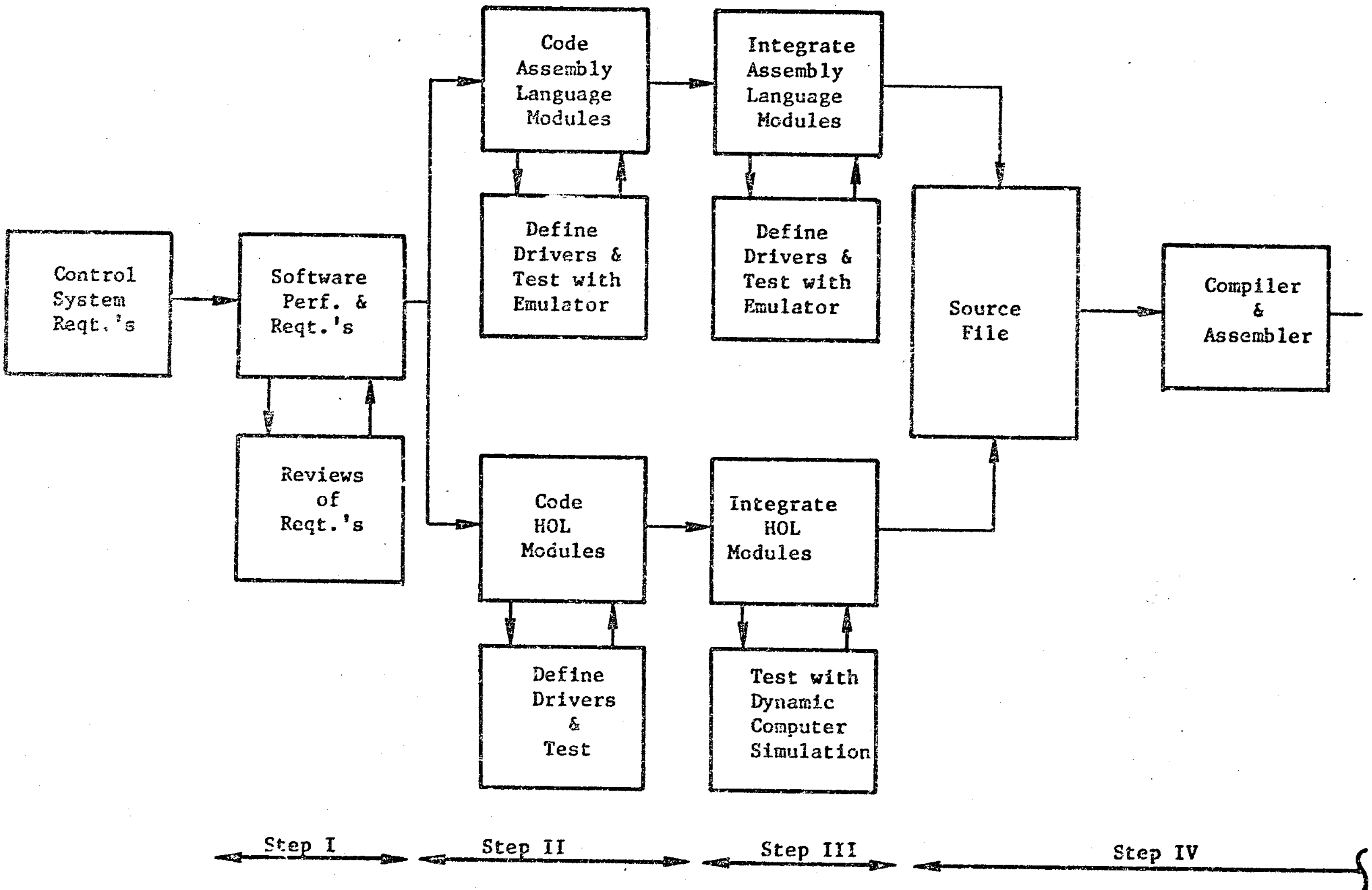


Figure 34. Software Development and Verification Process (Sheet 1 of 2)

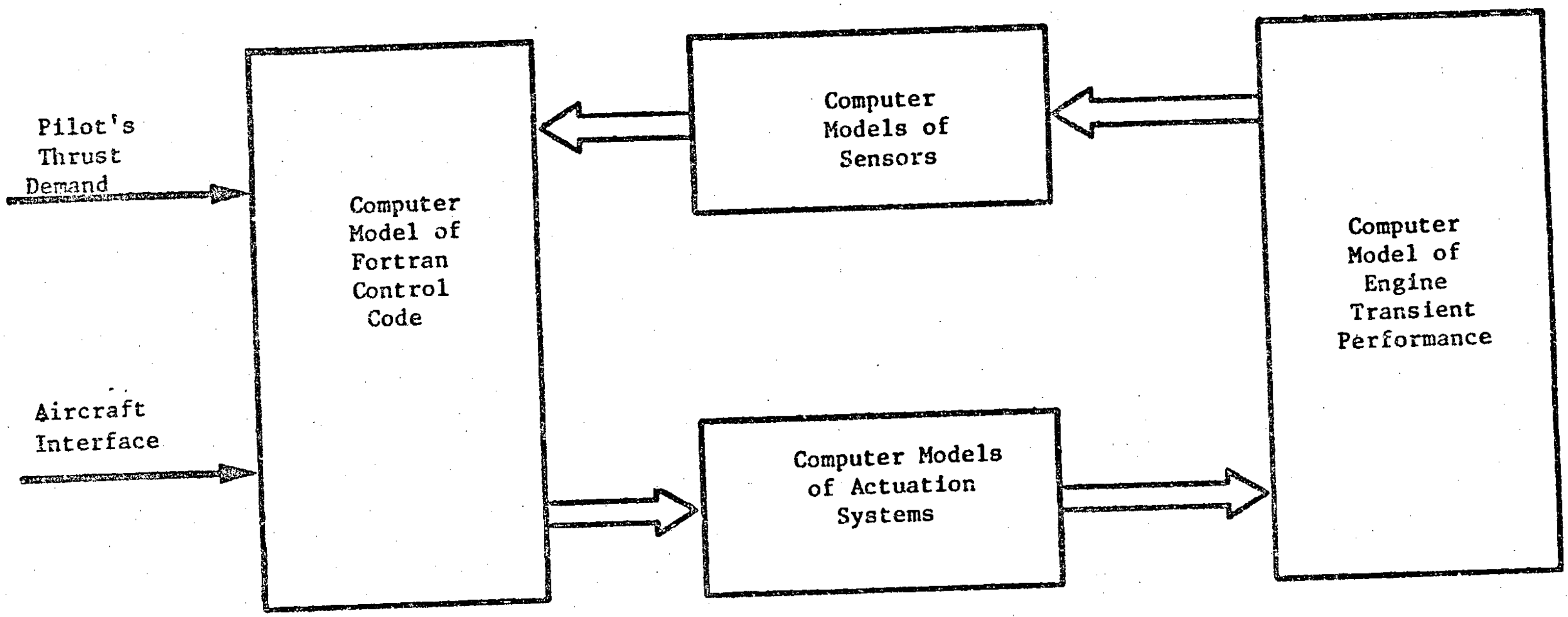


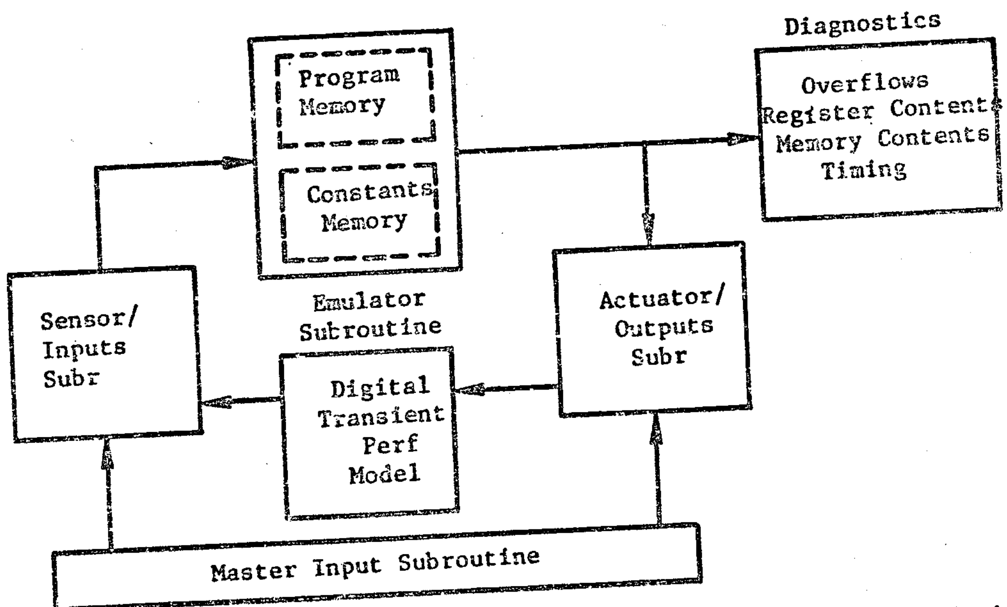
Figure 35. Dynamic Computer Simulation to Test Integration of High Order Language (HOL)

code and the HOL coded portions of the software) in the Host Computer, using a FADEC emulator to simulate the operation of the target computer. The Software Transient Simulator makes possible closed-loop testing of the machine code in a total computer environment and has proven to be quite effective in de-bugging the total code over a range of operating conditions, both statically and dynamically. As illustrated in Figure 36, the elements of the Software Transient Simulator are the emulator subroutine, the actuator/outputs subroutine, an engine digital transient performance model, the sensors/input subroutine, and the master input subroutine. The emulator subroutine simulates the functional operation of the target computer with respect to the software instructions contained in the files for the program and constants memories. Diagnostics from the emulator provide information on overflows, timing, register contents, and memory contents.

5. Load machine code into breadboard for the control and test with an electronic test bench, which includes an interface simulation and a real time engine model.

6. Using the machine code validated in step 5 above, this code is programmed into Programmable Read-only memories (PROM's) and the PROM's are inserted into the actual FADEC which is then tested with the electronic test bench.

The above described six steps for the software development and verification process were used to generate the software for the Control System. Subsequent to this development and verification process are the control systems tests, which are discussed in Section 6.



Used to Test Software Over a Matrix of Engine Operating Conditions

Figure 36. Software Transient Simulator

6.0 CONTROL SYSTEMS TEST

Two control systems tests were conducted: one prior to the core vehicle test and the second prior to the ICLS vehicle test.

The same hardware was used for both system tests (the core control system test did not include hardware required for the ICLS test vehicle).

Results of the core control systems test demonstrated the functional characteristics prior to its use on the core, which due to the similarity of the two control system tests, only the results of the ICLS control systems test results will be covered in detail.

6.1 TEST PURPOSE

This program was conducted in order to demonstrate the functional characteristics of the ICLS engine control system prior to its use on an engine.

6.2 CONCLUSIONS

- The overall functioning of the E^3 control system is satisfactory.
- The fuel control will automatically switch to the backup hydromechanical control if:

a. Backup is manually selected

b. Engine is shutdown

c. Alternator fails or digital core speed signal fails out-of-limits strategy

d. Metering valve feedback signal fails out-of-limits or feedback sensor failure strategy

e. Core stator valve feedback signal fails out-of-limits or feedback sensor failure strategy

f. Core speed as sensed by hydromechanical control exceeds overspeed trip point

To engage the primary mode all faults must be cleared and the operator must momentarily select the "primary" position on the B/U relay control (until the control data display no longer shows the backup mode in effect) and then select the "normal" position.

- The backup hydromechanical control could be used for starting, providing provisions are made to position the main zone valve.

- Sufficient flexibility has been programmed into the digital control to provide manual or automatic transition from pilot only to pilot and main zone combustion.

- Accel schedule, fuel flow calibration, core stator schedule, and PLA schedule are with acceptable limits.

- Overspeed trip to the backup mode is fully functional.

- Operation of all air valve actuators is satisfactory.

- Dynamic elements of the control system, as evidenced by the core and fan speed frequency response test and the five position loop step responses, are satisfactory.

- Protection features of the digital control are operational.

- Failure Indication and Corrective Action (FICA) can demonstrate single software failures of core speed, fan speed, compressor inlet temperature, compressor discharge temperature, LP Turbine inlet temperature, and Compressor Discharge Pressure (CDP). It should be noted that enabling FICA with nominal PS3 error tolerance will disable the function of the stall dump kit by substituting estimated (FICA) PS3 for sensed PS3.

6.3 RECOMMENDATIONS

- The control system as tested (except for the fuel pump drive spline) should be used for engine test. Note: Vissble wear was observed on the drive spline, so it was replaced prior to shipment to the engine.

- Ensure that all connectors are properly installed and secured (lockwire or RTV) prior to engine running.

- Prior to switching to primary mode determined that: Compressor, HP Turbine, LP Turbine clearance valves are closed. The main zone shutoff valve is open. The core stator valve has positioned the stator per the backup schedule. This is an indication that these valves are in their proper position and that they will function properly.

- The preferable way to transition from pilot only to pilot and main is by using the automatic mode. This mode ensures proper sequencing of the valves and is repeatable. Note it will be necessary to utilize the manual mode to optimize transition prior to using the automatic mode.

- The actual engine fuel flow, as measured by instrumentation vs. digital control calculated fuel flow calibration should be validated and adjusted as required.

- The engine operation, where FICA is to be demonstrated, be thoroughly mapped prior to activating FICA. The PS3 tolerance limit be set to the maximum prior to activating FICA, and set to nominal value only when demonstrating a PS3 failure.

- The stall dump kit should be tested with FICA in the track mode and recorded on a strip chart recorder to determine FICA tracking when the stall dump trip is made.

6.4 GENERAL INFORMATION

TPS No. SB1156

Date Test Started: December 23, 1982

Date Test Completed: January 21, 1983

Total Test Hours: 48

6.5 TEST PARTS

6.5.1 ENGINE HARDWARE

Nomenclature	Description
Digital Control	4013295-416
Adaptor Box	EC1691
Control Alternator	9728M71P04
Fuel Pump (MFP)	4013295-286P01
Fuel Control	4013295-028G01
Main Filter	4013295-034G01
Servo Filter (2)	ACV-2466-610Z
Overspeed Pressure Switch	401345-677P01
Main Zone Shutoff Valve	4013145-684G01
Pilot Zone Shutoff Valve	4013295-360G01
Core Stator LVPT	4013145-357P03
Core Stator Mech. Feedback	4013296-570P02
T12 Sensor	7059M47P01
T25 Sensor	7059M47P01
T3 Sensor	4013295-246
Compressor Clearance Control Actuator	4013295-297G01
HP Turbine Clearance Control Actuator	4013295-031G02
LP Turbine Clearance Control Actuator	4013295-031G01

6.5.2 CONTROL ROOM EQUIPMENT

Aircraft Interface Simulator (AIS)

Operator/Engineering Panel (OEP)

Data/Compluter Display (CRT)

Display Interface Unit (PIU)

Digital to Analog Connector (D/A)

Data Printer

Shaft Encoder (PLA) Baldwin 5V242

Backup Selectro Unit

Power Supply (28V) HP6267B

6.5.3 CABLES

W1	4013295-795G01
W2	-544G01
W3	-546G01
W4	-547G01
W5	-541G01
W8	-545G01
W9	4013295-543G01
W40	4013295-549G01
W51	4013262-045G01
W52	-045G02
W53	-045G03
W55	4013262-045G05

Adaptor Box Cable EC1691

6.5.4 FACILITY HARDWARE

Core Stator Actuator (2) 9607M29P06

6.6 TEST SET-UP

6.6.1

The test parts were set-up in Cell 44, Building 703. The various test parts were set-up as shown in Figure 37. The control room set-up and electrical cables were connected as shown on the E^3 ICLS engine fuel and control system drawing.

6.6.2

Separate simulations of the pilot zone and main zone fuel nozzles were provided.

6.6.3

Shop air was provided for cooling the FADEC.

6.6.4

Power to the digital control was provided from two sources: a 28 volt DC power supply and the engine alternator. The control power supply is designed to use DC power (below (40%) and transition to alternate power as speed in increased. Transition is completed at approximately 60% speed.

6.6.5

Two decade boxes were provided to simulate fan and core air inlet temperature, as required.

6.6.6

A dial-a-volt source was provided to simulate thermocouple inputs.

6.6.7

Two Systron Donner SD-20 Analog Computers were used to tie the two drives (pump and alternator), simulated pneumatic (PS3), and simulated LP Turbine Inlet Temperature (T42) together to provide transient testing capability.

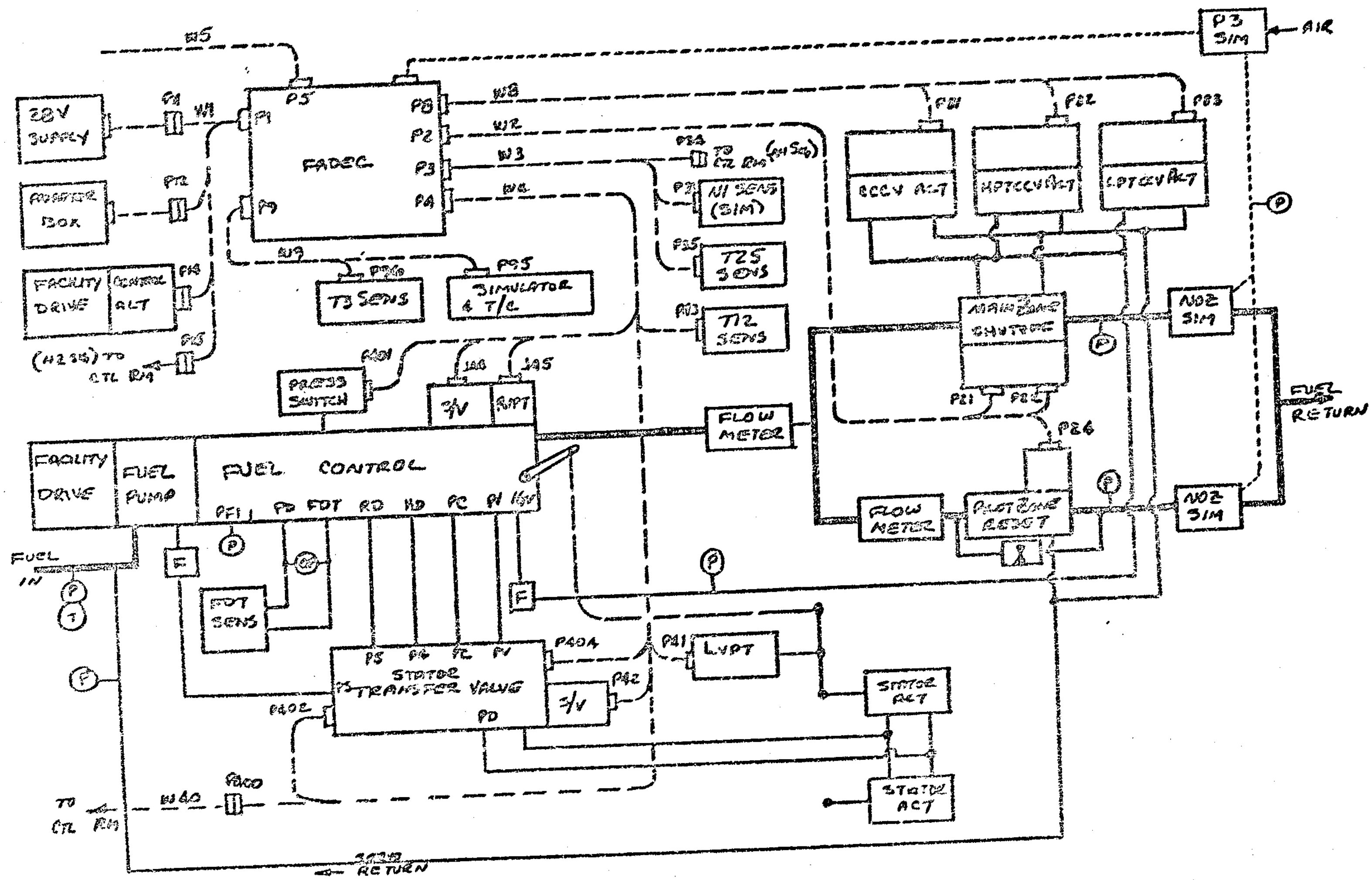


Figure 37. System Test Setup Schematic.

6.7 INSTRUMENTATION

6.7.1 TEST FACILITY

Instrumentation provided as part of the test facility and test set-up are listed below and shown in Figure 37.

Parameter	Symbol	Range	
Fuel Pump Inlet Pressure	PØ	(0-100-PSIG)	689.5 kPa
Fuel Pump Inlet Temperature	TØ	(0-100°F)	17.8 - 37.8°C
Fuel Pump Disch. Pressure	P1	(0-1500 PSIG)	10,343 KPa
Fuel Pump Disch. Temperature	T1	(0-250°F)	-17.8 - 121.1°C
Fan Disch. Temp. Sensor Δ	ΔPFDT	(0-200 PSID)	1379 KPa
Hydromech. Control Disch. Pressure	P2	(0-100 PSIG)	6895.0 KPa
Hydromech. Control Disch. Temperature	TWFM	(0-250°F)	-17.3 - 121.1°C
Hydromech. Control Disch. Flow (Turbine)	WFM	(300-12000 PPH)	136-5443 kg/hr
Hydromech. Control Disch. Flow (Ramapo)	WFMR	(300-12000 PPH)	136-5443 kg/hr
Pilot Zone Manifold Pressure	PPZ	(0-100 PSIG)	6895.0 KPa
Pilot Zone Manifold Flow	WPFZ	(0-7000-PPH)	0-3181 kg/hr
Main Zone Manifold Pressure	PMZ	(0-1000 PSIG)	6895.0 KPa
Fuel System Return Pressure	PRET	(0-100 PSIG)	689.5 KPa
Simulated CDP Pressure	PS3	(0-600 PSIG)	4137.0 KPa
Servo Return Pressure	PB	(0-100 PSIG)	489.5 KPa
Servo Supply Pressure	PS	(0-1500 PSIG)	10,343 KPa
Hydromech. Power Lever Angle	PLA	0-130 DEG	
Main Drive Speed	N2	0-8000 RPM	
Alternator Drive Speed	N2'	0-30000 RPM	

NOTE: 100% Main Drive Speed = 6317 RPM

100% Alternator Speed = 23690 RPM

100% Core Engine Speed = 12303 RPM

To eliminate different speed scaling, all speeds were converted to an equivalent engine rpm and will be referred to as N2 unless otherwise specified.

6.7.2 DIGITAL CONTROL MONITORING

Table 1 is a tabulation of the ICLS Monitor Output variables with scale factors, conversion units, and a description of each. Raw data, that is, data from the digital control displayed on page 5 of the CRT display and on the D/A readout is in terms of a bit count. In order to determine the value of a variable (in engineering units) it is necessary to convert the bit count to a scaled fraction number. The 16 bit digital control uses two's complement arithmetic with the most significant bit as a sign bit, therefore, the scaled fraction number will go from 0 to .99997 as the bit count goes from 0 to 32767 and from -1.0 to -0.00003 as the bit count goes from 32768 to 65535. The scaled fraction number positive or negative, is then multiplied by the scale factor obtained from Table 1 to get the value in engineering units.

Conversion of signals to DV voltages from bit count are as follows: the voltage goes from 4.991 volts to - .005 volts as the bit count goes from 0 to 32767 and from 9.990 to 5.071 volts as the bit count goes from 32768 to 65535.

Note: This is a linear relationship.

TABLE 1 (1 of 8)

ICLS MONITOR OUTPUT DATA

Name	Scale	Units	Description
TSTWRD	---	---	AIS test word (43690)
STWRD	---	---	Self test word (43690)
MODE	---	---	Mode word carrying per bit info

Bit	Function
0	1 - MUX data bad, 0 - mux data good
1	Spare
2	Spare
3	Spare
4	Spare
5	Spare
6	1 - enable backup, 0 - disable backup
7	1 - backup disengaged, 0 - backup eng.
8	Spare
9	Spare
10	1 - Block #1 good, 0 - f;ailed
11	1 - Block #2 good, 0 - failed
12	1 - PLA Fault, 0 - no PLA fault
13	1 - Recovery on, 0 - recovery off
14	1 - Operator Panel disconnected, 0 - connected
15	Spare

Name	Scale	Units	Description
OTOLIM			Out-of-limits word

Bit	Function
0	1 - XCCC out-of-limits, 0 - in limits
1	1 - XHPTC
2	1 - PLA
3	1 - XMZSO
4	1 - XWFM
5	1 - XLPTC
6	1 - PTØ
7	1 - PS3

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
			Bit / Function: 8 — 1 - XBC; 9 — 1 - XMH; 10 — 1 - XML; 11 — 1 - T12; 12 — 1 - T42; 13 — 1 - T3; 14 — 1 - T25; 15 — 1 - Disable action, 0 - do not disable action
MZSOL	--	--	Mode word carrying logic
			Bit / Function: 0 — Spare; 1 — Spare; 2 — Spare; 3 — Spare; 4 — XMV F/B Sensor 1 - failed 0 - good; 5 — BC F/B sensor 1 failed, 0 - good; 6 — Spare; 7 — PZR Auto DMD 1 - close, 0 - open; 8 — Clear Cont man override 1 - close 0 - normal; 9 — Spare; 10 — PZR Valve mode 1-manual, 0 - auto; 11 — TCHPT 1-out of limits, 0 - in limits; 12 — TCCMP 1 - out of limits, 0 - in limits; 13 — TCLPT 1 - out of limits, 0 - in limits; 14 — Spare; 15 — Spare
OMODE	--	--	Operator panel switch information

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
			Bit / Function
			0 WFM mode 1 - manual, 0 - auto
			1 MXSO mode 1 - manual, 0 - auto
			2 CCC mode 1 - manual, 0 - auto
			3 HPTC mode 1 - manual, 0 - auto
			4 LPTC Mode 1 - manual, 0 - auto
			5 Disable BC & WF 1 - disable, 0 - norm.
			6 BETA mode 1 - approach, 0 - normal
			7 BETA bias 1 - resets, 0 - bias out
			8 Sens fail bais, 0 - no bias
			9 Disable OTOLIM 1 - Disable, 0 - do not disable
			10 PZR man mode 1 - closed, 0 - open
			11 EOP fail update 1 - do not update. 0 - update (1/min)
			12 Alternate PS3 1-alternate, 0 - primary
			13 Idle mode 1-flt idle, 0 - gnd idle
			14 FICA 1 1 - on, 0 - off
			15 FICA 2 1 - on, 0 - off
ST12 (T12)	700	°F	Fan inlet temperature
ST25P1	725	°R	Actual core inlet temperature
ST3	1960	°R	Compressor discharge temperature
ST42 (T42)	2860	°R	HP turbine disc temperature
STCCMP (TCCMP)	1960	°R	Compressor case temperature
STCHPT (TCHPT)	1960	°R	HP turbine case temperature
STCLPT (TCLPT)	1960	°R	LP turbine case temperature
SXNL (XNL)	4375	RPM	Fan speed

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
SXNH	16120	RPM	Core speed
PTO	23	PSIA	Total inlet pressure
SPS3 (PS3)	500	PSIA	Compressor discharge pressure
XWFM	1	S.U.	Fuel metering valve position (stroke = .813 in.)
XMZSO	1	S.U.	Main zone valve position (stroke - .7 in.)
XCCC	1	S.U.	Compressor clear valve position (stroke = 1.5 in.)
XHPTC	1	S.U.	HP Turbine clear valve position (stroke = 1.5 in.)
XLPTC	1	S.U.	LP Turbine clear valve position (stroke - 1.5 in.)
ST25 (T25)	725	°K	Sensed compressor inlet temperature
XBC	1	S.U.	Core stator actuator (stroke = 3.315)
IWFM	100	MA	Fuel metering valve T/M current
IMZSO	100	MA	Main zone valve T/M current
ICCC	100	MA	Compressor clearance valve T/M current
IHPTC	100	MA	HP Turbine clearance valve T/M current
ILPTC	100	MA	LP Turbine clearance valve T/M current
PCNHR	150	%	Corrected core speed
IBC	100	MA	Core stator T/M current
PLA	150	DEG	Power lever angle
WF36A	14000	PPH	Adjusted fuel flow
WFACC	14000	PPH	Accel fuel limit
AMODE	--	--	Fuel flow control mode

Value	Function
0	Error
0.1	Accel schedule
0.15	Min stop
0.2	Decel schedule

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
			0.25 Max stop
			0.3 T42 limit
			0.4 Decel J/R
			0.5 Accel J/R
			0.6 XNH
			0.7 XNL
			0.8 PS3 limit
			0.9 T41 calc limit
RXMV	1	S.U.	Metering valve position demand (stroke = .813 in.)
RMZSO	1	S.U.	Main zone position demand (stroke - .7 in.)
RXCCC	1	S.U.	Comp clear valve position demand (stroke = 1.5 in.)
RXHPTC	1	S.U.	HP turb clear valve position demand (stroke - 1.5 in.)
RXLPTC	1	S.U.	LP turb clear valve position demand (stroke = 1.5 in.)
FMODE	–	–	Mode word for FICA status

Bit	Function
0–3	Bit count indicating no. of allowed FICA substitutions
4	Spare
5	FICA activated
6	FICA tracking
7	FICA armed
8	XWFM 1 - substitute, 0 - do not
9	T25 1 - substitute, 0 - do not
10	T3 1 - substitute, 0 - do not

TABLE 1 (6 of 8)

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
			11 PS3 1 - substitute, 0 - do not
			12 T42 1 - substitute, 0 - do not
			13 XNH 1 - substitute, 0 - do not
			14 XNL 1 - substitute, 0 - do not
			15 Spare
			NOTE: The following states can be derived from bits 5, 6, and 7
			Armed Bit 5 + 6 + 7 = 1
			Tracking Bit 5 + 6 = 1, Bit 7 = 0
			Reset Bit 5 = 1, Bit 6 = 0, Bit 7 = 0
			Off Bit 5 = 6 = 7 = 0
RXBC	1	S.U.	Core stator position demand (LVPT stroke - 2.134 in.) (Actuator stroke = 3.315 in.)
RPZR	1	--	Pilot zone valve demand
RSRTC (ET25)	100	%	Compressor inlet temp (sensed-est)/sensed
YD7 (EXMV)	100	%	Metering valve (sensed-est)/sensed
Y7 (EXNL)	100	%	Fan speed (sensed-est)/sensed
RASBV (EXNH)	100	%	Core speed (sensed-est)/sensed
RABLD (ET3)	100	%	Compressor inlet temp (sensed - est)/sensed
XSBV (ET42)	100	%	HP Turbine disch temp (sensed - est)/sensed
TTSR1 (EPS3)	100	%	Compressor disch press (sensed - est)/sensed

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
XDTMP (TFADEC)	250	°F	OEU internal temperature
ST41 (T41)	3500	°R	Calc HP Turbine inlet temperature
PCNLR	150	%	Corrected fan speed
ERRORM	--	--	Mode word sensors out-of-tolerance

Bit	Function
0	Spare
1	Spare
2	Spare
3	Spare
4	Spare
5	Spare
6	Spare
7	Spare
8	XWFM 1 - out-of-tolerance, 0 - in tol
9	T25 1 - out-of-tolerance, 0 - in tol
10	T3 1 - out-of-tolerance, 0 - in tol
11	PS3 1 - out-of-tolerance, 0 - in tol
12	T42 1 - out-of-tolerance, 0 - in tol
13	XNH 1 - out-of-tolerance, 0 - in tol
14	XNL 1 - out-of-tolerance, 0 - in tol
15	Spare

Name	Scale	Units	Description
DXNHCL (DXNH)	5000	RPM/SEC	Core speed derivative
RXNL	4375	RPM	Fan speed demand
RXNH	16120	RPM	Core speed demand
TR42	2860	°R	HP Turbine disch temperature demand
TSHIS (RTCHPT)	1960	°R	HP Turbine case temperature demand

ICLS MONITOR OUTPUT DATA (Cont'd)

Name	Scale	Units	Description
TSL2S (ETCLPT)	1960	°R	LP Turbine case temperature demand
TSC9S (ETCCMP)	1960	°R	Compressor case temperature demand
TE27	1960	°R	Calculated compressor stage 5 temperature

6.7.2 DIGITAL CONTROL MONITORING (Continued)

Table 2 tabulates the conversion factors.

TABLE 2

DIGITAL CONTROL MONITORING - CONVERSION FACTORS

Bits	Volts	Scaled Fraction Number
0	4.991	0
32767	-.005	.99997
32768	9.990	-1.0
65535	5.071	-.00003

Example:

Core speed (XNH) reads 14000 bits, determine the scaled fraction number, DC voltage and speed in RPM.

$$\frac{14000}{32767} = \frac{SFN}{.9997}, \quad SFN = .42725$$

$$\frac{14000}{} = \frac{(4.991 - DCV)}{4.991}, \quad DCV = 2.8564 \text{ volts}$$

Look-up scale factor for core speed in Table 1 = 16120

Core speed = .42725*16120 = 6887.2 RPM.

The monitoring data is available from the D/A connector as voltage readings or digital count readings on the connector front panel. Duplicate sets of remote outputs are provided, each including the first fifty channels of monitoring data, plus fifteen selectable channels that can be connected to any of the monitoring signals.

The control systems CRT also processes many of the monitoring signals and displays them on the screen in engineering units.

6.7.3 TRANSIENT INSTRUMENTATION

All transient data was taken in Cell 61 by Data Systems Operation (DSO) and all X-Y plotting was done in Cell 44.

6.7.4 OPERATOR/ENGINEERING PANEL SWITCHES AND POTENTIOMETERS

Table 3 is a list of the adjustment potentiometers (10 turn) on the operator/engineering panel showing the base setting (i.e., setting at 5 turns) and adjustment ranges.

Table 4 is a list of the switches on the operator/engineering panel.

The potentiometer and switch settings are displayed on the system CRT in digital counts and engineering units.

6.8 CONTROL SOFTWARE

The control software was modified once during the system test. Data taken is identified by the software version used for that test. The two versions are listed below.

- ICLS 1 - Control software as originally delivered to cell 44 for system test.
- ICLS 2 - Same as ICLS 1 except:
  a. Added feature to stay in primary control in event that stall dump kit is tripped.
  b. Modified main zone shutoff logic to provide proper staging sequencing after closing on a deceleration. Note: The main zone will be closed during a decel only if it is required to keep the engine from blowing out during a decel.
  c. Lowered position loop gain of LP Turbine clearance by a factor of 2.

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ENGINEERING PANEL ADJUSTMENTS

NAME	SCALE	UNITS	DESCRIPTION	BASE	MIN	MAX
Q1	.83	IN	MAN WFM DMD	.06350	-.06350	+.28309
Q2	1.0	S.U.	MAN MZSO DMD	.5	-.45	+.45
Q3	1.0	S.U.	MAN CCC DMD	.5	-.45	+.45
Q4	1.0	S.U.	MAN HPTC DMD	.5	-.45	+.45
Q5	1.0	S.U.	MAN LPTC DMD	.5	-.45	+.45
Q6	2.0	S.U.	T25 FAILURE	1.0	-.5	+.5
Q7	1.0	—	BC APP SCH MULT	1.0	-1.0	+1.0
Q8	60	DEG	BC BAS SCH BIAS	0	-15	+15
Q9	2.0	SU	XNH FIALURE	1.0	-.5	+.5
Q10	150	%	NJK SCH BIAS	0	-10.3	+10.3
Q11	4375	RPM	N1 MAX LIMIT	3500	-625	+875
Q12	16120	RPM	N2 MAX LIMIT	13260	-2160	+2840
Q13	16120	RPM	GROUND IDLE	8243	-1250	+1250
Q14	16120	RPM	FLIGHT IDLE	9227	-1250	+1250
Q15	2850	DEG. R	T42 SCH BIAS	0	-720	+720
Q16	500	PSIA	PS3 MAX LIMIT	425	-75	+75
Q17	500	PSIA	PS3 ADDER	0	-25	+25
Q18	1.0	—	PS3 MULT	1.0	-.1	+.1
Q19	3500	DEG. R	T41C MAX LIMIT	3122	-1000	+378
Q20	1.2	—	T41C WFOP3 MULT	1.0	-.2	+.2
Q21	1.2	—	T41C T3 MULT	1.0	-.2	+.2
Q22	3500	DEG. R	T41C ADDER	0	-700	+700
Q23	.83	IN	MIN WFM LIMIT	.06350	-.06350	+.10841
Q24	100	MA	XBC TM BIAS	0	-10	+10
Q25	1.0	SU	LPTC MIN REF LIM	.05	-.02	+.1
Q26	1.0	IN/SEC.	ACCEL RATE LIMIT	.02293	-.01354	+.01633
Q27	1.0	IN/SEC	DECEL RATE LIMIT	.02147	-.01208	+.01529
Q28	1960	DEG. R	T3 ADDER	0	-250	+250
Q29	23	PSIA	ALT PRESS	14.696	-14.696	+8.304
Q30	1.0	—	MACH NO	0	-0	+1.0
Q31	50	UNITS	ACC SCH BIAS	0	-5	+5
Q32	1.0	—	ACC SCH MULT	1.0	-.2	+.2
Q33	50	UNITS	DEC SCH BIAS	0	-5	+5
Q34	1.0	—	DEC SCH MULT	1.0	-.2	+.2
Q35	18500	RPM	MZ HYST. BAND	500	-500	+500
Q36	327.68	SEC	MZ FILL TIME BIAS	50.0	-50.0	+50.0
Q37	1.0	S.U.	MZSO FILL AREA	.30715	-.25715	+.64285
Q38	1.0	S.U.	MZSO MAX AREA	.95	-.9	+0
Q39	2.0	S.U.	T3 FAILURE	1.0	-.5	+.5
Q40	10.0	S.U.	NO. OF FICA SUB.	5.0	-5.0	+5.0
Q41	2.0	S.U.	PS3 FAILURE	1.0	-.5	+.5
Q42	2.0	S.U.	T42 FAILURE	1.0	-.5	+.5
Q43	1	S.U.	XMV ERR CNTR RES	.02	-.01	+.08
Q44	20.0	S.U.	DXMV/DT CNTR RES	5	0	+10.0
Q45	1	S.U.	XMV ERR JUMP LIM	.06	-.01	+.20
Q46	5000	RPM/SEC	MZ OFF DEC RATE	-5000	0	+5000
Q47	100	MA	XMV TM BIAS	0	-10	+10
Q48	3.0	—	XMV LOOP GAIN	1.0	-.66667	+2.0
Q49	2	—	X3 MULT ON WF36	0	-.2	+.2
Q50	2	—	X2 MULT ON WF36	0	-.2	+.2
Q51	2	—	X1 MULT ON WF36	1.0	-.2	+.2
Q52	2	—	ADDER ON WF36	0	-.2	+.2
Q53	1960	DEG. R	CCC TSCH BIAS	0	-700	+700
Q54	1960	DEG. R	TE27C ADDER	0	-700	+700
Q55	1960	DEG. R	HPTC TSCH BIAS	0	-700	+700
Q56	1960	DEG. R	LPTC TSCH BIAS	0	-700	+700
Q57	18500	RPM	[illegible] INPUT BIAS	0	-1000	+1000
Q58	1.0	—	BC TR RES MULT	1.0	-1.0	+1.0
Q59	2.0	SU	N[illegible] GAIN ADJUST	1.0	-0.9	+1.0
Q60	1.0	—	BC RAIN RES MLT	1.0	-1.0	+1.0
Q61	1.0	—	BC SPD RES MULT	1.0	-1.0	+1.0
Q62	60	DEG	BC MAX LIMIT	44.7396	-15	+15
Q63	60	DEG	BC MIN LIMIT	2.3360	-15	+15
Q64	1	—	CLEAR CONT MAN RE	0	-.5	+.5
Q65	1	—	PZRV RESET MODE	0	-.5	+.5
Q66	5000.0	RPM/SEC	PZRV DECEL RATE	1000	-1000	+1000
Q67	2.0	S.U.	[illegible]NL FAILURE	1.0	-.5	+.5
Q68	100	PCT	XNFM SUBST. TOL.	10	-90	+100
Q69	100	PCT	SXNL SUBST. TOL.	10	-90	+100
Q70	100	PCT	SXNH SUBST. TOL.	10	-90	+100
Q71	100	PCT	ST25 SUBST. TOL.	10	-90	+100
Q72	100	PCT	ST3 SUBST. TOL.	10	-90	+100
Q73	100	PCT	ST42 SUBST. TOL.	10	-90	+100
Q74	100	PCT	SPS3 SUBST. TOL.	10	-90	+100
Q75	2.0	—	NF TM BIAS INTEG.	1.0	-1.0	+1.0
Q76	2.0	—	BC TM BIAS INTEG.	1.0	-1.0	+1.0
Q77	1.0	SU	BC ERROR CNTR RES	.02	-.01	+.08
Q78	20.0	SU	BC/DT CNTR RES	5	0	+10.
Q79	2.0	SU	NL GAIN ADJUST	1.0	-0.9	+1.0
Q80	327.68	SEC	PZ TIMER RESET	2.0	-2.0	+8.0

****

Table 3. Baseline Monitor Data

ENGINEERING PANEL SWITCHES

SWITCH NO	FUNCTION	ON	OFF
1	WFM MODE	MANUAL	AUTO
2	MZSO MODE	MANUAL	AUTO
3	COMP CLEAR MODE	MANUAL	AUTO
4	HP TURB CLEAR MODE	MANUAL	AUTO
5	LP TURB CLEAR MODE	MANUAL	AUTO
6	DISABLE BC&WF	DISABLED	NORMAL
7	BC CONT MODE	APPROACH	NORMAL
8	BC BIAS	RESETS	BIAS OUT
9	SENSOR FAILURE BIAS	BIAS	NO BIAS
10	DISABLE OTOLIM	DISABLE	DO NOT DISABLE
11	MAN PZR VALVE	CLOSED	OPEN
12	EOP FAIL UPDATE	NO UPDATE	UPDATE
13	BACKUP PS3	USE	DO NOT USE
14	IDLE MODE	FLT IDLE	GND IDLE
15	FICA 1	ON	OFF
16	FICA 2	ON	OFF

Table 4. Simulated Start- Manual WF Mode.

ICLS 2 is the software used for ICLS engine test.

6.9 DISCUSSION OF TEST PARAGRAPHS

This test was conducted according to a formal, Control System Test & Instrumentation Plan. (Reference 2). Format of the discussion will use the paragraph numbering system of this test plan.

III.A. Pre-Start Baseline

A full set of digital control monitoring data readings was taken to provide a pre-start baseline for the control systems test (Reference Figure 38, Baseline Monitor Data).

III.B. Start Range Checkout - Manual WF Mode

A simulated start was made, twenty second speed ramp to 30 percent speed, to demonstrate manual starting capabilities. The control comes into regulation at approximately 10% speed. This test shows that the control is well within regulation prior to opening the stopcock (15% or higher).

The manual fuel adjustment was tested and functioned properly.

The manual full flow mode will be used for the first start and for starting investigation studies.

III.D. Simulated Primary Mode Start/Normal Shutdown

A simulated 30 second start was accomplished and the control came into regulation at 10% speed and the stopcock was opened at 25% speed.

A second simulated start was the same except that the stopcock was opened at 30% speed and after idle speed has been achieved a stopcock and deceleration is simulated (normal shutdown).

The control properly scheduled fuel flow in the start region was well within regulation prior to opening the stopcock.

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PAGE 1 EEE MONITOR DATA

PLA	44.4	XNH	2031	PCNHR	16.3	T3	81	WF36A	122
[illegible]2	99.4	XNL	1000	PCNLR	27.2	T41	248	MFACC	273
T25	38.9	RXNH	8470	DXNH	0	T42	401	PHIACC	19.3
PT0	14.77	RXNL	1483	AMODE MIN		PS3	14.3	PHIENG	8.7
TFAD	74.4	RTCMP	999	TCCMP	76	RT42	2000	WFDEC	109
QIDLE	8243	RTHPT	721	TCHPT	55	RT41	2442		
TE27	59	RTLPT	683	TCLPT	71	RPS3	423.0		

FMODE OFF		EXNV	EXNH	EXNL	ET25	ET3	ET42	EPS3
SUB	2	2.4	.0	.0	.0	.0	.0	.0
DISABLED SEN MUL			1.000	1.000	1.000	1.001	1.001	1.000

MODE		ACTUAL	SELDMD	MANUAL	TM CURRENT	STROKE	SELDMD
MAN	FUEL	122	2994	2994 PPH	25.0 MA	.014	.347 IN
MAN	MAIN	.116	.116	.116 SQIN	39.8 MA	.696	.700 IN
MAN	COMP	2.642	1.000	1.020 SQIN	- 30.0 MA	1.386	.006 IN
MAN	HPTRB	90.00	23.28	23.26 DEG	- 30.0 MA	1.492	.234 IN
MAN	LPTRB	88.96	14.32	12.00 DEG	- 30.0 MA	1.462	.116 IN
NORM	BETA	23.90	44.72	DEG	75.0 MA	1.820	3.302 IN
AUTO	PILOT		OPEN	OPEN	- 93.0 MA		OPEN

OTOLIM DISABLED XBC XNFM RCFD XMVFB

SYS FAULT

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST IPS SS1156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 1 of 7)

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PAGE 2 EEE COMMAND DATA

PLA	44.4	XNH	2031	PCNHR	16.8	T3	81	WF36A	122
2	39.4	XNL	1020	PCNLR	27.2	T41	248	WFACC	273
T25	58.9	RXNH	8870	DXNH	0	T42	401	PHIACC	19.5
PT0	14.77	RXNL	1683	AMODE MIN		PS3	14.3	PHIENG	8.7

001 MAN WFM DMD	32760	2994 PPH	017 PS3 ADDER	16384	.00 PSIA
002 MAN MZ80 DMD	32760	.116 SQIN	018 PS3 MULT	16384	1.000
003 MAN CCC DMD	17624	1.030 SQIN	019 T41C MAX LMT	16384	2662 DEGF
004 MAN HPTC DMD	3568	23.26 DEG	020 T41 WFGP3 MU	16384	1.000
005 MAN LPTC DMD	1800	12.00 DEG	021 T41C T3 MULT	17208	1.010
006 T25 FAILURE	16408	1.000	022 T41C ADDER	13920	-105.3 DEGF
007 BC APP MULT	0	.000	023 MIN WF LMT	16384	.064 IN
008 BC SCH BIAS	16424	.03 DEG	024 XBC TM BIAS	16392	.00 MA
009 XNH FAILURE	16384	1.000	025 MIN RXLPTC	20224	.120 SU
010 N1K SCH BIAS	16384	.0 RPM	026 ACC J/R LMT	16472	.023 IN/SEC
011 N1 MAX LMT	16384	3900 RPM	027 DEC J/R LMT	16400	.021 IN/SEC
012 N2 MAX LMT	16392	13261 RPM	028 T3 ADDER	16384	.0 DEGF
013 GROUND IDLE	16384	8243 RPM	029 ALT PRESS	16384	14.70 PSIA
014 FLIGHT IDLE	18808	9412 RPM	030 MACH NO	16384	.000 UNITS
015 T42 SCH BIAS	16384	.0 DEGF	031 ACC SCH BIAS	16384	.000
016 PS3 MAX LMT	16384	423.0 PSIA	032 ACC SCH MULT	16416	1.000 UNITS

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST ....TPS 591156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 2 of 7)

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PAGE 3 DEC COMMAND DATA

PLA	64.6	XNH	2031	PCNHR	16.3	T3	81	WF36A	122
..2	59.4	XNL	1060	PCNLR	27.2	T41	848	WFACC	273
T25	88.9	RXNH	8470	BXNH	0	T42	601	PHIACC	19.5
PT0	14.77	RXNL	1683	AMODE MIN		PS3	14.3	PHIENG	8.7

033 DEC SCH BIAS	16320	- .020	UNITS	049 X3 MULT WF36	16384	.000	
034 DEC SCH MULT	16384	1.000		050 X2 MULT WF36	16424	.000	
035 NZ HYST BAND	16344	499	RPM	051 X1 MULT WF36	16384	1.000	
036 NZ FILL TIME	1648	9.0	SEC	052 ADDER WF36	16384	.000	
037 NZSO FILL ST	14744	.150	IN	053 CCC TSCH BIA	18392	85.3	DEGF
038 NZSO MAX ST	16896	.700	IN	054 TE27C ADDER	16384	.0	DEGF
039 T3 FAILURE	16424	1.001		055 HPTC TSCH BI	19656	139.8	DEGF
040 FICA SUB LMT	5376	2		056 LPTC TSCH BI	23048	284.7	DEGF
041 PS3 FAILURE	16384	1.000		057 BC INPUT BIA	16384	0	RPM
042 T42 FAILURE	16416	1.001		058 BC TR RES MU	0	.000	
043 XMV CNTR RES	16384	.0200	SU	059 NH GAIN ADJ	16360	.998	
044 DX/DT CTR RS	16384	5.00		060 BC GAIN MULT	0	.000	
045 XMV ERR LMT	32760	.1999	SU	061 BC SPEED MUL	0	.000	
046 NZ DEC RATE	14036	- 5000	RPM/S	062 BC MAX LIMIT	16464	44.81	
047 XMV T/M BIAS	16352	- .02	MA	063 BC MIN LIMIT	21784	4.94	DEG
048 XMV LOOP GAI	16384	1.000		064 RESET RAN CL	22960	7.01	TURNS

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST TPS 881156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 3 of 7)

PAGE 4 BEN COMMAND DATA

PLA	44.4	XNH	2001	PCNHR	16.5	T3	81	WF36A	122
2	59.4	XNL	1000	PCNLR	27.2	T41	248	WFACC	273
T25	58.9	RXNH	2470	DXNH	0	T42	401	PHIACC	19.5
FTO	14.77	RXNL	1633	AMBDC MIN		PS3	14.3	PHIENG	8.7

065 PZRV MODE 22564 7.28 TURNS

066 PZRV DEC RAT 16384 1000 RPM/S

067 XNL FAILURE 16384 1.000

068 XWFM SUB TOL 32680 100.0 %

069 XNL SUB TOL 16384 10.0 %

070 XNH SUB TOL 16392 10.0 %

071 T25 SUB TOL 16392 10.0 %

072 T3 SUB TOL 16384 10.0 %

073 T42 SUB TOL 16384 10.0 %

074 PS3 SUB TOL 17216 15.1 %

075 WF TM BI INT 16384 1.000

076 BC TM BI INT 16336 .997

077 BC ERR CNTR 16384 .0200 SU

078 BC/DT CNTR 16384 5.00 SU

079 NL GAIN ADJ 16384 1.000

080 PZ TIMER RES 16384 2.00 SEC

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST TPS 881156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 4 of 7)

PAGE 5 EEE MONITOR DATA

PLA	44.4	XNN	2001	PCNHR	14.5	T3	81	WF36A	122
P2	97.4	XNL	1000	PCNLR	27.2	T41	248	WFACC	273
T25	58.9	RXNH	8470	DXNH	0	T42	401	PHIACC	19.9
PTO	14.77	RXNL	1603	ANODE MXM		PS3	14.3	PHIENR	8.7

00 TSTWRD	43690	10 PS3	943	20 WF36A	226	2F ET3	0
01 STWRD	43690	11 XWFM	2208	21 WFACC	641	30 ET42	0
02 MODE	2200	12 XMZSD	30963	22 ANODE	4915	31 EPS3	0
03 OTCLIM	32768	13 XCCC	28891	23 RXMV	14233	32 TFADEC	14504
04 MZSDL	48	14 XHPTC	30988	24 RMZSD	31121	33 T41	6635
05 OMODE	575	15 XLPTC	20330	25 RXCCC	17499	34 PCNLR	5937
06 T12	24313	16 T25	23494	26 RXHPTC	6649	35 ERRORM	0
07 ST25P1	23495	17 XBC	17838	27 RXLPTC	3942	36 DXNH	0
08 T3	9033	18 IWFM	8192	28 FMODE	2	37 RXNL	12605
09 T42	9867	19 IMZSD	13047	29 RXBC	31019	38 RXNH	17217
0A TCCMP	8966	1A ICCC	55706	2A RPZR	34406	39 RT42	23186
0B TCHPT	8615	1B IHPTC	55706	2B ET25	0	3A RTCHPT	19741
0C TCLPT	8391	1C ILPTC	55706	2C EXMV	807	3B RTCLPT	19151
0D XNL	7640	1D PCNHR	3606	2D EXNL	0	3C RTCCMP	17716
0E XNH	4130	1E IBC	24376	2E EXNH	0	3D TE27	8676
0F PTO	21044	1F PLA	9699				

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST TPS 881156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 5 of 7)

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PAGE 6 COMMAND DATA

PLA	44.4	XNH	2031	PCNHR	16.9	T3	81	WF36A	132
1	39.4	XNL	1020	PCNLR	27.2	T41	248	WFACC	273
T25	58.9	RXNH	8470	DXNH	0	T42	401	PHIACC	19.3
PT0	14.27	RXNL	1403	AMODE MIN		PS3	-14.3	PHIENG	8.7

TSTWRD	43690	011	16384	027	16400	043	16384	059	16340	075	16384
CKSUM	21844	012	16392	028	16384	044	16384	060	0	076	16336
MODE	3408	013	16384	029	16384	045	32760	061	0	077	16384
PLA	12164	014	16808	030	16384	046	14056	062	16464	078	16384
OPTEST	21845	015	16384	031	16384	047	16352	063	21784	079	16384
ROMODE	573	016	16384	032	16416	048	16384	064	22760	080	16384
001	32760	017	16384	033	16320	049	16384	065	23864		
002	32760	018	16384	034	16384	050	16424	066	16384		
003	17624	019	16384	035	16344	051	16384	067	16384		
004	5568	020	16384	036	1648	052	16384	068	32680		
[illegible]	1800	021	17208	037	14744	053	16392	069	16384		
006	16408	022	13920	038	16896	054	16384	070	16392		
007	0	023	16384	039	16424	055	19656	071	16392		
008	16424	024	16392	040	5376	056	23048	072	16384		
009	16384	025	20224	041	16384	057	16384	073	16384		
010	16384	026	16472	042	16416	058	0	074	17216		

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST TPS 581156
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 6 of 7)

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PAGE 7 EEE POT SETTINGS

PLA	44.4	XNH	2031	PCNHR	16.3	T3	81	WF36A	122
..2	89.4	XNL	1020	PCNLR	27.2	T41	245	WFACC	273
T25	80.9	RXNH	8470	DXNH	0	T42	401	PHIACC	19.5
PT0	14.77	RXNL	1653	AMODE MIN		PS3	14.3	PHIEMS	8.7

001	10.00	017	5.00	033	4.98	049	5.00	065	7.28
002	10.00	018	5.00	034	5.00	050	5.01	066	5.00
003	5.38	019	5.00	035	4.99	051	5.00	067	5.00
004	1.70	020	5.00	036	.50	052	5.00	068	9.97
005	.54	021	5.25	037	4.50	053	5.61	069	5.00
006	5.00	022	4.25	038	5.15	054	5.00	070	5.00
007	.00	023	5.00	039	5.01	055	6.00	071	5.00
008	5.01	024	5.00	040	1.64	056	7.03	072	5.00
009	5.00	025	6.17	041	5.00	057	5.00	073	5.00
010	5.00	026	5.02	042	5.01	058	.00	074	5.25
011	5.00	027	5.00	043	5.00	059	4.99	075	5.00
012	5.00	028	5.00	044	5.00	060	.00	076	4.98
013	5.00	029	5.00	045	10.00	061	.00	077	5.00
014	5.74	030	5.00	046	4.29	062	5.02	078	5.00
015	5.00	031	5.00	047	4.99	063	6.65	079	5.00
016	5.00	032	5.01	048	5.00	064	7.01	080	5.00

NOTES
E3 FADEC ICLS CONTROL SYSTEM TEST TPS 881136
PRE-START BASELINE

Figure 38. Baseline Monitor Data (Sheet 7 of 7)

III.E. Simulated Backup Mode Start/Normal Shutdown

A simulated start and shutdown were made in the backup mode. The control came into regulation at approximately 10% speed and the stopcock was opened at 30% speed. The control was stopcocked prior to decelerating. PS3 and speed were ramped the same as in III.D. above.

If it becomes necessary to start the engine in the backup mode, provisions must be made to properly position the main zone shutoff and pilot zone reset in the start region and to provide transition capability.

III.F. Main Zone Shutoff-Manual Mode

The main zone shutoff was evaluated with a 200 lohm orifice in the pilot zone bypass leg. Two flow conditions each with the pilot zone valve opened and closed were run to show the percent of flow thru the main leg. Figure 39 shows approximately 50% flow through the main leg when the pilot zone is open and between 62% and 70% when the pilot zone is closed.

Figure 40 is a plot of fuel pump discharge pressure versus total metered flow for two conditions: one with the main zone valve open and the pilot zone valve closed, the other the main zone valve closed and the pilot zone valve open. These data were run to confirm that system would not go on pump relief in the event alternate strategy is used to prevent blowouts on decels. Note: Plan is to decelerate the engine with both the pilot zone and main zone valve open, if a blowout occurs the pilot zone will be closed during the decel, then reopen when decel is complete. If a blowout occurs for this condition the main zone will be closed during the decel it will then reopen and re-light when the decel is over.

III.G. Main Zone Shutoff-Auto Mode

Figure 41 is a slow accel showing the action of the main zone and pilot zone valves in the automatic mode. To successfully transition from single to double annular burning it is necessary to:

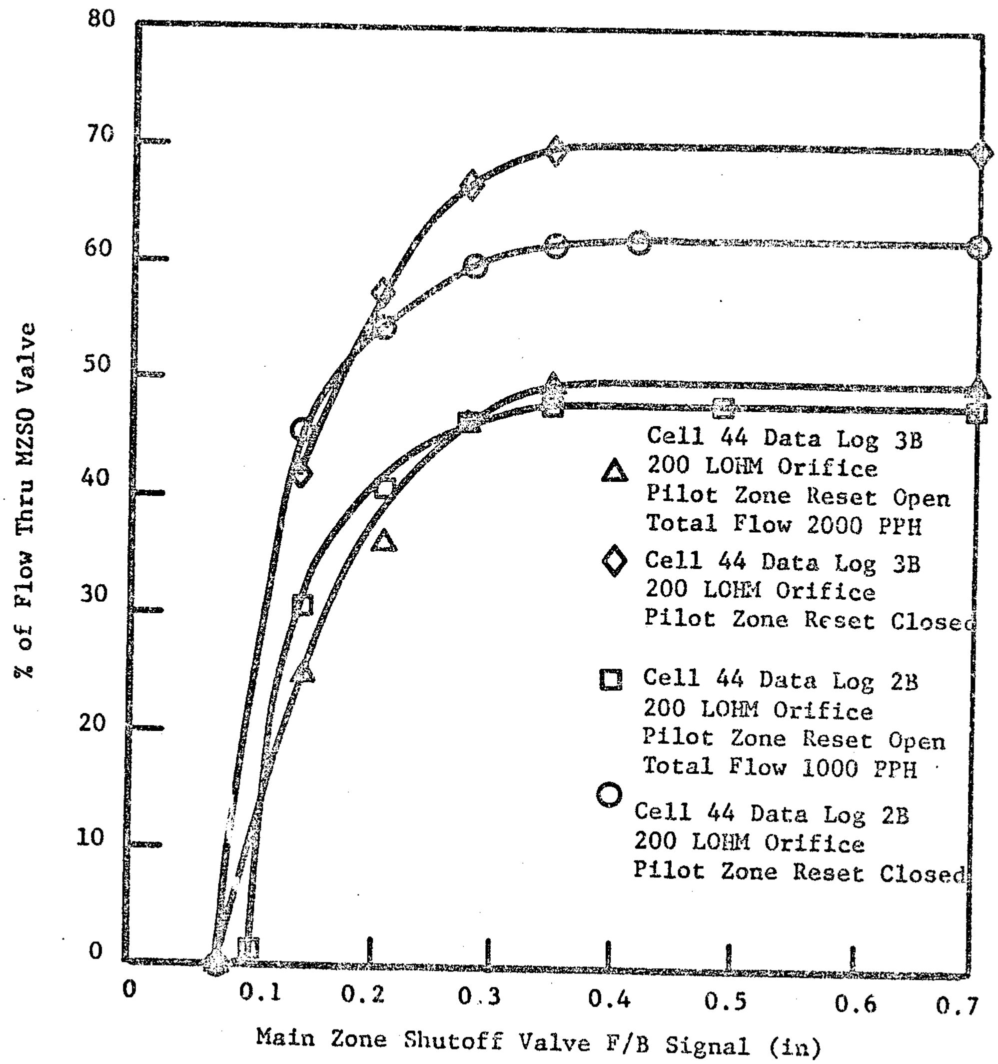


Figure 39. Fuel Flow Split Characteristics.

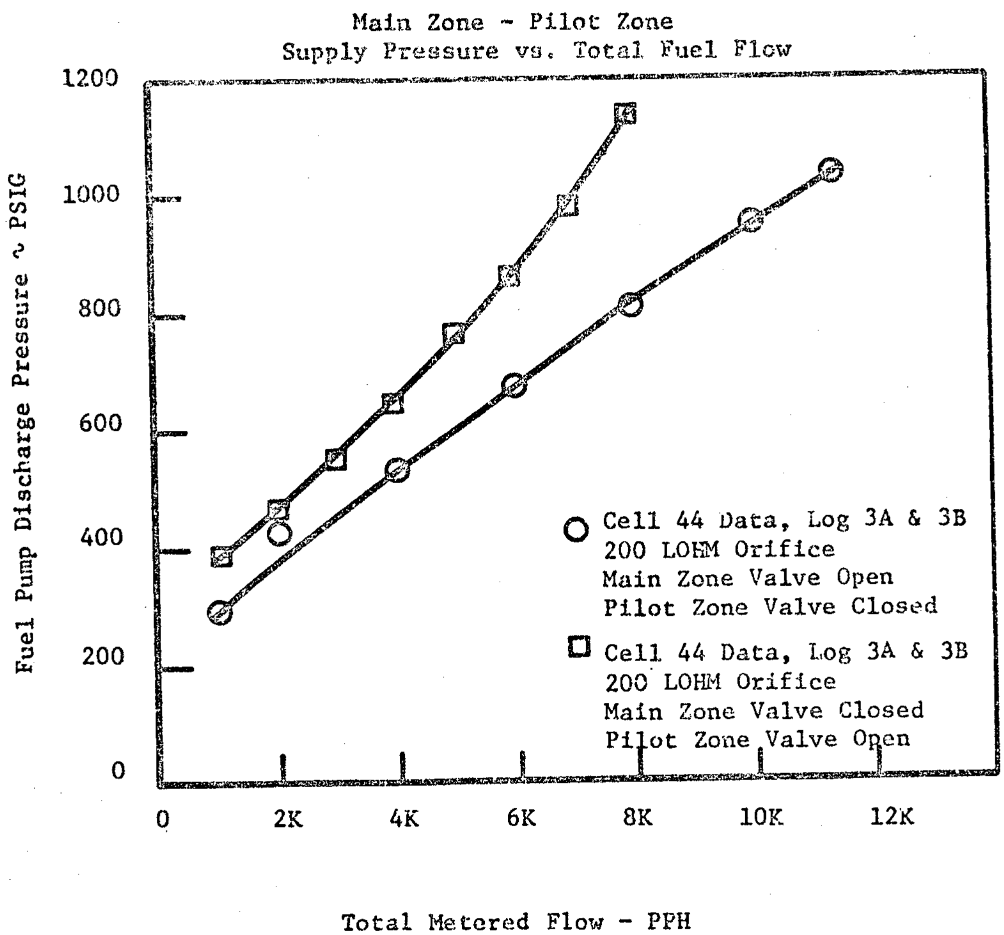


Figure 40. Main Zone Pilot Zone Pressure vs. Flow Characteristics.

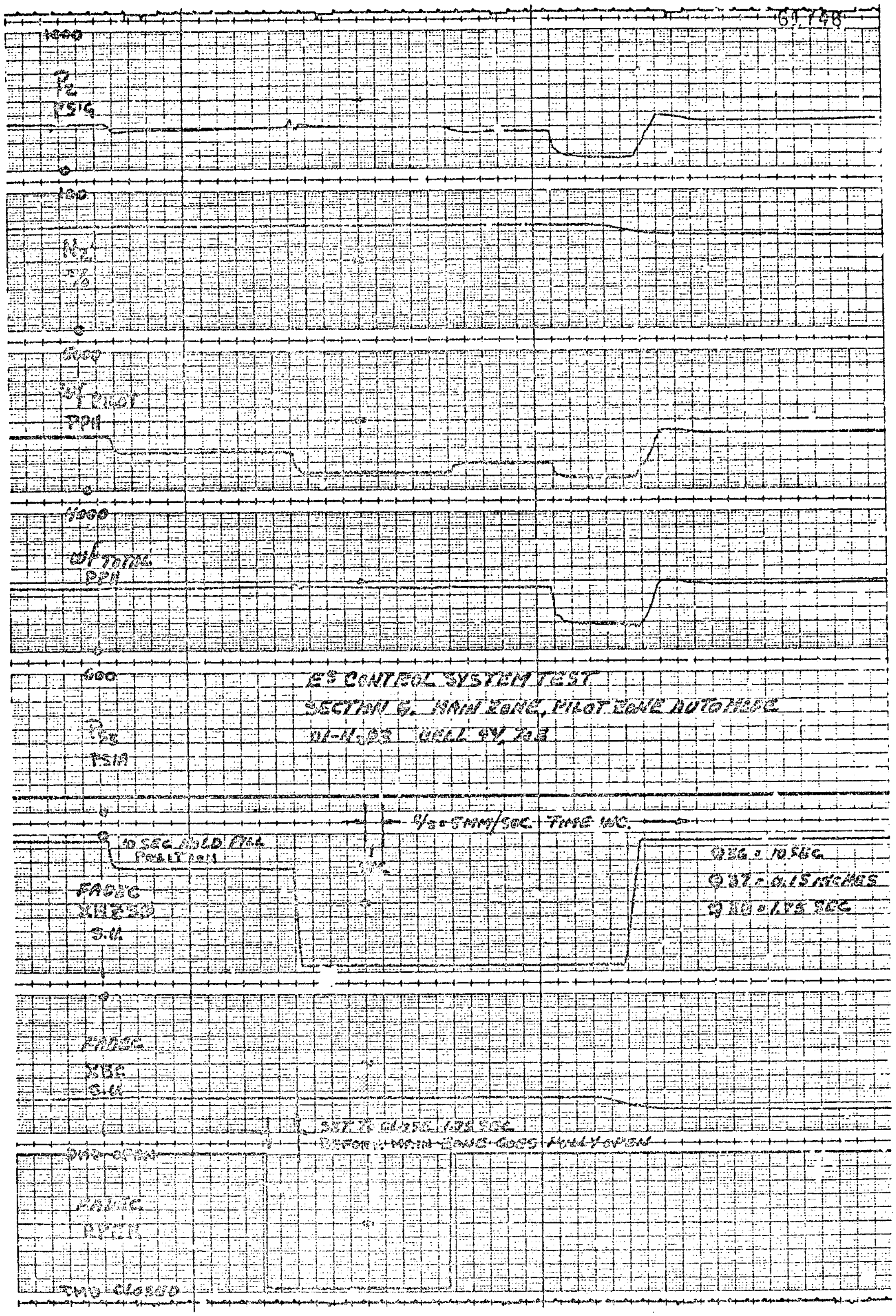


Figure 41. Single to Double Annular Auto Transition.

a. Fill the main zone nozzles - this was set at ten seconds for this demonstration but can be from 1.75 to 100 seconds. Note that the fill position (i.e., amount of flow in the main zone during filling) is adjustable and will be set so the engine does not decelerate during filling.

b. Close the pilot zone to enrich the main zone to allow the main burner to light. Note that the pilot zone valve is signalled closed 1.75 seconds before the main zone goes fully open. This is a slow (.25 gpm servovalve) system and takes that long to close.

c. Open the main zone when the pilot zone is going fully closed.

d. Reopen the pilot zone valve after transition to double annular.

Adjustments will be made to the control system to optimize automatic transition during engine test.

The optional feature of closing the main zone during decels to prevent blowout and the transition back to double annular combustion was tested and performed satisfactorily.

The optional feature of closing the pilot zone during decels to prevent blowout during the decel was also verified.

Note: these two optional features will be used only if blowouts are actually encountered during engine testing. They are adjustable from the operator/engineering panel.

III.H. Primary Mode Acceleration Schedule/WF Calibration

Figure 42 shows test data plotted on the design schedule of accel phi (WF/ps3) vs. corrected core speed obtained by varying speed and compressor discharge pressure. These data show that the digital control schedules accelerate fuel flow accurately. The backup control acceleration schedule

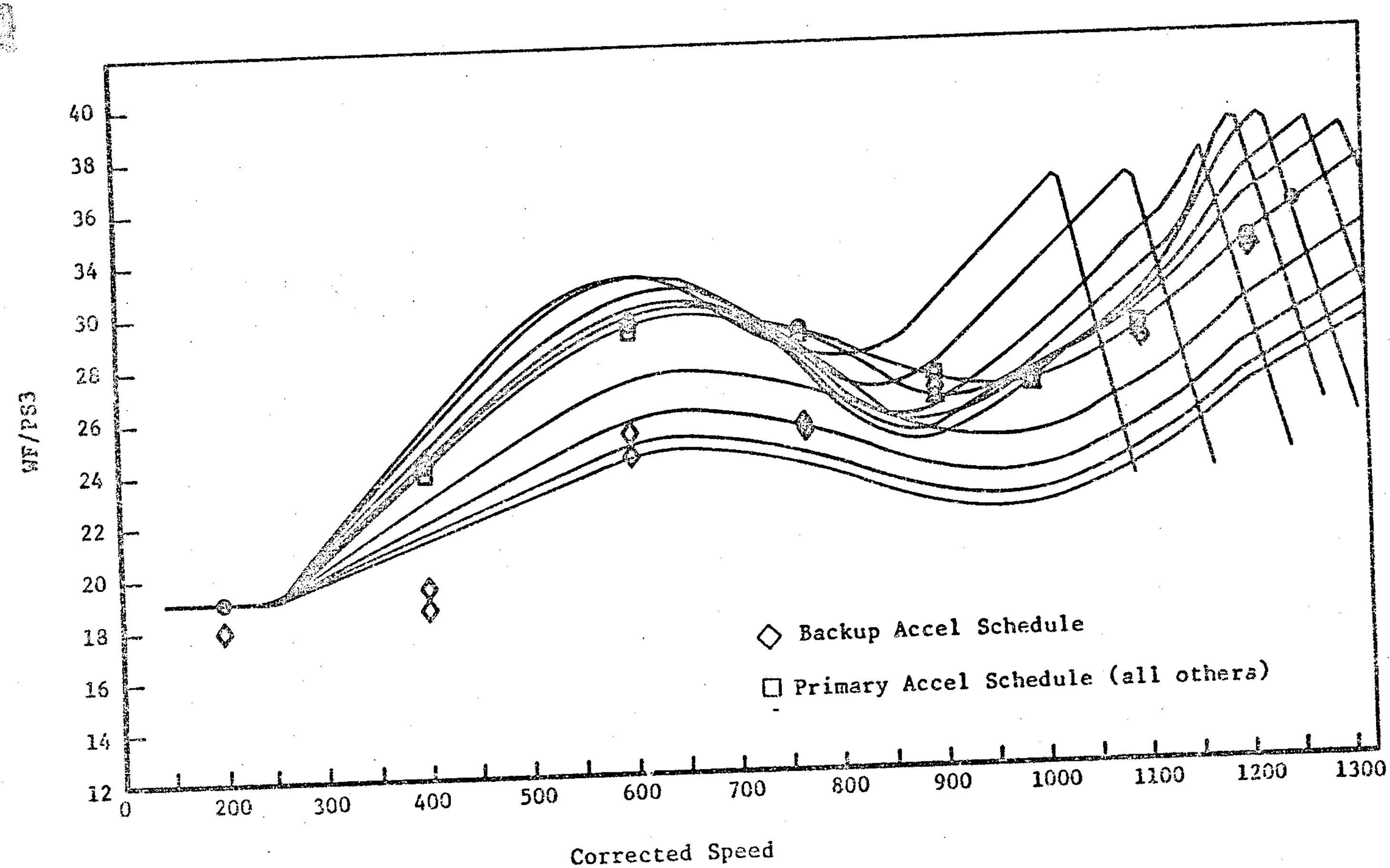


Figure 42. Acceleration Fuel Schedule Data - Primary Mode

was low in the start region but this was not a concern because all starts were to be made using the digital control. The schedule cam in the backup control was made before core engine testing showed engine fuel flow requirements in the start region to be higher than originally predicted. A cam change was not considered to be justified.

Figure 43 is a plot of measured fuel flow vs. calibrated fuel flow. These data indicate that the fuel flow calculated by the digital control from fuel metering valve position is quite accurate. This was accomplished by utilizing the operator/engineering panel adjustments which modify the coefficients of the digital controls fuel flow calculation polynominal.

III.I. PLA Schedule - Primary

Figure 44 is a plot of the core speed governor cut-in as a function of power lever angle plotted on the E^3 control system specification schedule while operating on the primary control. The data indicates that the core speed schedule is the same as the core engine PLA schedule and not the desired ICLS PLA schedule. This will require a slight adjustment to the fan speed PLA schedule to ensure controlling on fan speed at high power. This should cause no operational problems.

Figure 45 is a plot of the fan speed governor cut-in as a function of power lever angle plotted on the E^3 control system specification schedule while operating on the primary control. The data indicataes that the digital control governs fan speed in accordance with the desired schedule.

Figure 46 is a plot of the core speed governor cut-in as a function of power lever angle plotted on the E^3 control system specification schedule while operating on the backup control. Speed governing by the backup control is within acceptable limits. It should be noted that the digital control PLA and backup control PLA correspond at 0° and increase at a ratio of 1.6993 digital degrees per backup degree. Comparison of the data on Figures 44 and 46 on this basis shows the backup schedule slightly below the primary schedule, as desired, so that fuel flow will decrease rather than increase in the event of a switchover from the primary to backup mode.

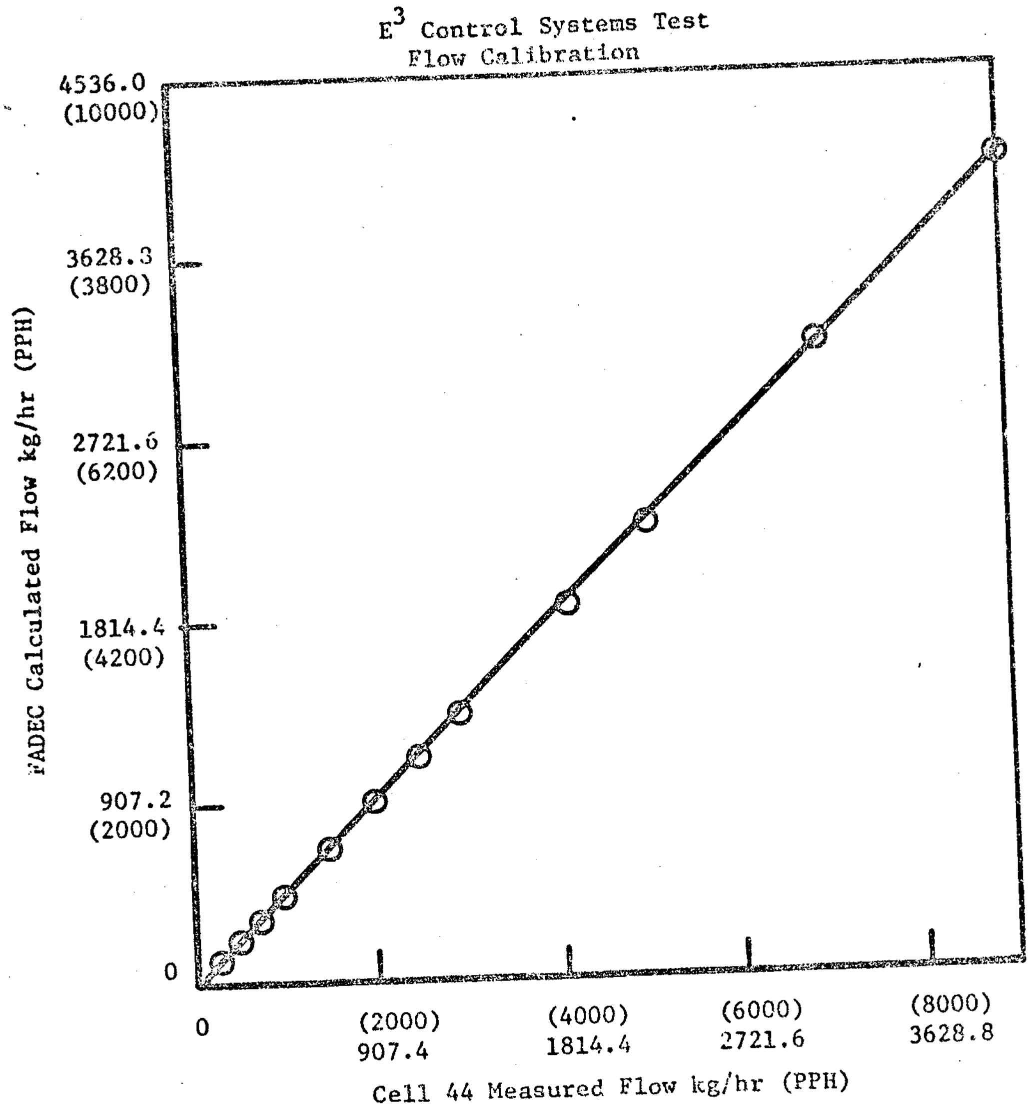


Figure 43. Digital Fuel Flow Calibration.

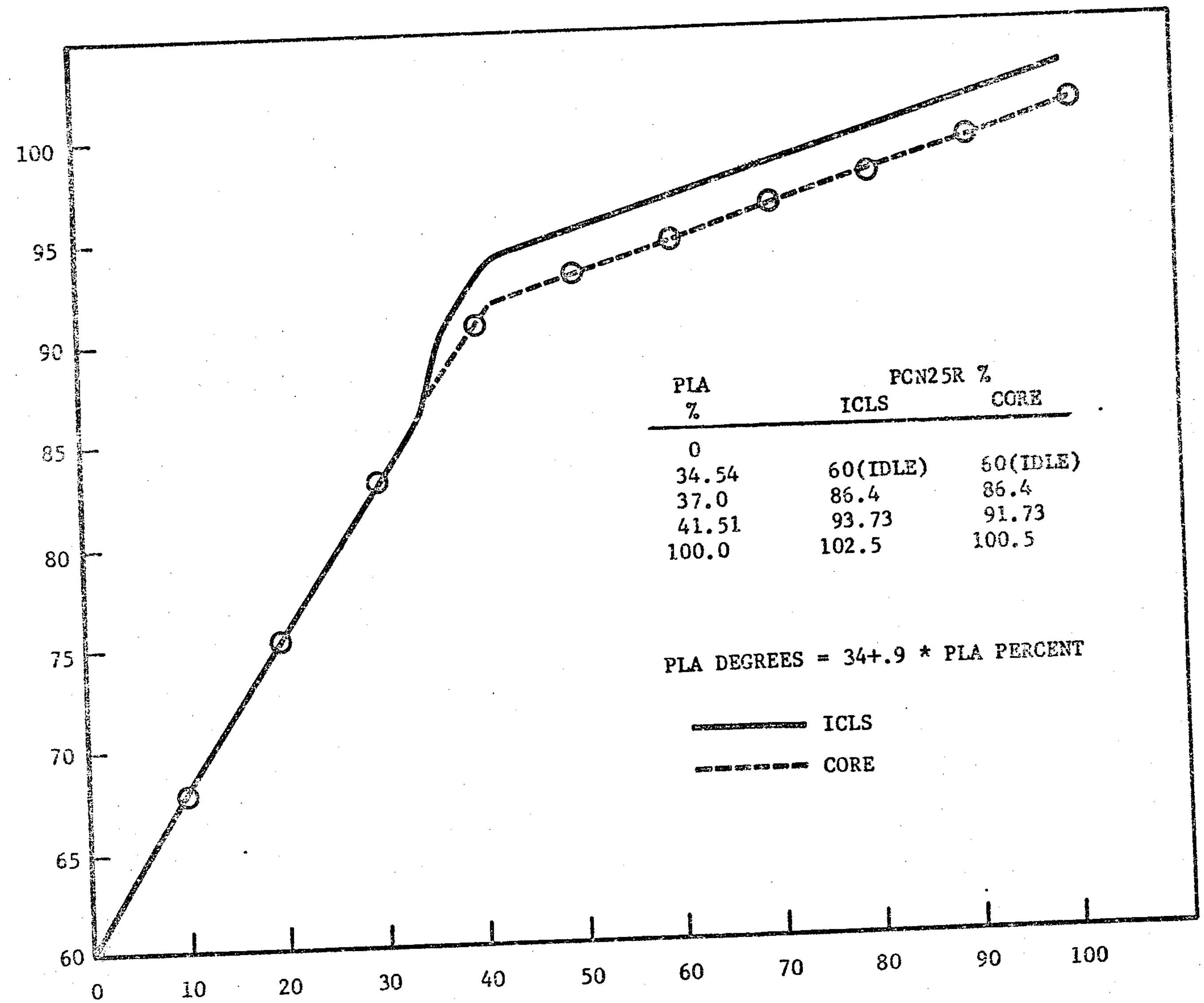
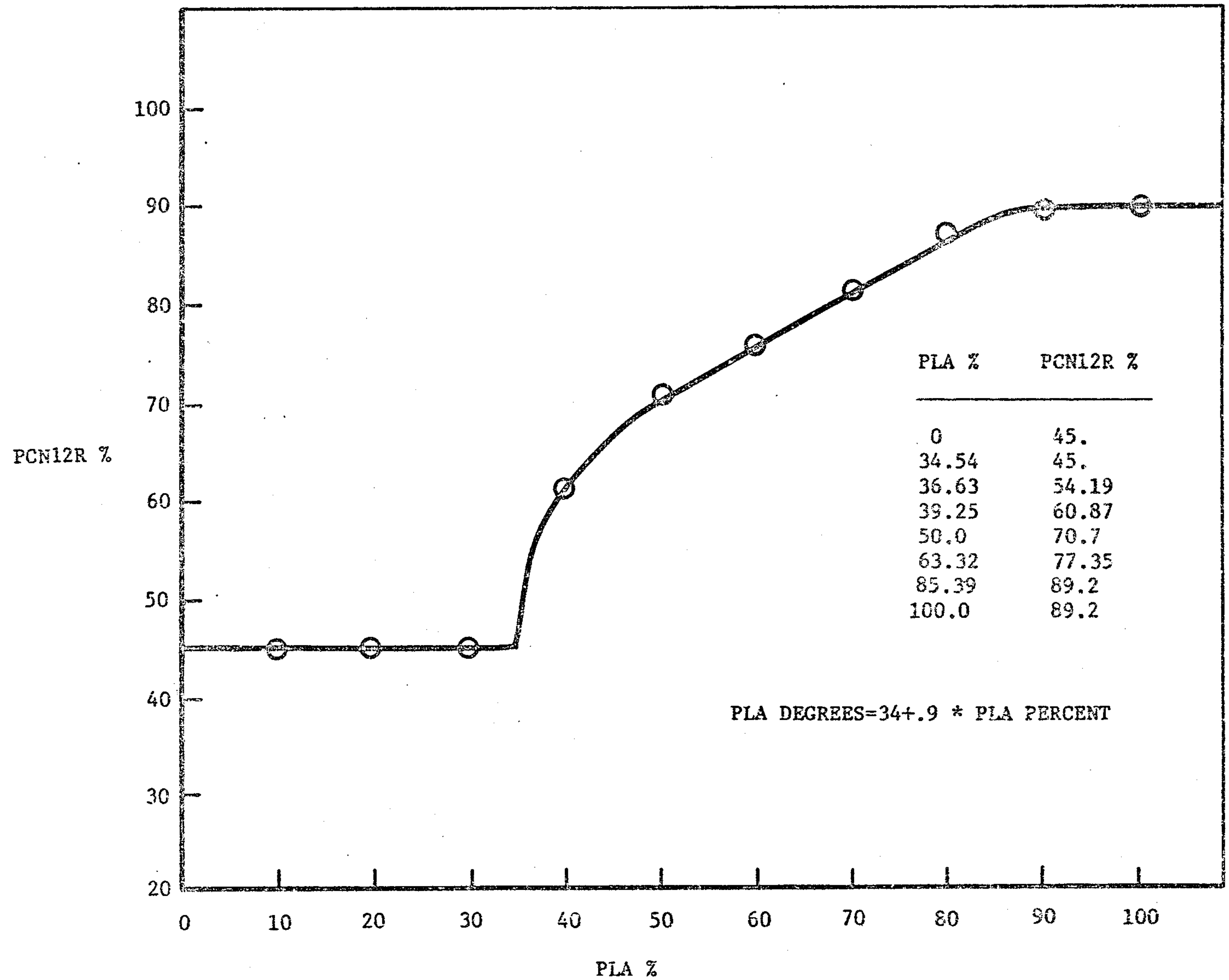
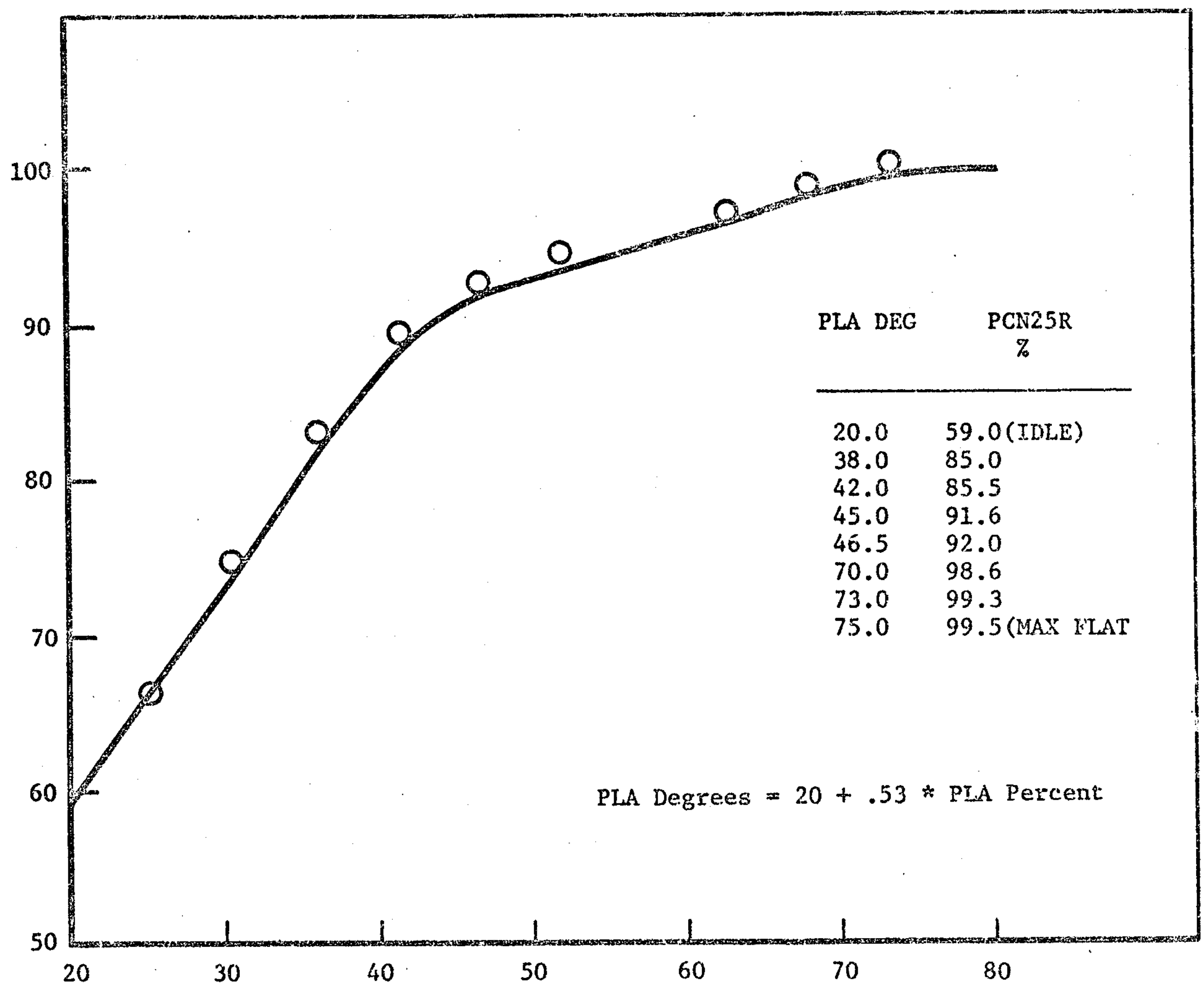


Figure 44. Corrected Core Speed Schedule



PLA %	PCN12R %
0	45.
34.54	45.
36.63	54.19
39.25	60.87
50.0	70.7
63.32	77.35
85.39	89.2
100.0	89.2

Figure 45. Corrected Fan Speed Schedule



PLA DEG	PCN25R %
20.0	59.0(IDLE)
38.0	85.0
42.0	85.5
45.0	91.6
46.5	92.0
70.0	98.6
73.0	99.3
75.0	99.5(MAX FLAT

Figure 46. Hydromechanical Core Speed Schedule

III.J. Core Stator Schedule

Figure 47 is a plot of the core stator schedule in the primary and backup mode plotted on the specification line in terms of feedback stroke. The system was rigged on the open stop and the LVPT was adjusted to obtain the correct digital reading on the stop. The same procedure will be used for rigging the stators on the engine.

Figure 48 is a plot of the core stator schedule in the primary mode plotted on the specification line in terms of LVPT position.

III.K. Primary Mode Acceleration Transients

A series of accel/decel transients were run in accordance with this part of the test request. The main conclusion from this transient testing is that acceleration fuel flow is scheduled satisfactorily in the primary mode and that transitions to N2 governing or the T42 limit are smooth.

III.L. Primary Mode Deceleration Transients

A series of decel transients were run in accordance with this part of the test request. The main conclusion from this transient testing is that acceleration fuel flow is scheduled satisfactorily and that transitions to N2 governing at idle are satisfactory.

III.M. Backup Mode Acceleration Transients

A 30 second accel in the backup mode indicates proper governor cut-in at the 100% pla set point. The conclusion is that acceleration transients could be made in the backup mode.

It should be noted here that the main zone shutoff value is open because the control is in the backup mode.

III.N. Backup Mode Deceleration Transients

A 30 second decel in the backup mode shows that decel transients can be made in the backup mode.

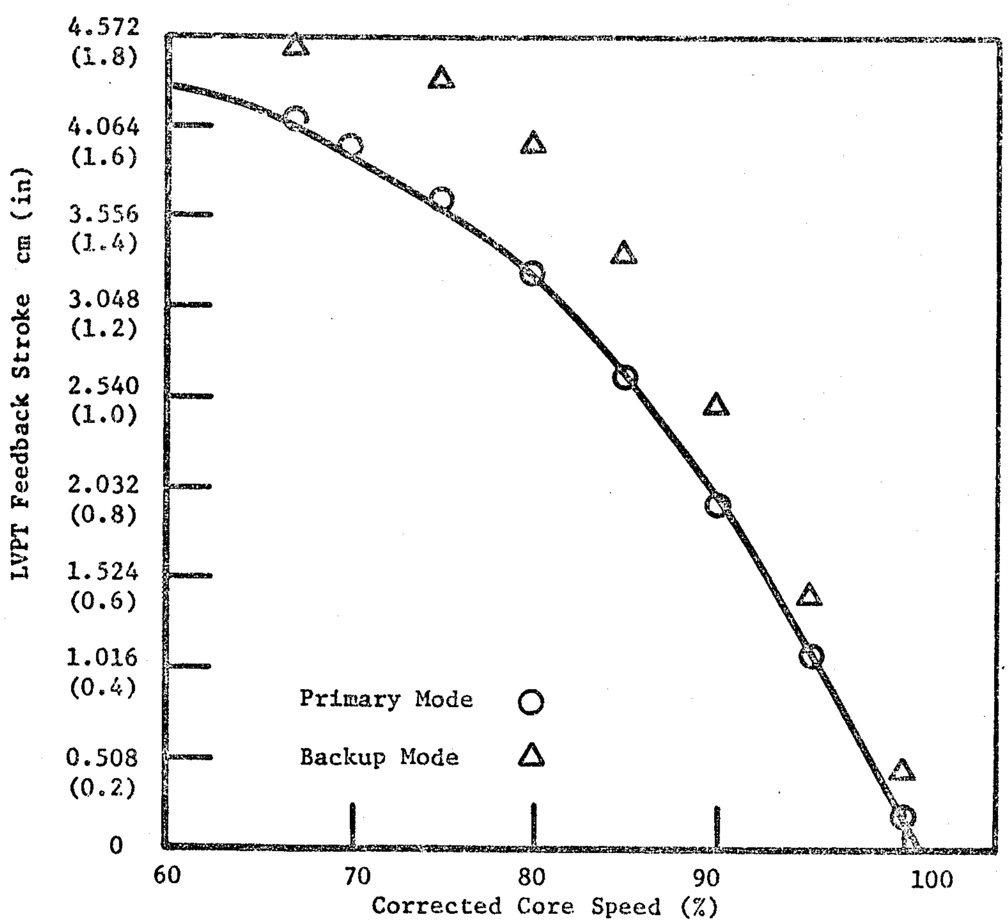


Figure 47. Core Stator Schedule Primary and Backup.

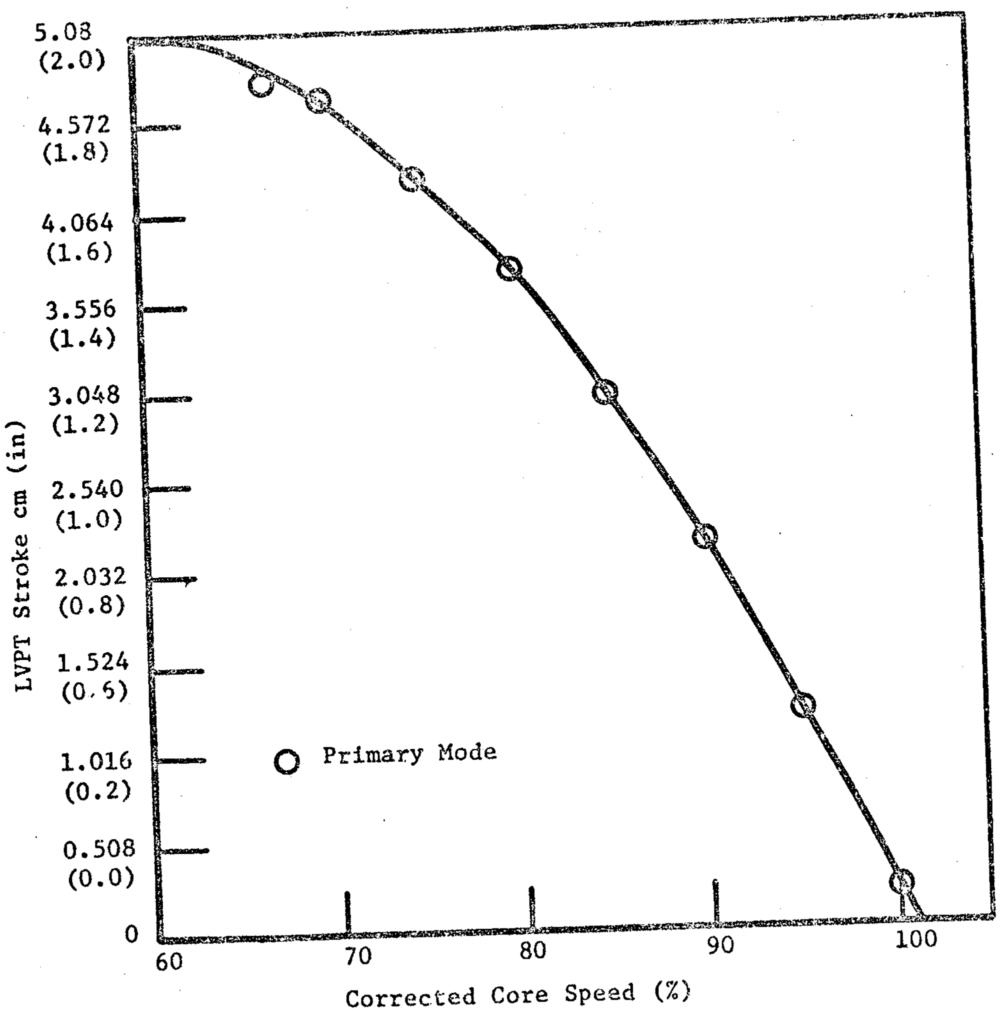


Figure 48. Core Stator Schedule - Primary LVPT Position

III.O. Overspeed Selection of Backup Mode

Test results show the control automatically switches to the backup mode at 109.9 percent speed. The control speed was then decreased until the control went on the accel schedule. This occurred at 96.2 percent. The control was then switched back to primary control.

III.P. Governor Frequency Response Primary Mode

Figure 49 is a plot of gain and phase shift as a function of frequency for the primary Mode N2 speed control. Two conditions were tested, a low power (idle speed, 4536 Kg/hr (1000 pph) fuel flow) and a high power (Takeoff speed, 3120 Kg/hr (6900 pph) fuel flow). The nominal line, as defined, is plotted on the curves for comparison purposes. The plots indicate both phase and gain are slightly below this nominal line. The net result should be a stable, somewhat more sluggish, but adequate N2 speed control.

Figure 50 is a plot of gain and phase shift as a function of frequency for the primary Mode N1 speed control. One condition was tested, a high power (Takeoff speed, 3894 Kg/hr (6380 pph) fuel flow). The nominal line, as defined, is plotted on the curves for comparison purposes. The plots indicate both phase and gain are slightly below this nominal line. The net result should be a stable, somewhat more sluggish, but adequate N1 speed control.

III.Q. PS3 and T41C Limits

Testing shows the fuel flow cutback when PS3 is increased beyond the 2930.4 KPa (425 psia) limit.

A similar test was performed to illustrate the cutback on the calculated T41C limit (Note - T41C is calculated from T3 and WF/PS3). The T41C increase was simulated by increasing T3. T41C cutback occurs at 1322°C (2412°F) when the limit is set at 316°C (2400°F).

III.R. Compressor Clearance Control Checkout

Figure 51 is a plot of the compressor clearance control feedback

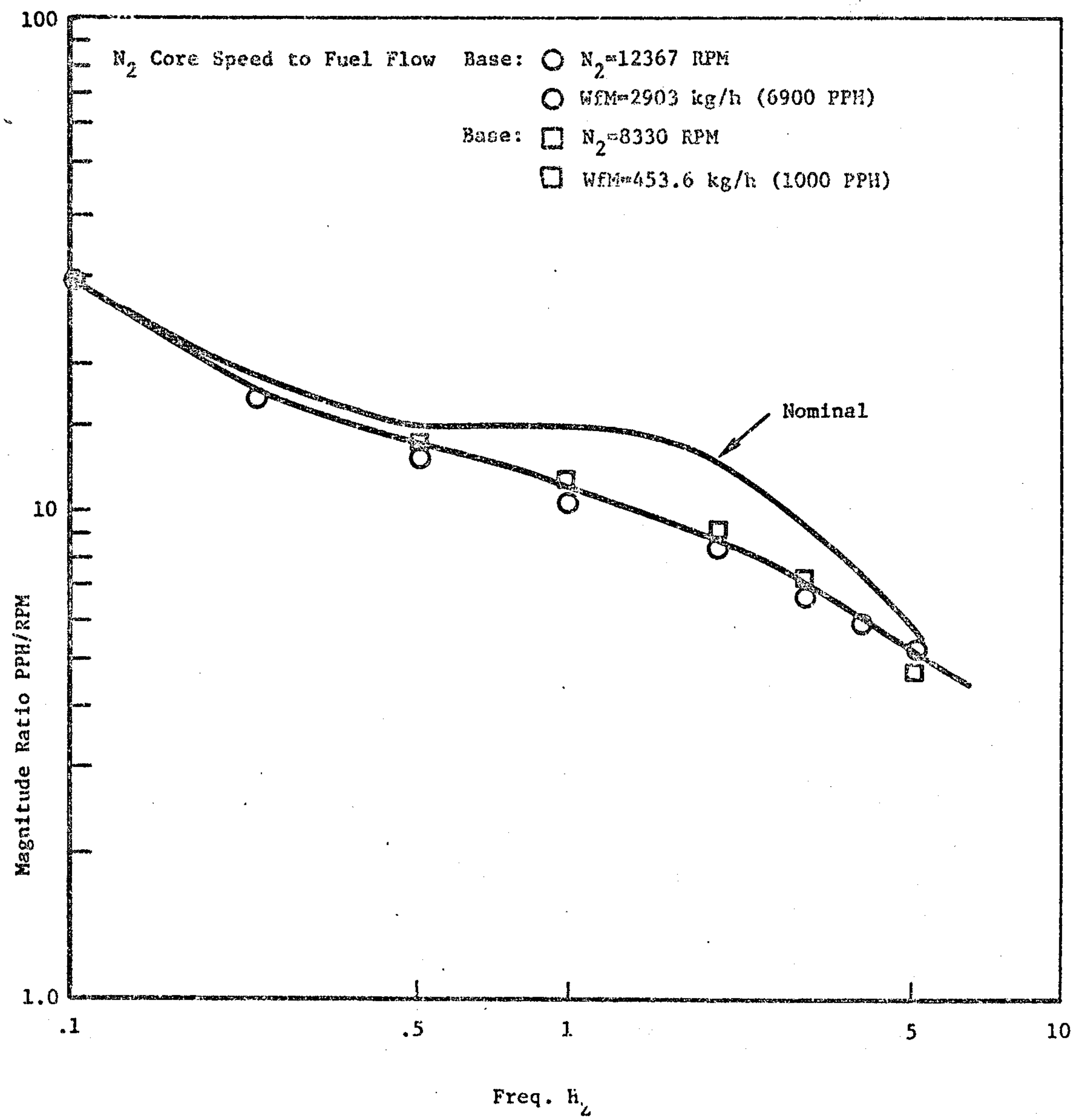


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Figure 49. Core Speed Frequency Response - Primary Mode

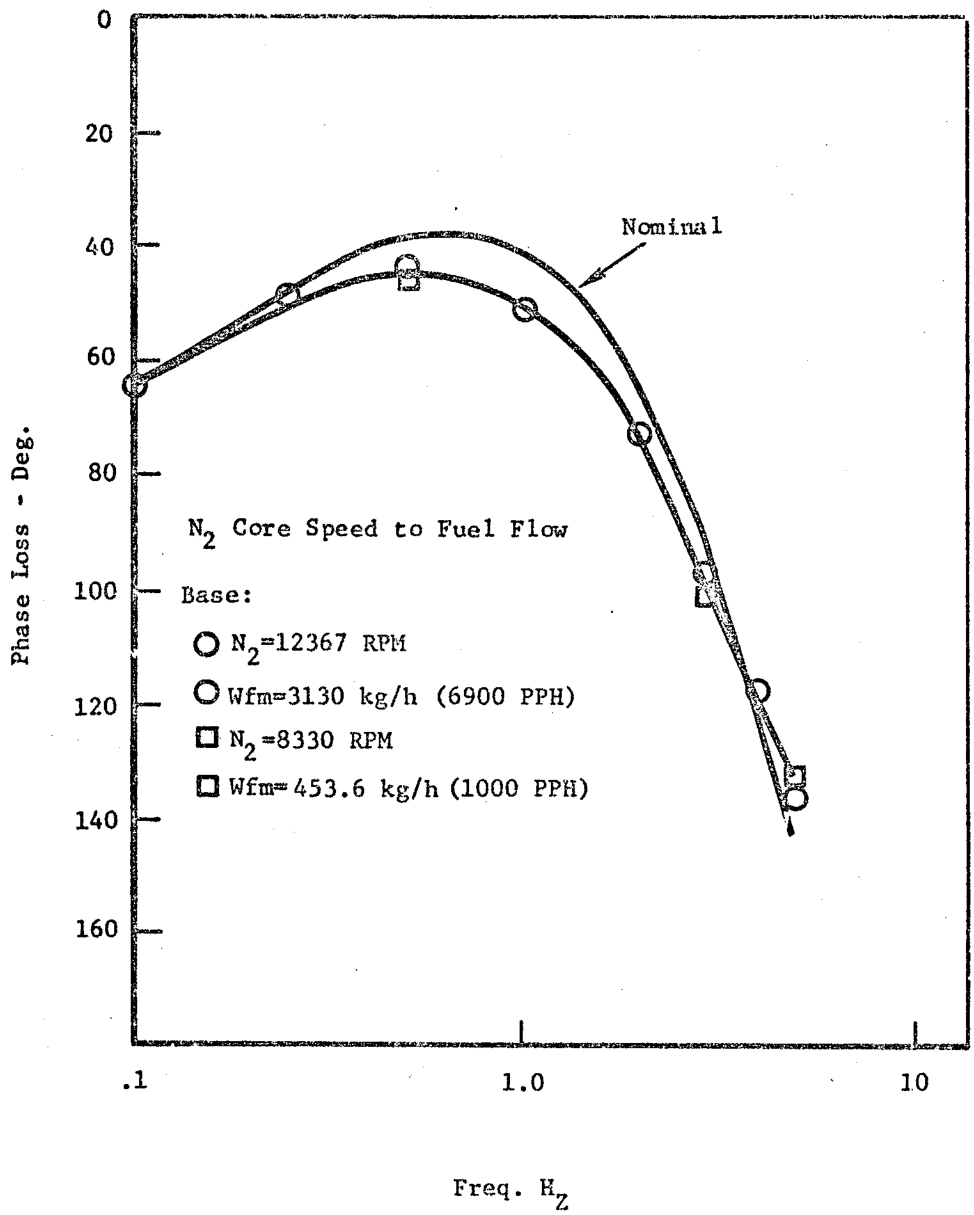

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Figure 49. Core Speed Frequency Response - Primary Mode

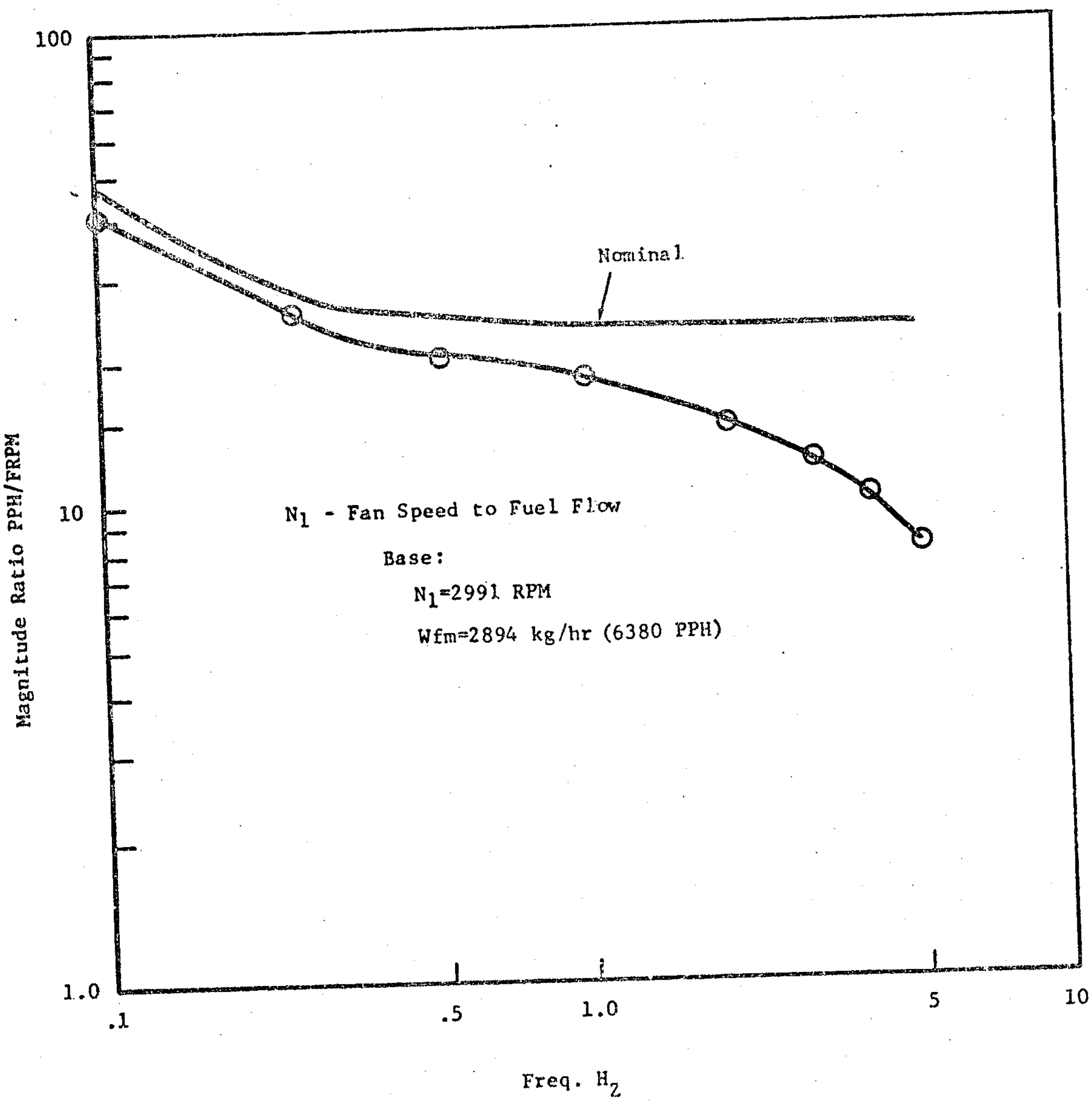

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Figure 50. Fan Speed Frequency Response - Primary Mode

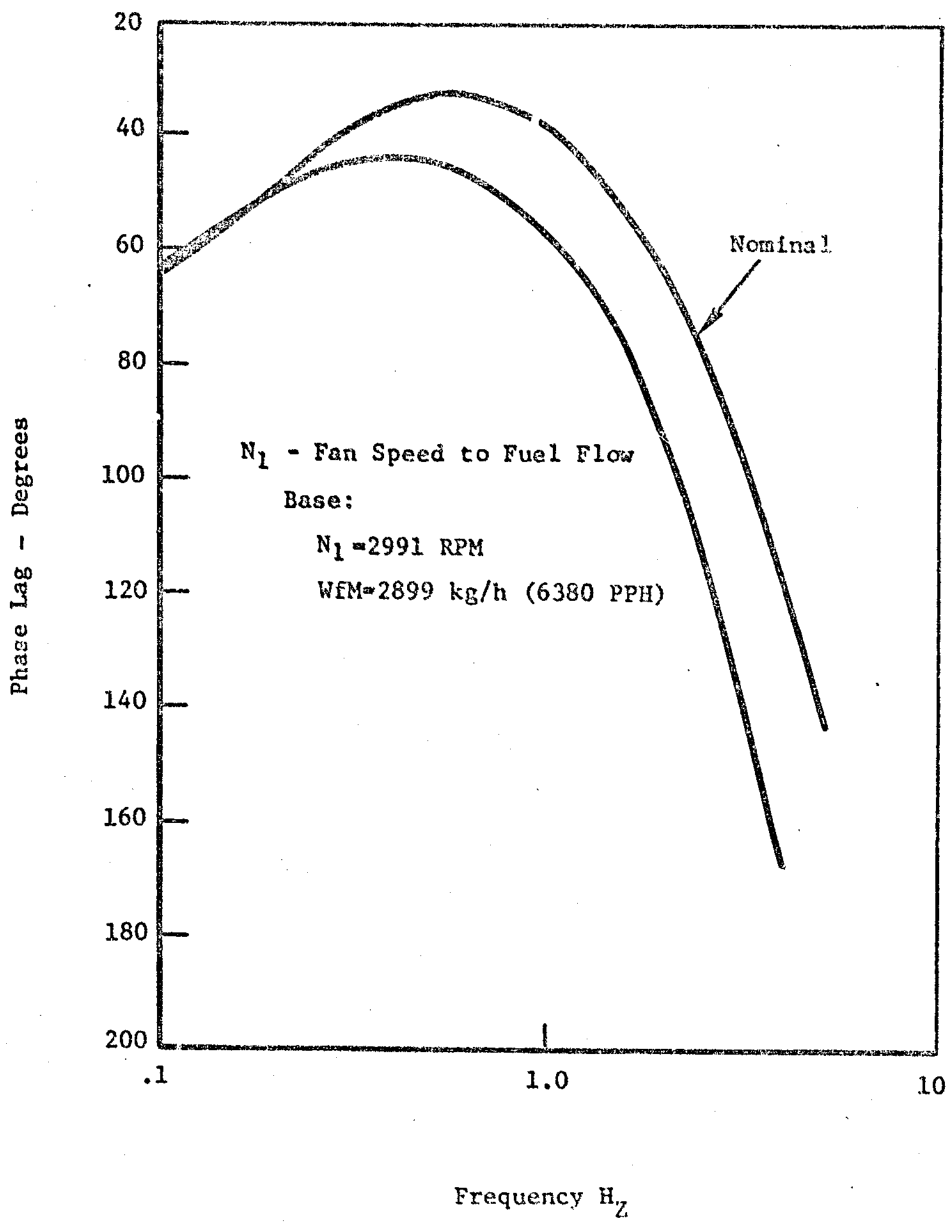

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Figure 50. Fan Speed Frequency Response - Primary Mode

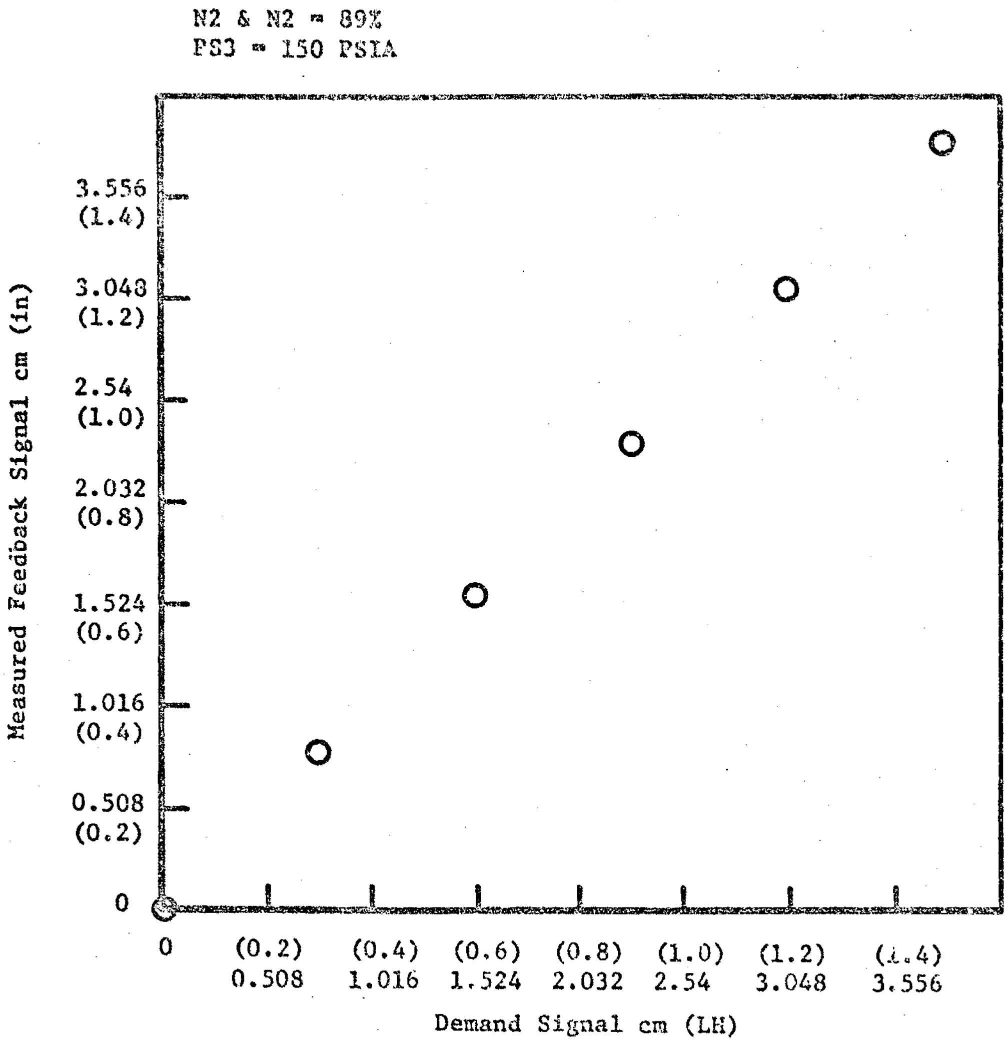

Figure 51. CCC Valve Feedback Calibration

signal calibration in terms of physical measurement of actuation stroke vs. digital control stroke demand.

A transient increase and decrease of the case temperature input was made verifying that the controlling action of the compressor clearance control was correct in the automatic mode. Increasing measured case temperature opens the valve and decreasing measured case temperature closes the valve.

A rapid decel was made while operating in the automatic mode. The valve starts to open as speed is decreased, then rapidly closes when core speed decel rate exceeds 150 RPM/sec. The system was then reaccelerated and the valve reopened.

A rapid decel was made, then the system was allowed to remain at the lower level and the casing temperature was reduced as it would have been on the engine after a decel. When the temperature went below the scheduled level for the lower speed, the valve properly reopened.

III.S. Turbine Clearance Control Checkout

Figure 52 is a plot of the HP Turbine clearance control feedback signal calibration in terms of the physical measurement of actuator stroke vs. digital control stroke demand.

A transient increase and decrease of the HP Turbine case temperature input was made to verify the controlling action of the HP Turbine clearance control in the automatic mode. Increasing temperature opens the valve and decreasing temperature closes the valve as it should.

Figure 53 is a plot of the LP Turbine clearance control feedback signal calibration in terms of the physical measurement of actuator stroke vs. digital control stroke demand.

A transient increase and decrease of the LP turbine case temperature input was made to verify the controlling action of the LP Turbine clearance control in the automatic mode. Increasing temperature opens the valve and decreasing temperature closes the valve as it should.

N2 & N2' = 89%
PS3 = 1034 kPa 150 PSIA

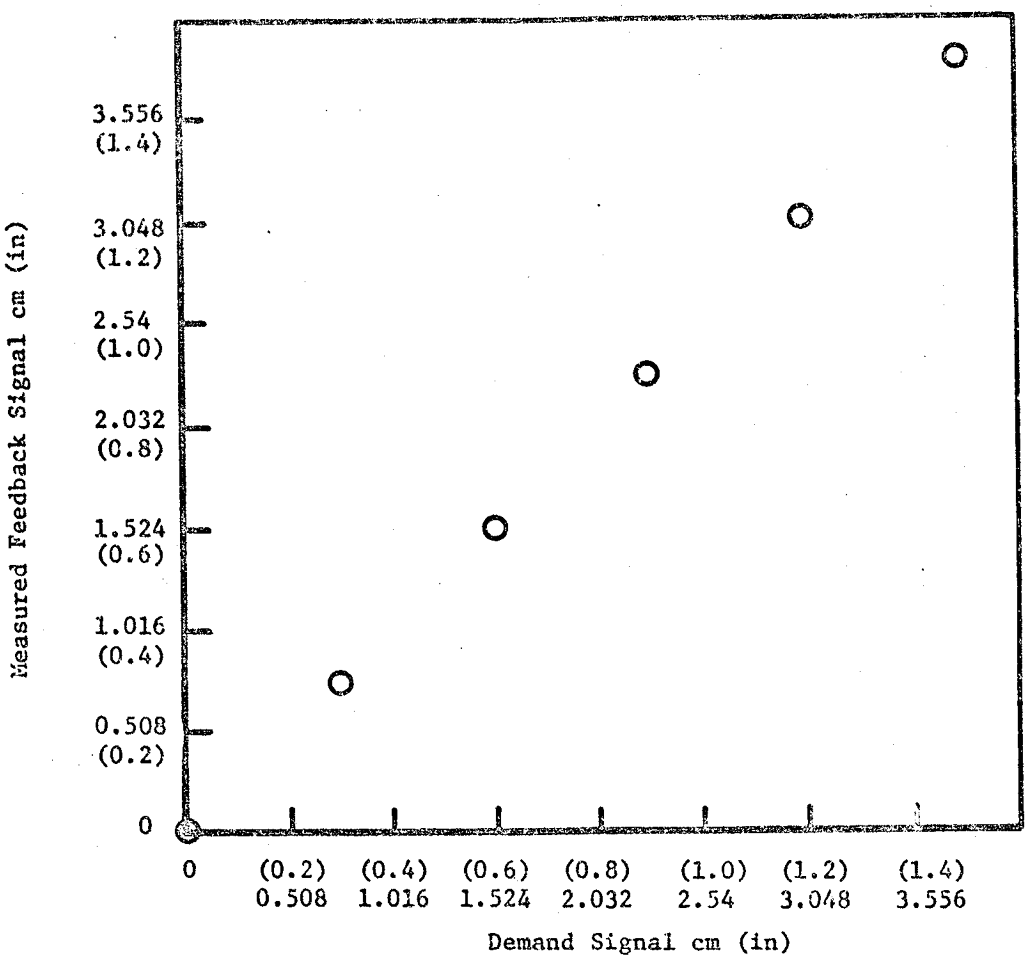

Figure 52. HP Turb Valve Feedback Calibration.

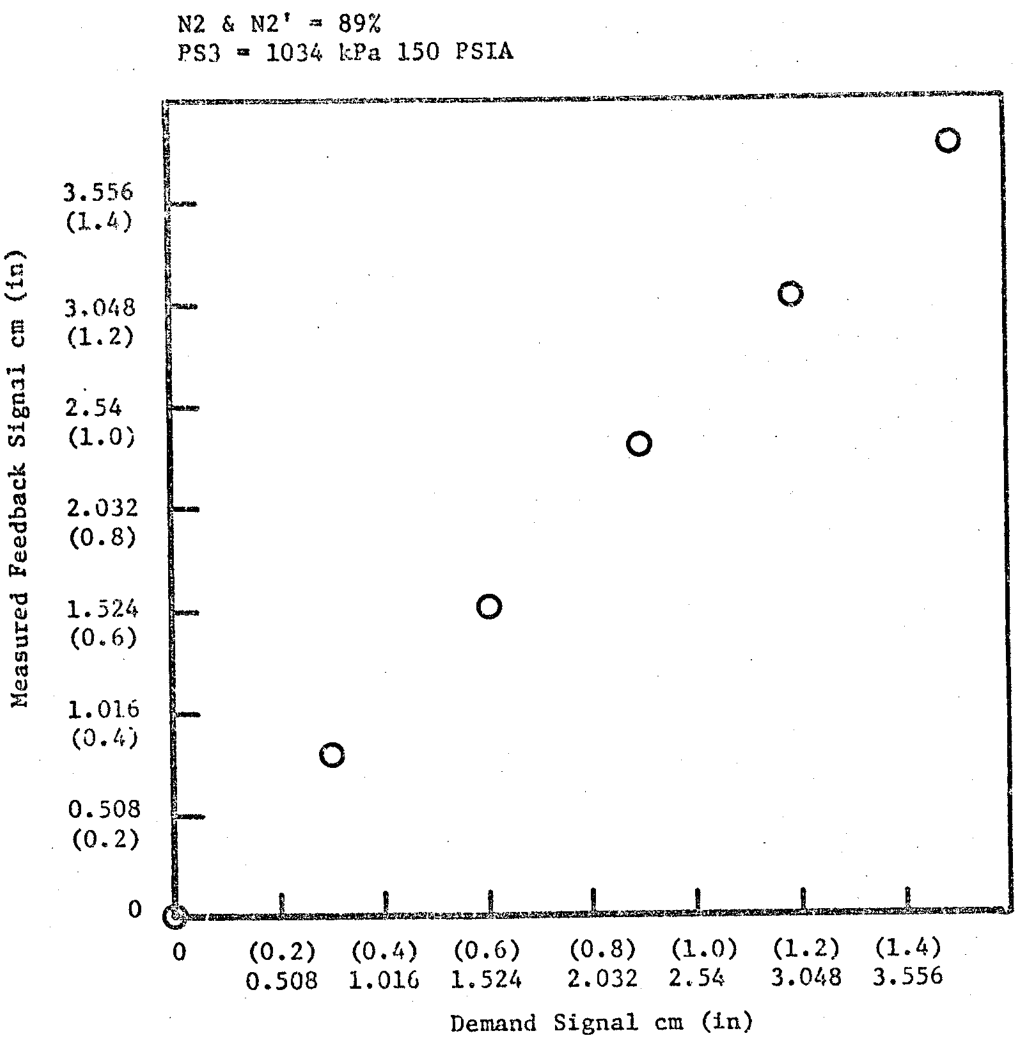

Figure 53. LP Turb Valve Feedback Calibration.

III.T. Position Loop Step Input Response

The metering valve response to a step input to the metering valve position demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.1524 cm/sec/ma (.060 in/sec/ma).

The main zone valve response to a step input to the main zone demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.0787 cm/sec/ma (0.031 in/sec/ma).

The LP turbine clearance valve response to a step input to the LP turbine clearance demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.1397 cm/sec/ma (.055 in/sec/ma).

The compressor clearance valve response to a step input to the compressor clearance demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.1397 cm/sec/ma (.055 in/sec/ma).

The HP turbine clearance valve response to a step input to the HP Turbine clearance demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.1499 cm/sec/ma (.059 in/sec/ma).

The core stator valve response to a step input to the core stator demand signal was measured. Average measured gain from digital torque motor current to measured feedback position is 0.1676 cm/sec/ma (.066 in/sec/ma).

III.U. Failure Effects

2.a. Disconnection of the alternator caused the control to trip to backup.

The FADEC power is disrupted by disconnecting the alternator and power must transfer to the 28 volt DC power supply. This is thought to cause the regulated 5 volt power supply to the FADEC to be momentarily interrupted, causing the trip to backup.

Any of the following will cause the control to trip to backup (if OTOLIM enabled):

1. PLA out-of-limits
2. XNH out-of-limits
3. XMV out-of-limits
4. XBC out-of-limits
5. XMV F/B Fail
6. XBC F/B Fail
7. Self test word fail

2.b. Disconnection of the metering valve feedback sensor causes the control to trip to backup because of the metering valve F/B failure effect, i.e., it senses that the metering valve is not moving when it should be.

2.c. The 28 volt DC power supply was disconnected to 90% speed with no effect on operation.

2.d. Disconnection of the data link to the digital control caused no change in systems operations, but no new data can be transmitted. Power lever angle is frozen at the value existing at the time of failure. A manual switch to backup will be required to decelerate the engine. Disconnection of the engineering operator panel caused no change in systems operation, but no new commands can be input from the panel. Engineering panel adjustments go to a pre-determined level or to levels which are reset every two minutes.

2.e. Disconnection of the fuel servovalve caused the system to trip to backup. If the F/B failure protection is deactivated, the system drifts to minimum flow when the fuel servovalve is disconnected.

2.f. Disconnection of the main zone feedback sensor causes the equivalent digital number to freeze but the number is unpredictable.

Results will be one of the following:

1. If the feedback signal as sensed by the control fails out-of-limits the valve will open.

2. If the feedback signal is calling for full open or full closed, the main zone valve will go to the demanded position.

3. If the feedback signal fails within limits and the demand signal is at an intermediate position, the error signal between demand and sensed feedback will determine direction and rate of closing or opening. Thus, for this case the valve may fail open or closed and is not predictable.

2.g. Disconnection of the main zone shutoff servovalve caused the valve to drift in the opening direction.

2.h. Disconnection of the compressor clearance servovalve and feedback sensor will do two things:

1. The feedback signal as sensed by the control will go to an indeterminate position and remain there until the sensor is reconnected.

2. Torque motor current to the servovalve will go to zero causing the actuator to drift in its fail safe direction (retracted). Drift rate is determined by null bias on the torque motor.

   Reconnecting the servo and feedback sensors will result in a recovery transient starting from the retracted position. The recovery transient will be affected by such factors as:

   a. Supply and return line lengths and restrictions.

   b. Actual characteristics of the particular T/M and servo valve involved.

   c. Actual pin reconnection sequence when connector is reconnected.

2.i. Disconnection of the HP turbine clearance servovalve and feedback sensor will have the same failure effect as the compressor clearance system described in 2.h. above.

2.j. Disconnection of the LP turbine clearance servovalve and feedback sensor will have the same failure effect as the compressor clearance system described in 2.h. above

2.k. The 28 volt DC power supply was disconnected at high speed (98%) and speed was gradually reduced. The control continued to function until speed was decreased to 47.7%, at which point alternator power was insufficient and the control went to the backup mode.

2.1. Disconnection of the fan speed sensor causes the fan speed sensor to fail to an indeterminate valve. No failure action is taken. The normal control strategy will determine action for the failed value.

2.m. Disconnection of the core stator feedback causes the digital number, which indicates stator feedback position to freeze, but the number is unpredictable. Feedback failure logic similar to the metering valve feedback failure logic has been incorporated into the core stator control system, thus the system will trip to backup when the feedback sensor is disconnected and the failure criterion has been met. Two successive disconnections of the core stator feedback signal caused different results. In the first case, the sensed failed position caused a trip to backup. In the second case the feedback failed to the same level it was operating at prior to the failure. Until torque motor current calls for a change in stator position the system will stay in primary. As soon as a new stator position is demanded the system will trip to backup. This was not demonstrated as all subsequent failures tripped to backup immediately.

2.n. Disconnection of the core stator servovalve caused the system to trip to backup with the failure protection described in 2.m. activated. With this failure protection deactivated the system drifted to the closed stator position.

2.o Disconnection of the pilot zone servovalve causes the pilot zone valve to open if closed or remain open if opened.

III.V. FICA

The control strategy incorporated a feature to simulate software failures for each FICA substituted variable (fan speed, core speed, comp. inlet temperature, compressor discharge temperature, LP turbine inlet temperature and compressor discharge pressure). Each sensor is multiplied by an engineering operator panel potentiometer which is scaled from .5 to 1.5 (nominal value is 1.0). A switch on the engineering operator panel is used to enable the multipliers.

To induce a software failure the potentiometer, associated with the sensor to be failed, is adjusted to a value beyond the FICA error tolerance and the switch is then activated causing a step change in the sensors value as seen by the control strategy. The FICA will then substitute the estimated value for the sensed value. This method was used to demonstrate single sensor failures.

III.V.a. & b. Core Speed Sensor Failure

A core speed software failure caused a substitution to estimated core speed (FICA core speed). Core speed prior to the failure was 12385 RPM and 12377 RPM after the substitution.

A core speed hardware failure was accomplished by inputting a step change to the simulated alternator signal and the estimated value from FICA was substituted. The core stator and metering value feedback error signal was disabled for this test.

A second core speed hardware failure which was the same as the first hardware failure except that the core stator and metering value feedback error signal was enabled. The control trips to backup as a result of the momentary large error in core stator control loop.

Disconnection of the alternator will cause a trip to backup whether FICA is active or not. (Ref. Section III.u.2.a.).

III.V.c. & d. Fan Speed Sensor Failure

A fan speed software failure caused a substitution to estimated fan speed (FICA fan speed). Fan speed prior to the failure was 2945 RPM and 2942 RPM after the substitution.

Two fan speed hardware failures were made. The first was done by disconnecting the sensor (the fan speed signal failed within the FICA error tolerance and no substitution occurred). The second was done by step changing the fan speed input frequency and the estimated value from FICA was substituted.

III.V.e. & f. Compressor Inlet Temperature Sensor Failure

A compressor inlet temperature (T25) software failure caused a substitution to estimated compressor inlet temperature (FICA T25). Compressor inlet temperature prior to the failure was 47.7°C (117.8°F) and 48.2°C (118.7°F) after the substitution.

The compressor inlet temperature hardware failure had the same result. This was accomplished by disconnecting the sensor and the estimated value from FICA was substituted.

III.V.g. & h. Compressor Discharge Temperature Sensor Failure

A compressor discharge temperature (T3) software failure caused a substitution to estimated compressor discharge temperature (FICA T3). compressor discharge temperature prior to the failure was 496.1°C (925°F) and 499.4°C (931°F) after the substitution.

III.V.i. & j. LP Turbine Inlet Temperature Sensor Failure

A LP turbine inlet temperature (T42) software failure caused a substitution to estimated LP turbine inlet temperature (FICA T42). LP turbine inlet temperature prior to the failure was 754.4°C (1390 °F) and 752.2°C (1386°F) after the substitution.

The LP turbine inlet temperature hardware failure had the same result. This was accomplished by disconnecting the sensor and the estimated value from FICA was substituted.

III.V.k. & l. Compressor Discharge Pressure Sensor Failure

A compressor discharge pressure (PS3) software failure caused a substitution to estimated compressor discharge pressure (FICA PS3). Compressor discharge pressure was 2182 kPa (316.5 psia) prior to failure and 2213 kPa (321 psia) after the substitution.

Two compressor discharge pressure hardware failures were made. Both failures were accomplished by activating a solenoid valve which dumps pressure in the compressor discharge pressure sensing line to ambient. The first failure was with the FICA error tolerance at nominal. The FICA PS3 was substituted for this case. This failure is the same action that is taken by the stall dump kit when it senses an engine stall. The second failure was with the FICA PS3 tolerance set at the maximum value. For this case PS3 is not substituted for, however, core speed was substituted for 250 milliseconds after PS3 was dumped. This appears to be the way to run FICA testing with PS3 tolerance set at the maximum value unless a PS3 substitution is to be demonstrated.

It was recommended that we test the stall dump kit with FICA in the track mode and recorded on a strip chart recorder to determine what will happen when the stall dump trip is made.

III.V.m. Metering Valve Feedback Sensor Failure

A metering valve feedback hardware failure was made. This was accomplished by disconnecting the metering valve feedback sensor. The system did substitute for metering valve error, but the feedback failure logic does trip the system to backup.

III.W. Fuel Boost Pressure Effect

The effect on fuel flow of changing the fuel inlet p ure is minimal.

III.X Post Potting Functional Test

After the control was returned to the assembly area for final potting, a functional test was conducted on the control. This brief test validated the FADEC was functioning properly after final potting.

III.Y. Final Monitor Data and Pot Settings

A list of the final monitor data and pot listings was taken. These settings were the pre-test ICLS engine baseline settings.

7.0 CORE CONTROL SYSTEM PERFORMANCE

The Full Authority Digital Electronic Control (FADEC) system on the core test vehicle performed well, providing the flexibility necessary for thorough exploration of engine characteristics. Areas of particular note are as follows:

7.1 SPEED GOVERNING

The FADEC provided the accurate speed governing necessary for orderly exploration of variable stator effects, compressor bleed, and active clearance control.

A mild governing instability (up to 30 rpm peak-to-peak at 0.2 to 1.0 Hertz) was initially present. However, a PROM change (new program memory for the digital electronic control) was made, allowing the metering valve position loop gain to be increased and the core speed governing gain to be decreased. These gains were then adjusted to minimize the effects of the instability and permit good data acquisition.

This instability, following the PROM change, is shown in Figure 54. Fuel flow, torque motor current, and speed derivative signals are greatly expanded for evaluation purposes. The saw tooth wave form of torque motor current, together with the flattened-off fuel flow wave form indicate that the instability was caused by a combination of torque motor and servovalve dead band (and/or hysteresis) coupled with the software compensation network.

ICLS software provided the adjustable gains and an adjustable compensation network that was fine tuned during the control systems test which minimized this instability.

7.2 FUEL LEAK

Fuel was observed leaking from the fuel control during the wet motoring post-test inspection. The fuel control was removed from the engine and taken to a component test cell where the leak was confirmed. The control cover was

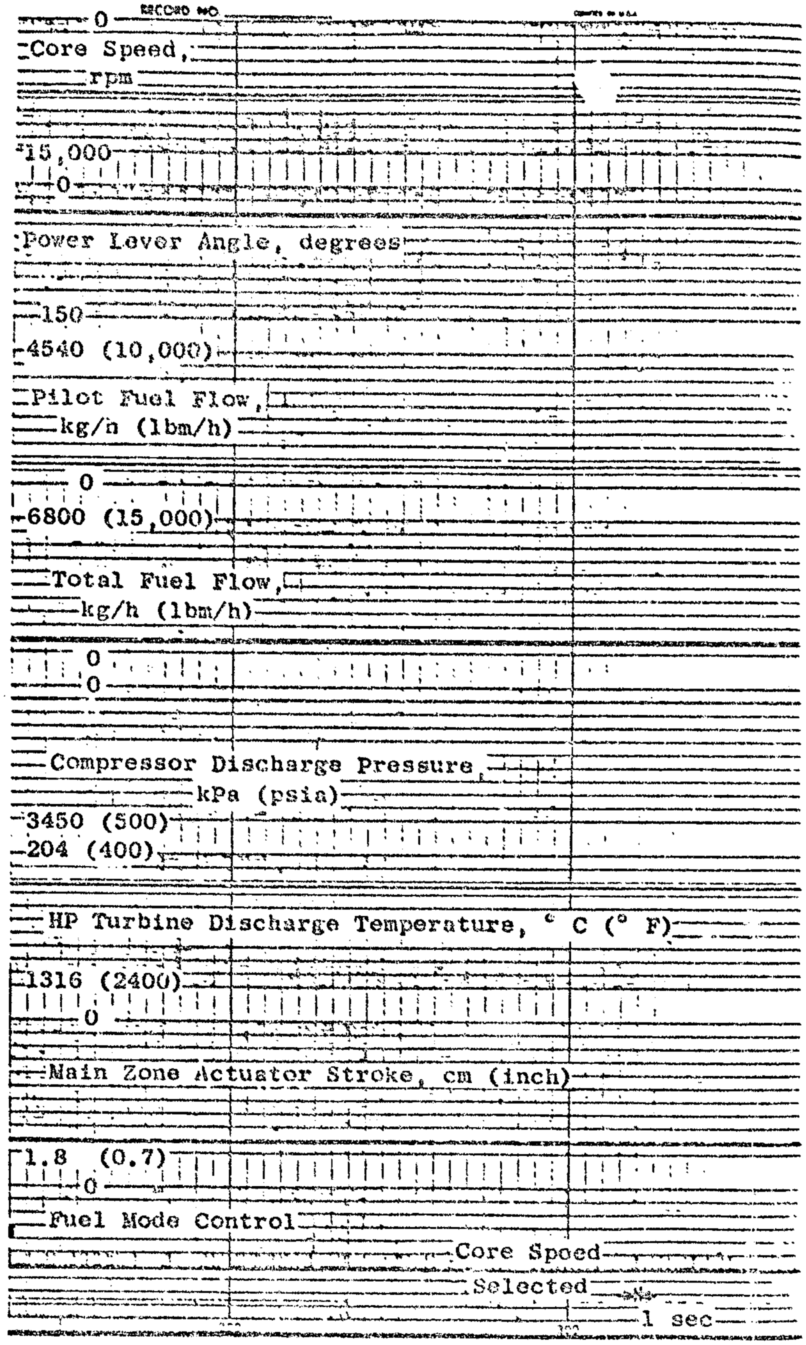

Figure 54. Speed Governing Instability.

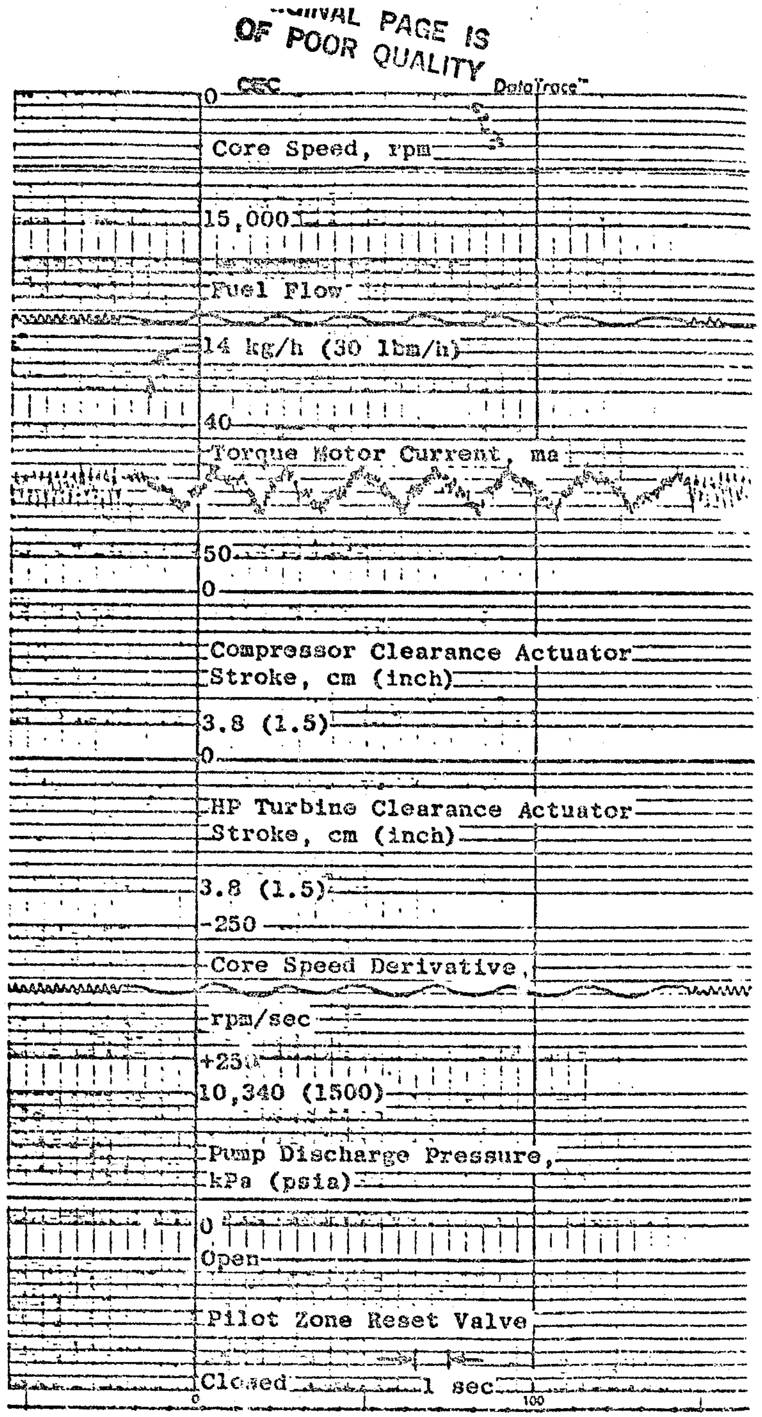

Figure 54. Speed Governing Instability (Concluded).

removed and an o-ring was found to be defective. The defective o-ring was replaced and the control was returned to the engine. No further leakage was observed during engine test.

7.3 DOUBLE ANNULAR COMBUSTOR CONTROL

Transition from single to double annular combustion initially proved only partly successful because of leaky fuel nozzle check valves which allowed manifold leakage and resulted in delayed initiation of main zone fuel while the manifold refilled. It was necessary to utilize the manual fuel split control mode capability to allow complete main manifold filling and achieve successful transitions to double annular combustion. Figure 55 shows a succcessful transition. Note the long main zone manifold fill time prior to closing the pilot zone valve and fully opening the main zone valve.

ICLS control strategy was modified to automatically transition from single annular to double annular combustion by the addition of adjustable timing of pilot zone reset valve and main zone shutoff valve sequencing.

7.4 ACTIVE CLEARANCE CONTROL

The compressor and HP turbine clearance control features were thoroughly explored during core testing, utilizing manual control loops. Casing thermocouples, intended for use for the automatic clearance control modes, proved to be incompatible with the FADEC. The core test thermocouples being used were grounded, while the FADEC requires insulated thermocouples. These thermocouples were insulated for ICLS testing. DMS data taken from core engine thermocouples in the same location were used to design the casing temperature scheduled for the ICLS control strategy.

7.5 START RANGE TURBINE COOLING SYSTEM

The start range turbine cooling valves which were supposed to be open during starting and closed at idle and above did not close as intended. The reason for this is unknown. The solenoid valve which ports either ambient or compressor discharge pressure to the start range turbine cooling valves was exercised during the controls systems test and was functional. Both start

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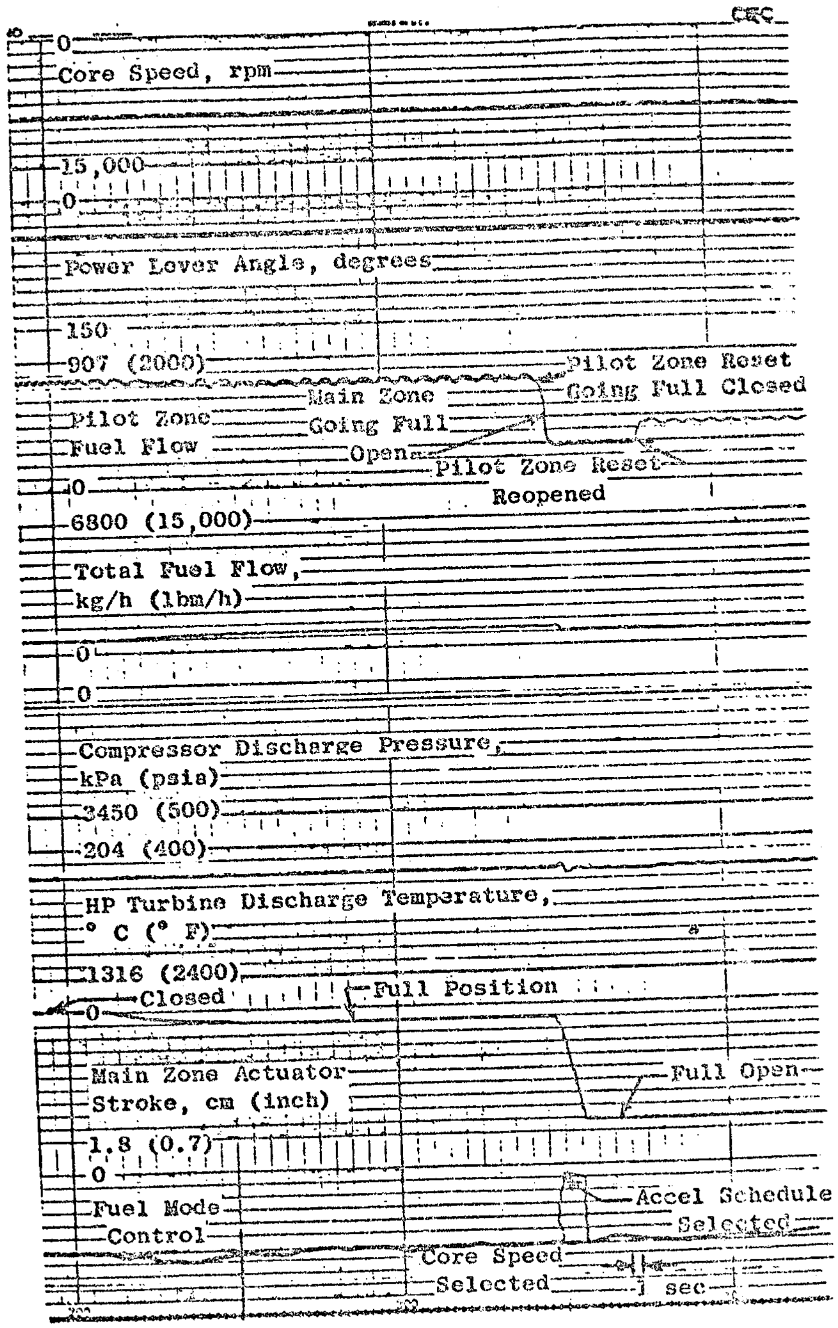

Figure 55. Switch From Single-to Double-Annular Combustion.

range turbine cooling valves were tested by the supplier and again in a component test cell and found to be functional. The engine piping was installed as intended and the solenoid would "click" when activated during a post-test investigation.

Successful starting without the use of 7th stage bleed deleted the requirement for the start range turbine cooling system and this system was removed from the engine early in the core test program.

7.6 STARTING

Provisions were made for variable 7th stage compressor bleed (up to 20 percent) and for simultaneous use of two large air turbine starters (Hamilton Standard PS600-3 starters). Testing revealed however that automatic starts can be made at simulated sea level static conditions using only one starter and without bleed. Light-off speed was progressively reduced from 35% to 20% speed and the starting fuel schedule was progressively increased to the point that, with fixed 5th stage compressor stator and no starting bleed, a measured start time of 46.5 sec. was achieved.

NOTE: Actual time from fuel initiation to governor cutback was 29 seconds. Starter air pressure was raised slowly resulting in a longer than necessary accel to the fuel initiation point. On an aircraft, starter pressure is brought up quickly so that a more realistic start time would be less than 40 seconds.

Figure 56 is a plot of start times showing the effects of fuel schedule increases and of changes in the speed at which fuel is introduced into the combustor.

Figure 57 and 58 are transient plots of starts 27 and 29 which show the relationship between core speed, corrected fuel flow and corrected compressor discharge pressure. Figure 59 is the Sanborn recording for start 27. Core speed must exceed 831 RPM (minimum FADEC detectable speed) before the speed derivative signal will respond. A lag in the core speed instrumentation

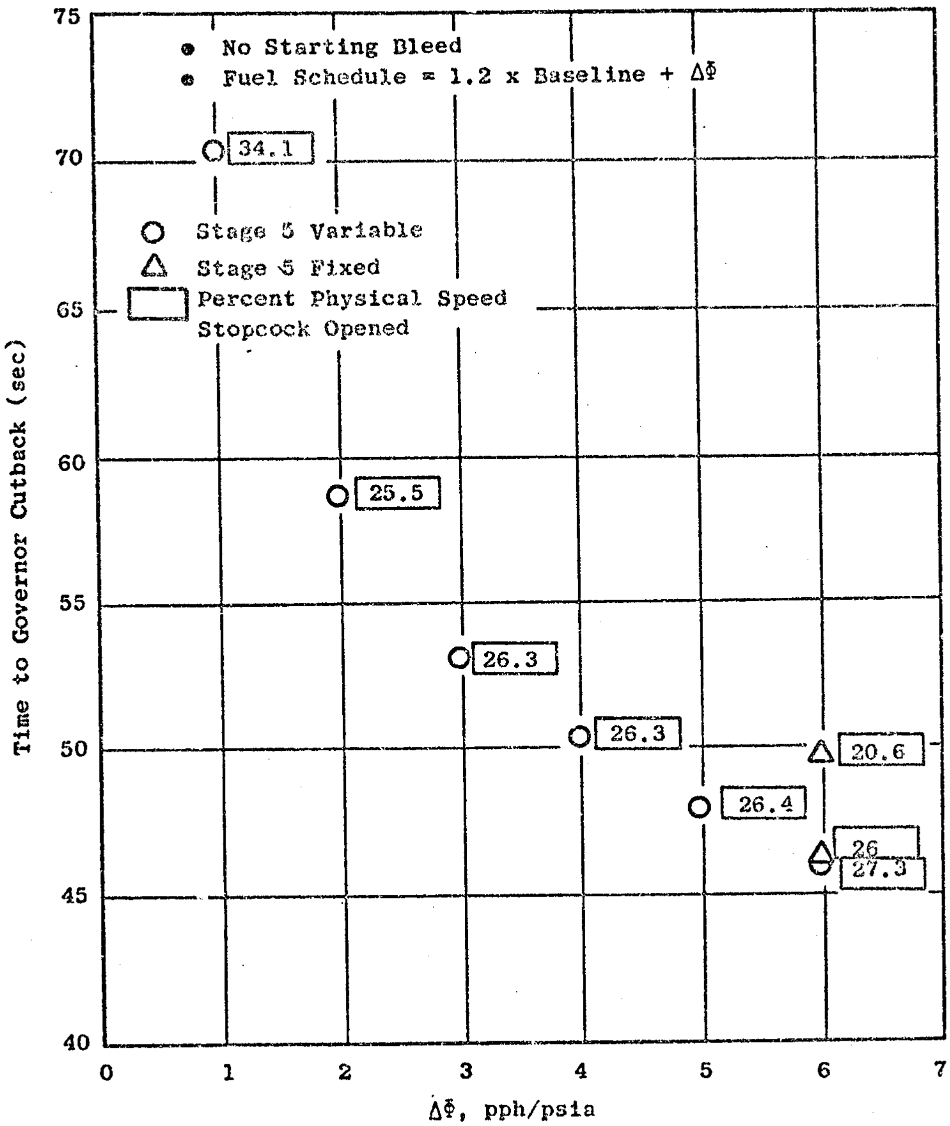

Figure 56. Start Time Investigation.

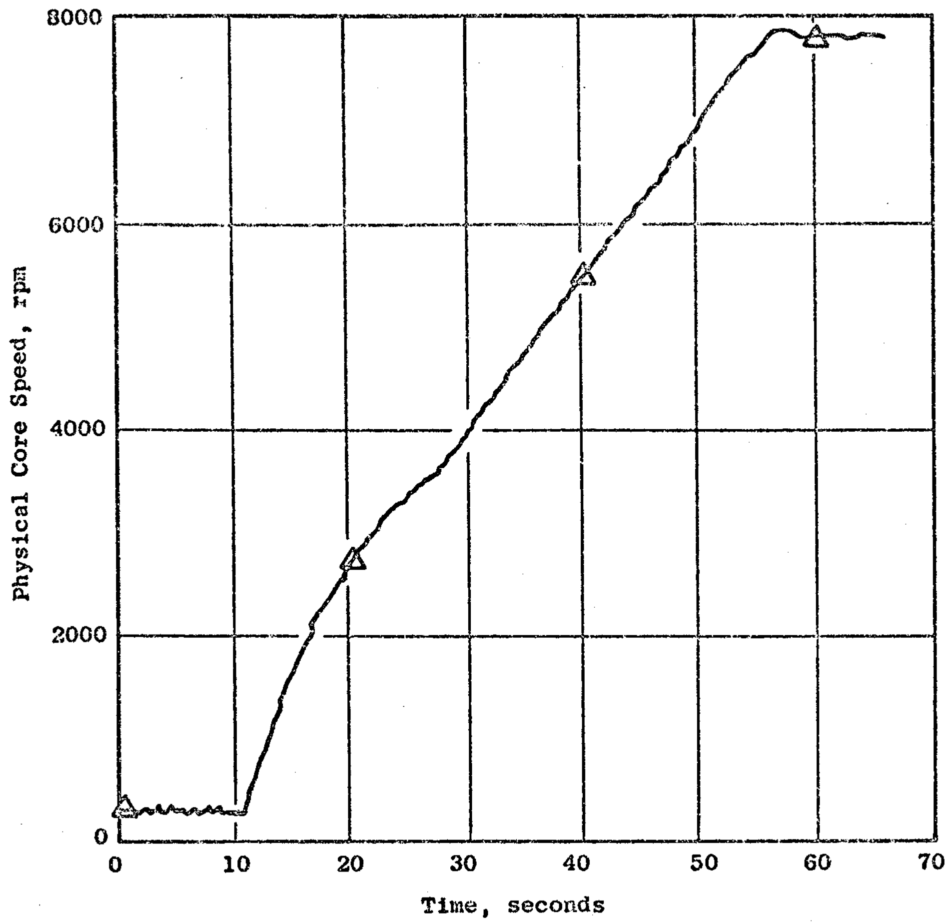

Figure 57. Start No. 27 - Transient Plot.

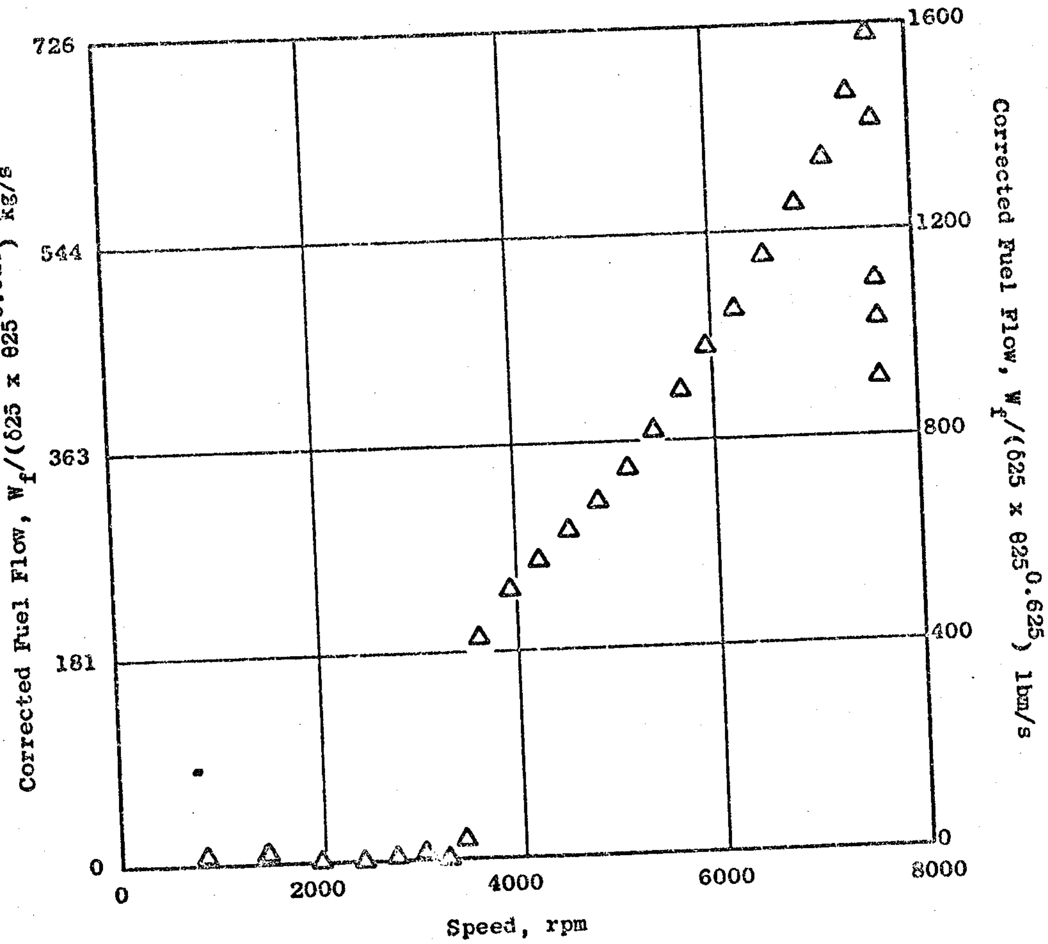

Figure 57. Start No. 27 - Transient Plot (Continued).

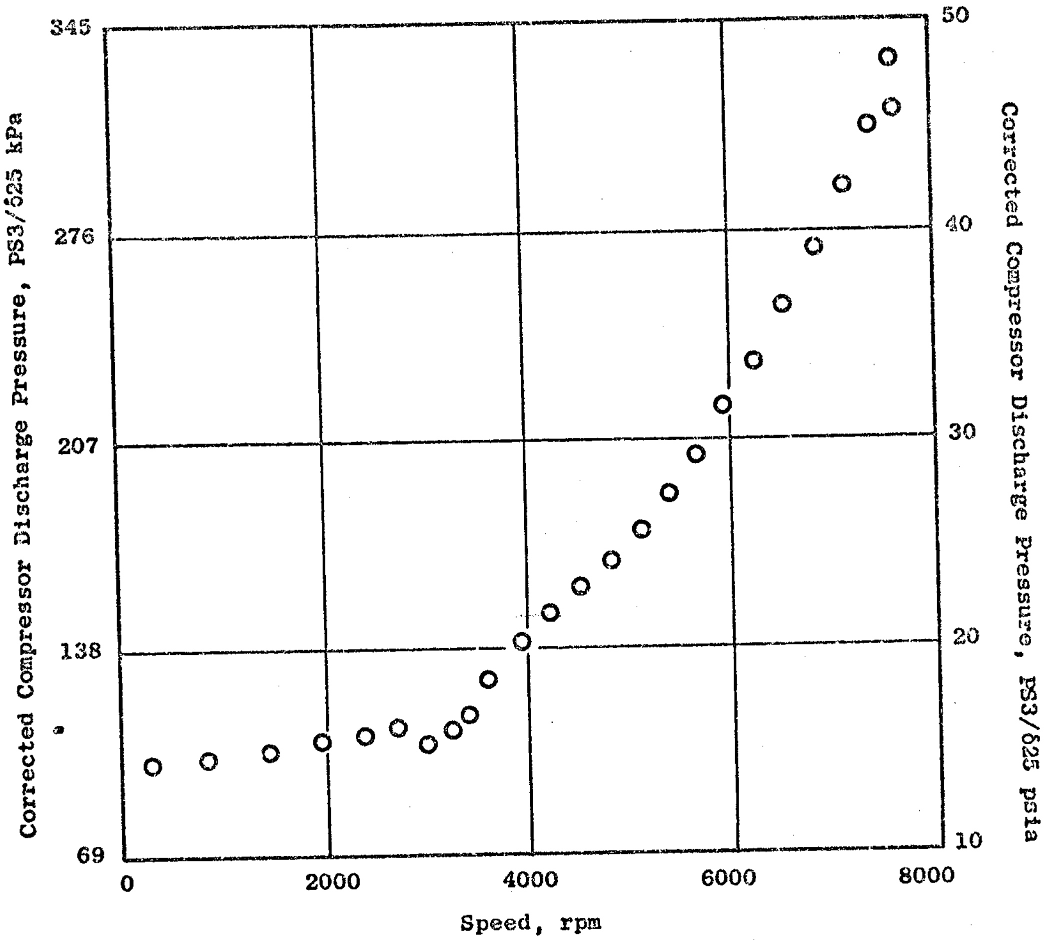

Figure 57. Start No. 27 - Transient Plot (Concluded).

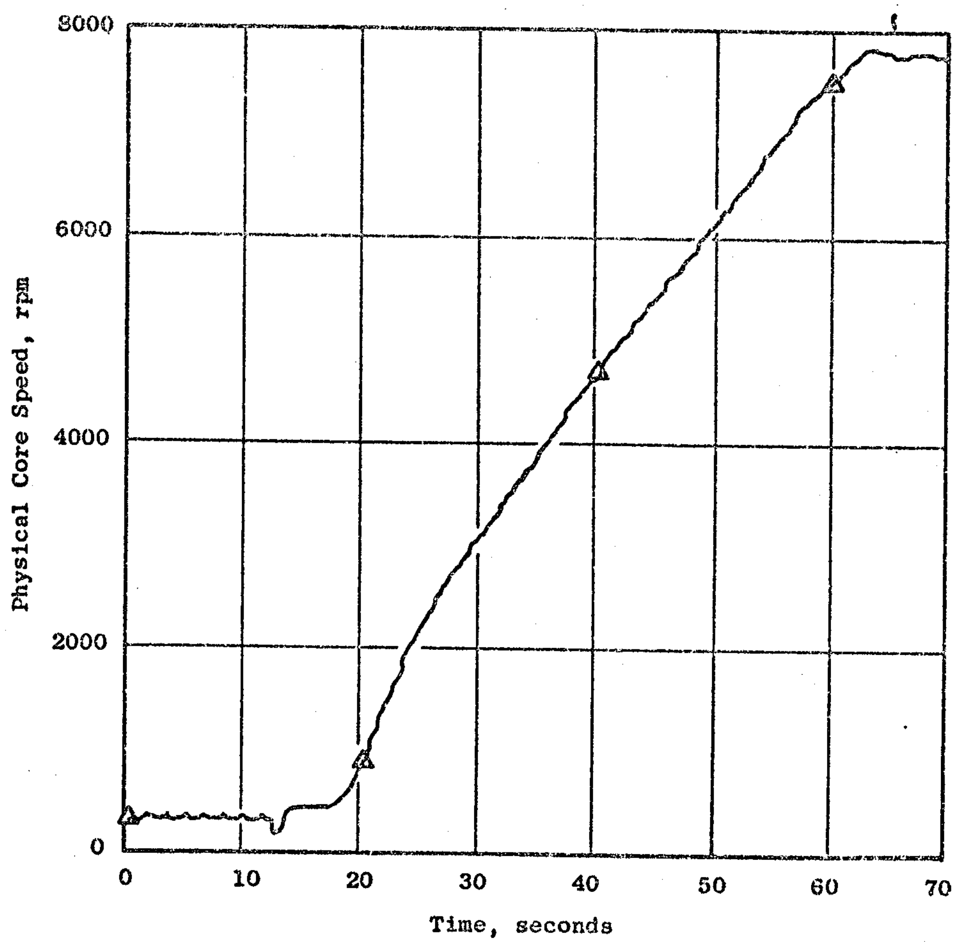

Figure 58. Start No. 29 - Transient Plot.

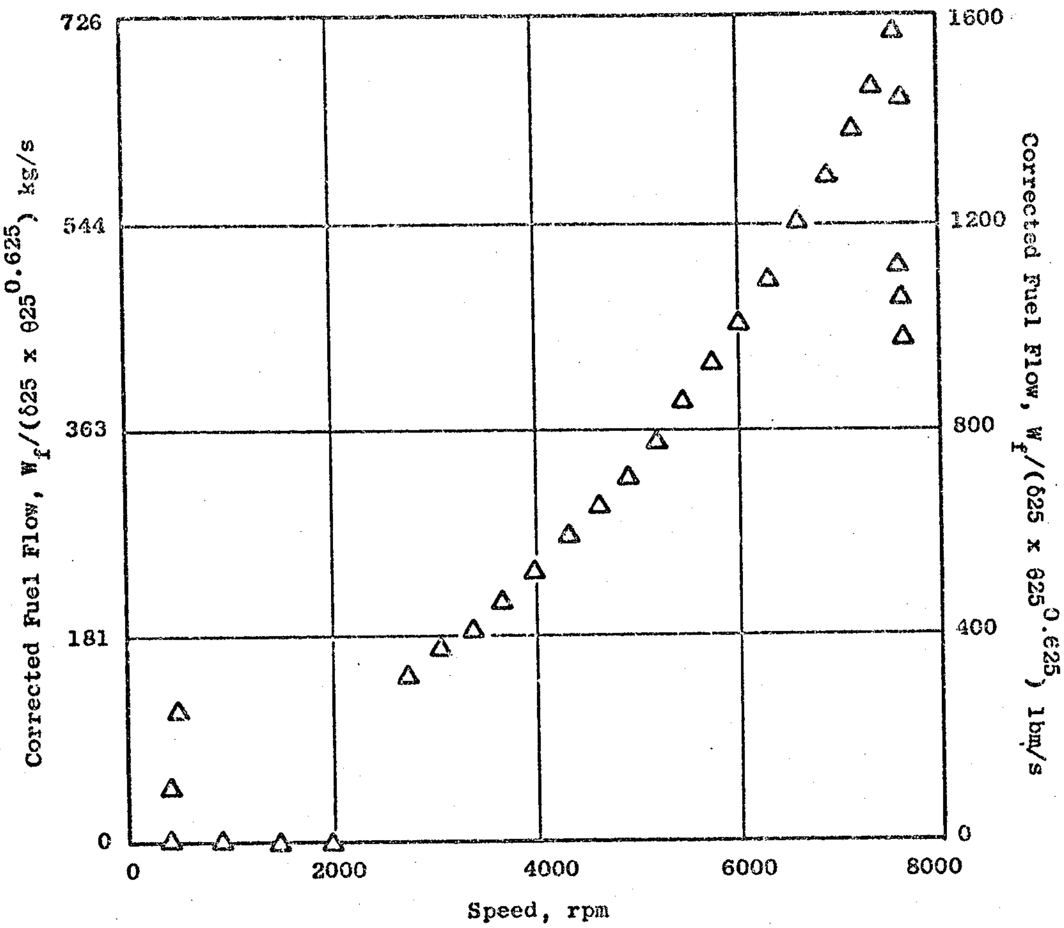

Figure 58. Start No. 29 - Transient Plot (Continued).

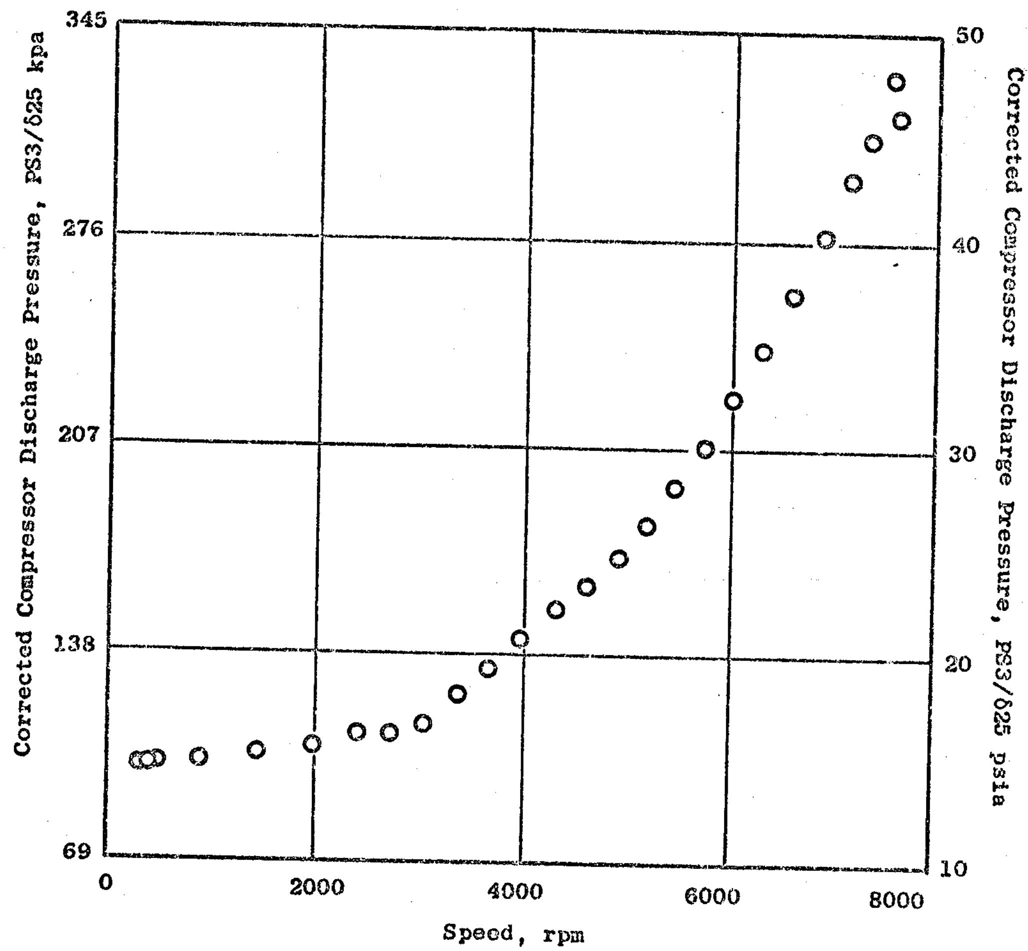

Figure 58. Start No. 29 - Transient Plot (Concluded).

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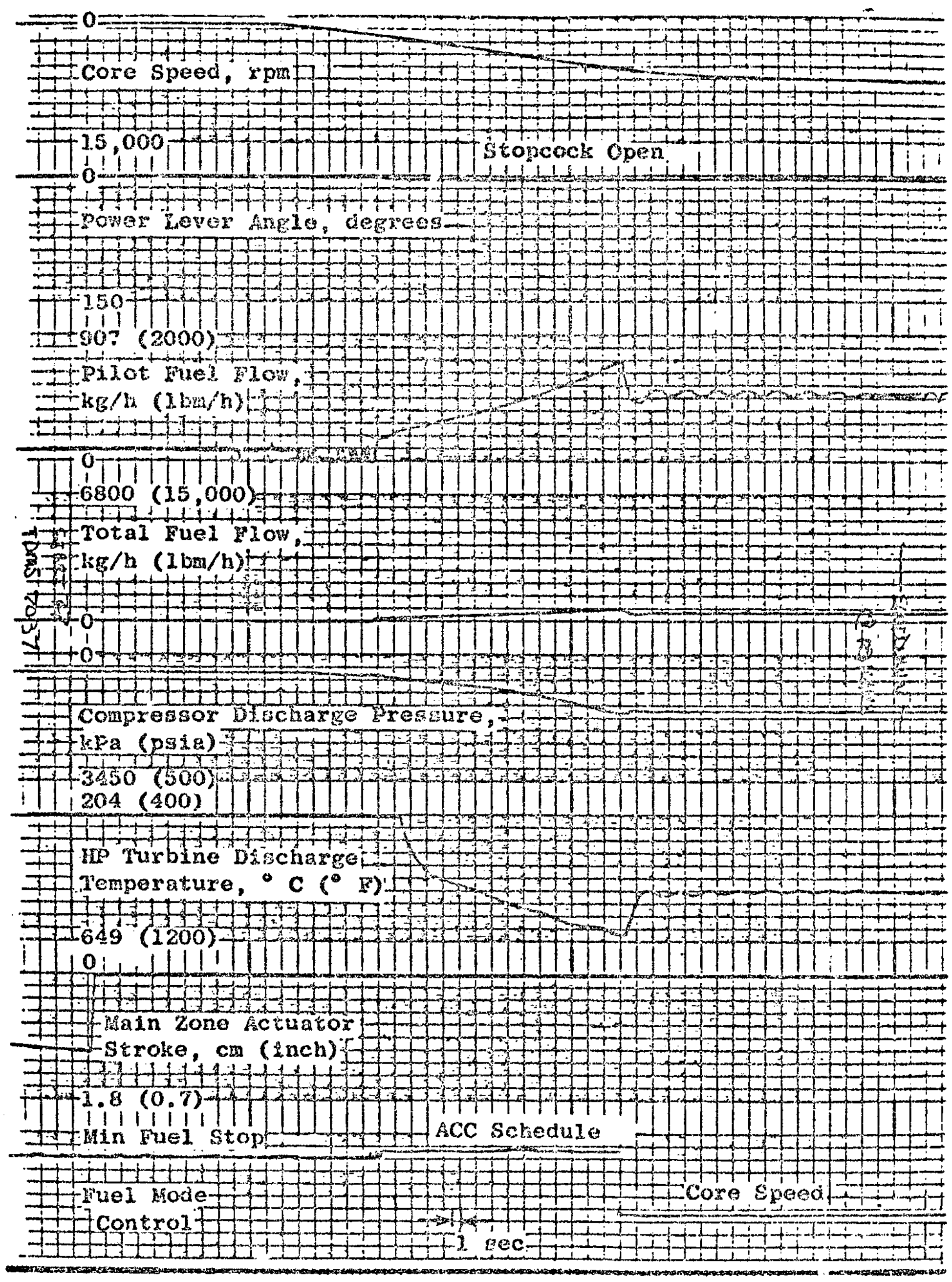

Figure 59. Start No. 27.

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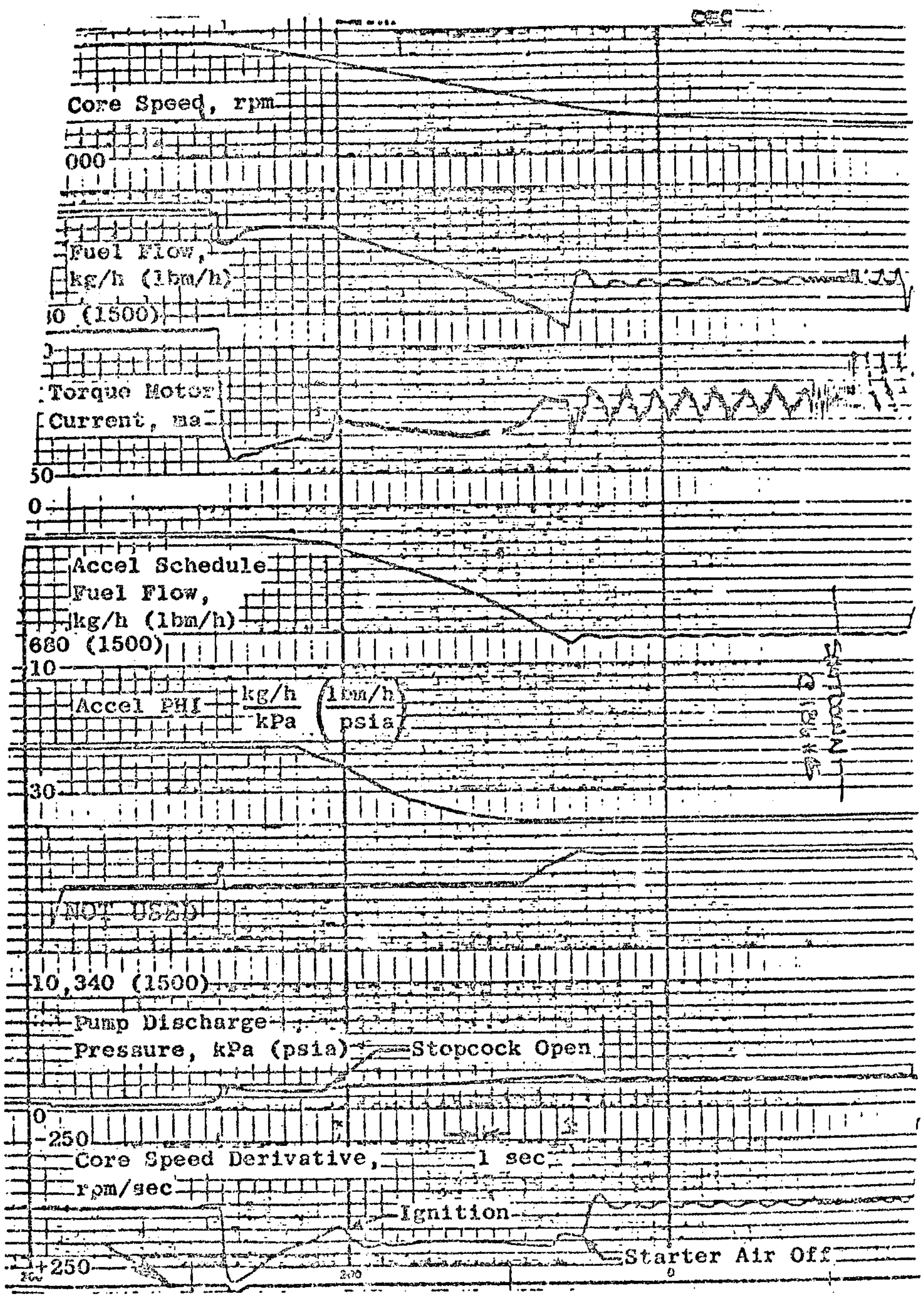

Figure 59. Start No. 27 (Concluded).

causes channel 1 (sensed speed) to continue to increase after fuel flow cutback. Figure 57 shows the correct representation of speed during auto start 27.

No evidence of compressor stall or turbine overtemperature was encountered during any core engine start.

Start times would have been less if actual starter output performance had been as expected and if starter pressure had been brought up more rapidly. It is estimated that, for reasons not known at this time, the performance of the starter was approximately 28.5% low in starter torque.

The conclusion that the starter has reduced output performance is based on the following analysis:

1. Core engine rotor unbalanced torque characteristics were calculated from unfired engine coastdown data as shown in Figure 60. The engine was motored with a Hamilton Standard PS600-3 starter (built for the RB211) to a stabilized maximum motoring speed point and the starter inlet conditions measured in order to calculate starter output torque using the pre-test predicted starter performance curves shown in Figure 61. The calculated starter output torque point was much higher than the core engine unbalanced torque calculated from engine coastdown data, indicating that the actual starter output torque was approximately 28.5% lower than predicted from the estimated performance curves.

2. Additional analyses of engine and starter torque were made at the starter cut-out region for start 27. Starting data were sampled 10 times per second and an accurate calculation of net engine rotor torque was made based on measured acceleration rate and rotor characteristics. Corresponding calculations were made of starter torque based on starter inlet data and pre-test predictions of starter performance. The difference between these two torque levels is the unbalanced torque between the turbine and compressor and it was plotted as shown on Figure 62. There should be no discontinuity in this unbalanced torque when the starter is cut off

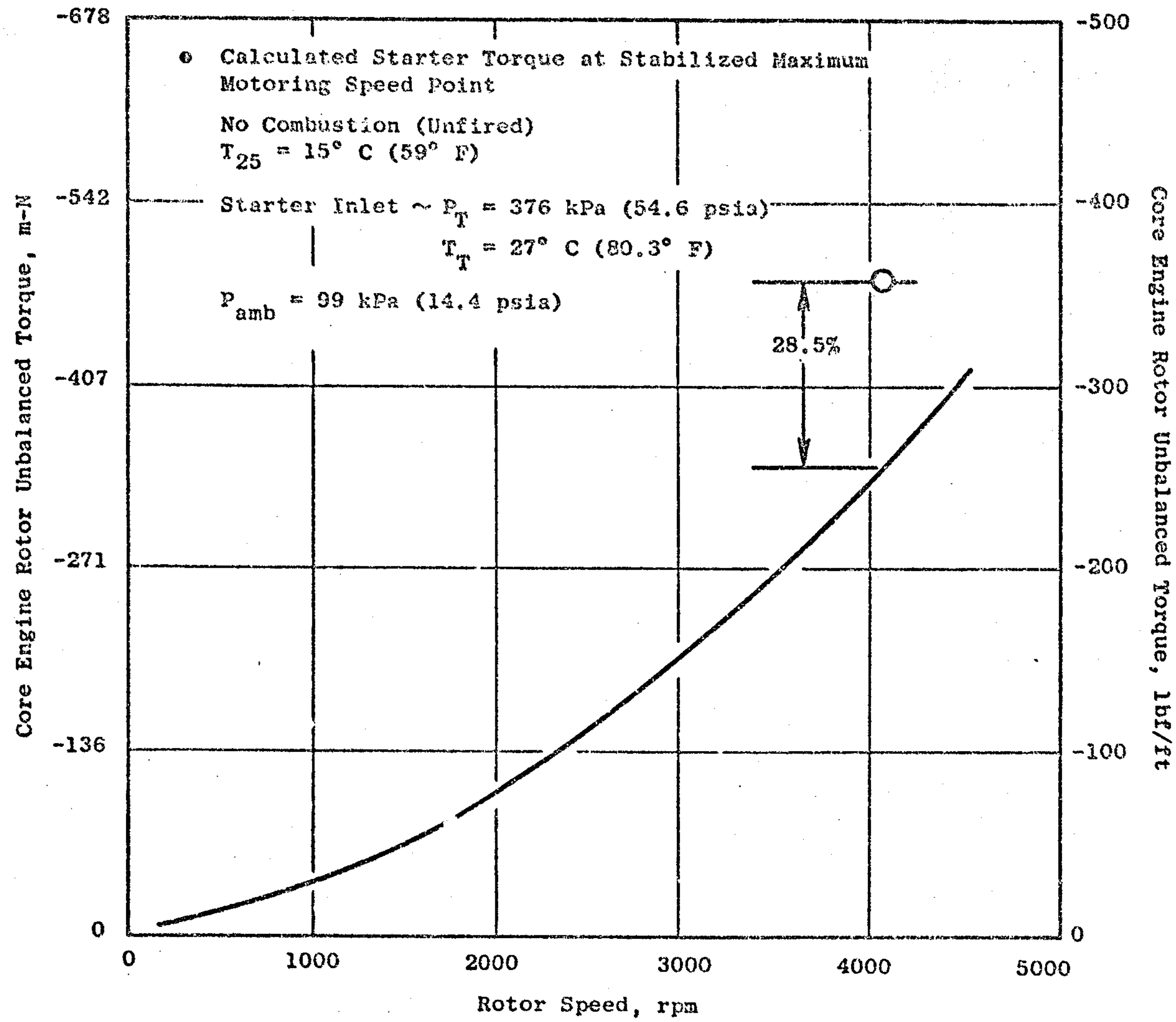

Figure 60. Core Engine Unbalanced Torque.

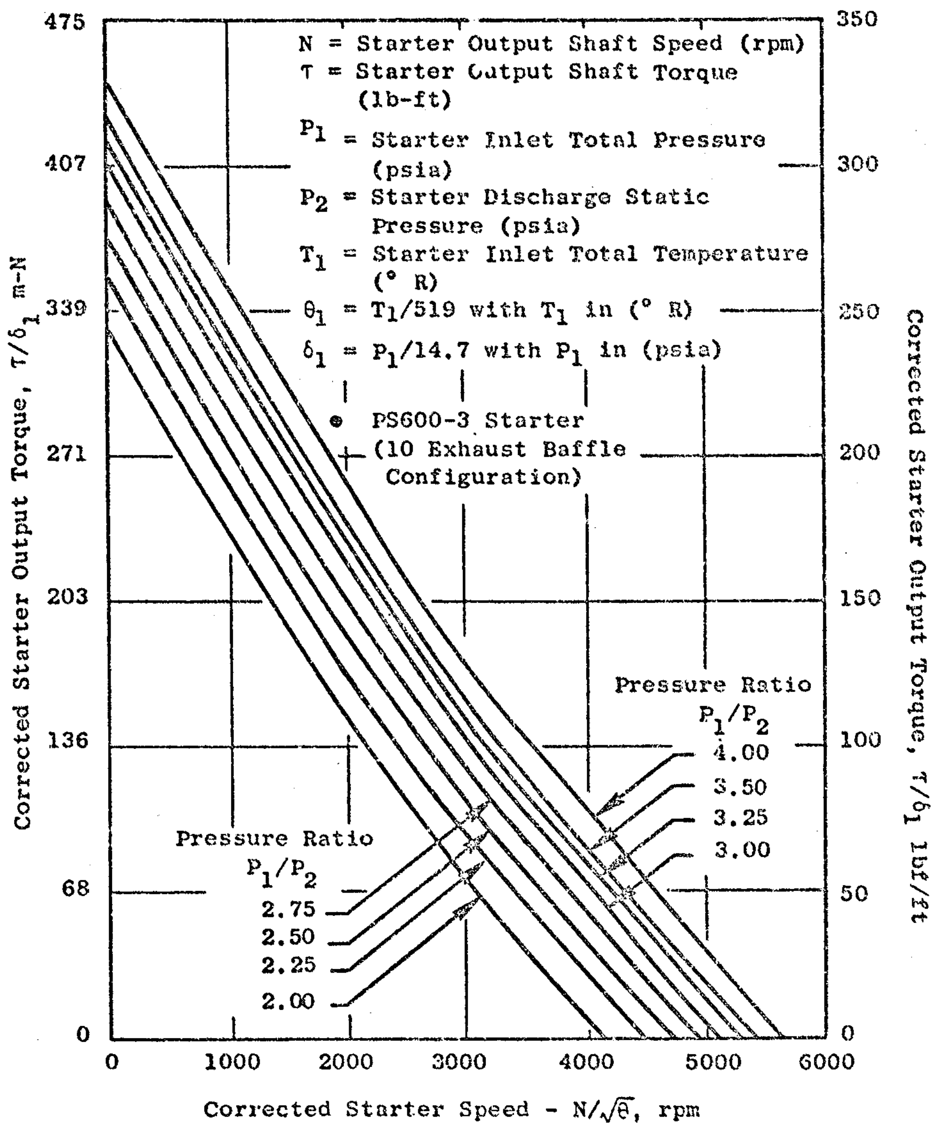

Figure 61. Pretest Predicted Starter Performance.

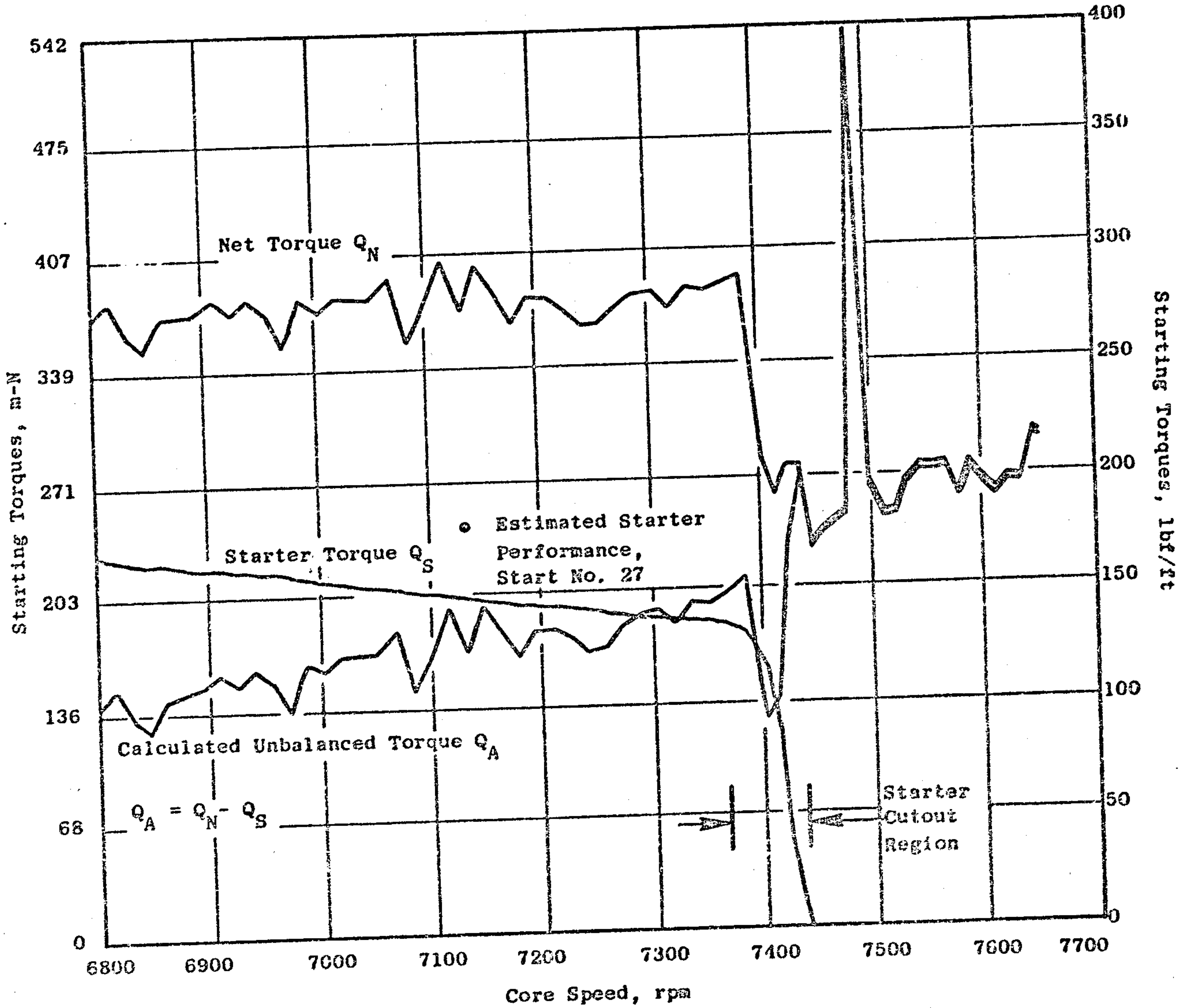

Figure 62. Core Engine Unbalanced Torque Characteristics.

because there is no abrupt change in cycle variables affecting this torque but the plot shows a step increase. This suggests that actual starter torque was lower than predicted. Figure 63 is a similar plot with the starter derated 28.5 percent below pre-test predictions. The absence of an unbalanced torque discontinuity at the starter cut-off point supports the conclusion that starter torque was approximately 28.5 percent low. The actual cause of the low starter torque is being investigated. The starter was returned to Hamilton Standard for test. Additional starter discussion is contained in the ICLS vehicle test results section.

The starting fuel schedule for the ICLS was redesigned and incorporated into the ICLS control strategy. Redesign was necessary because the actual steady state operating line (fuel flow/compressor discharge pressure vs. speed) was substantially higher than the pretest predicted operating line in the start region. The steady state pre-test and actual operating line comparisons and the pre-test core accel fuel schedule comparisons are shown in Figure 64.

For the same inlet conditions as during core engine testing, ICLS start times would be expected to be under 45 seconds. However, actual ICLS start times may be longer than this due to higher gearbox torques caused by increased oil vicosity at the lower ambient temperatures expected during ICLS testing.

7.7 SUB-IDLE EXPLORATION

The FADEC manual fuel control mode provided precise, stable, steady state control of the engine in the sub-idle region, making it possible to gather valuable data relative to the start testing results reported above.

7.8 SENSOR ACCURACY

Control system sensing accuracy was assessed by comparing control system data on the following variables with corresponding data from the extensive performance instrumentation on the engine.

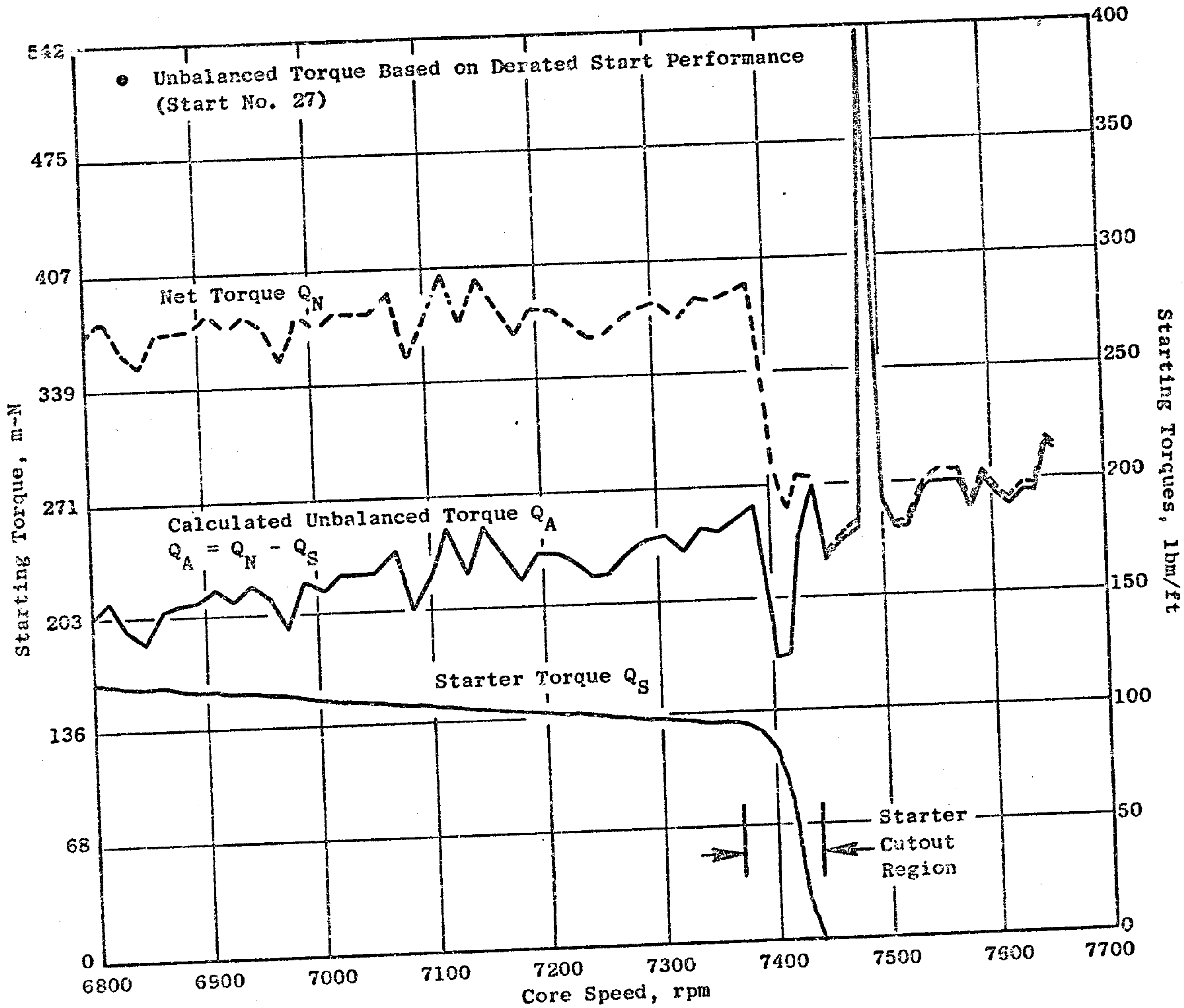

Figure 63. Estimated Starter Performance (Except Derated by 28.5%).

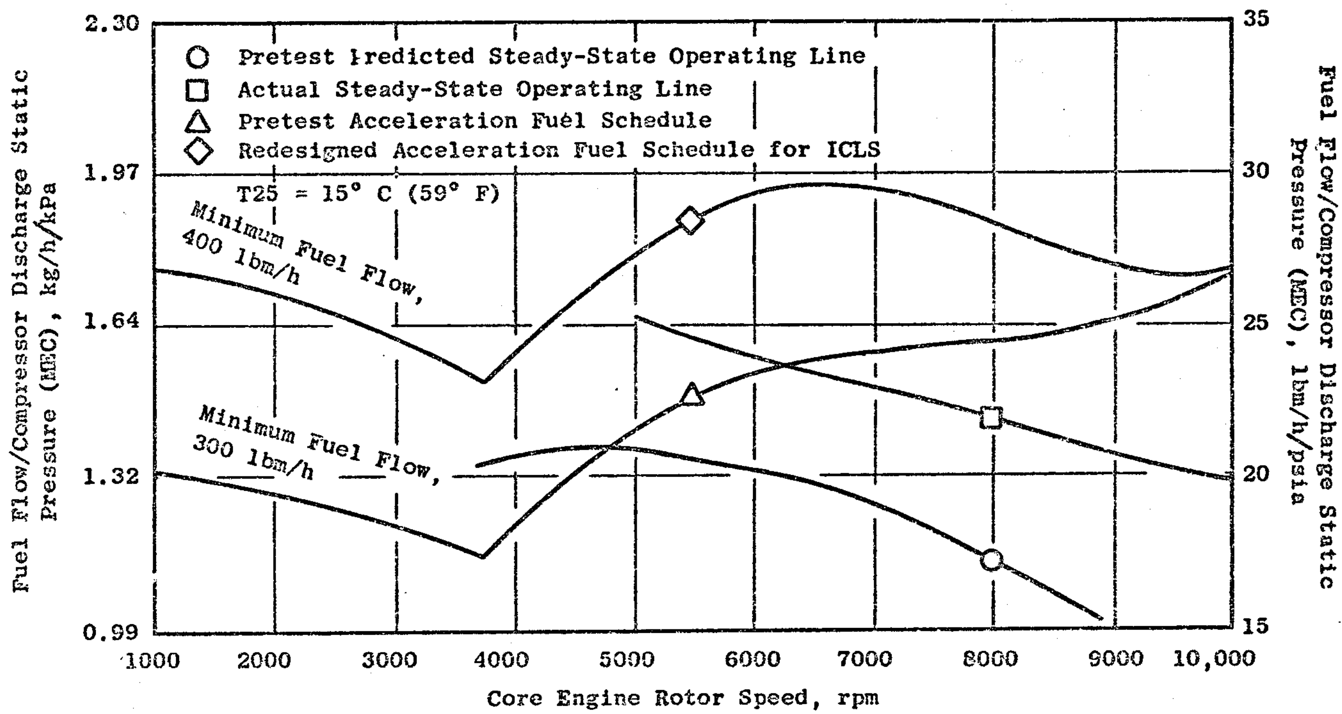

Figure 64. Starting Acceleration Fuel Schedule.

1. Compressor inlet temperature (T25)
2. Compressor discharge temperature (T3)
3. HP turbine discharge temperature (T42)
4. Compressor discharge pressure (PS3)
5. Total fuel flow (WF36)
6. Calculated HP turbine inlet temperature (T41)

The results of this comparison are given in Table 5. Inspection of this table indicates that all FADEC sensors are very close to cell instrumentation except for T42 in the low speed region. This is caused by the different temperature profile with single annular combustion. The FADEC uses thermocouples in only three of the five radial locations sensed by the test instrumentation.

7.9 FADEC CONFIGURATION

The FADEC used for this core engine testing was control room mounted. The same electrical dsign was implemented in a newly designed on-engine configuration for the ICLS engine.

TABLE 5

FADEC SENSOR ACCURACY

Table 5 tabulates engine instrumentation and the deviations of the FADEC data from this instrumentation.

Reading	PCN25R (RPM)	T25 (°R)	K	ΔT25 (% Point) Diff	T3 (°R)	K	ΔT3 (% Point) Diff	T42 (°R)	K	ΔT42 (% Point) Diff
**235	61.15	(529.7)	294.3	-.34	(826.3)	459.1	-1.97	(1396.2)	775.7	+9.07
**237	68.51	(531.8)	295.4	-.28	(884.9)	491.6	- .87	(1380.8)	767.1	+6.44
**238	76.54	(532.0)	295.5	-.24	(969.3)	538.5	-1.24	(1381.7)	767.6	+4.26
242	85.01	(532.5)	295.8	-.15	(1090.4)	605.8	- .54	(1442.4)	801.3	+ .6
248	89.53	(528.4)	293.5	+.07	(1157.6)	643.1	-1.07	(1515.7)	842.1	-1.58
251	92.30	(540.2)	300.1	+.11	(1249.7)	694.3	-1.14	(1709.4)	949.7	- .32
254	95.36	(541.6)	300.9	+.11	(1337.3)	742.9	-1.15	(1915.0)	1063.9	- .31
256	97.28	(541.4)	300.8	+.37	(1383.2)	768.4	-1.53	(2009.7)	1116.5	- .91
258	98.12	(542.7)	301.5	+.64	(1408.7)	782.6	-1.67	(2035.1)	1130.6	-1.09

Reading	PS3 (PSIA)	KPa	ΔPS3 (% Point) Diff	Kgm (PPH)		ΔWF36 (% Point) Diff	T41	(°K)	ΔT41* (% Point) Diff
235	(43.54)	300.21	- .98	(1001.5)	454.3	-2.04	(1800.5)	1000.3	-2.95
237	(53.44)	368.47	- .69	(1189.4)	539.5	-2.29	(1819.6)	1010.9	-2.61
238	(73.58)	507.33	- .03	(1611.9)	731.2	-2.39	(1886.1)	1047.8	-2.60
242	(111.19)	766.66	+ .04	(2474.5)	1122.4	- .93	(2055.1)	1141.7	+ .02
248	(155.22)	1070.24	- .06	(3665.3)	1662.6	- .84	(2188.3)	1215.7	- .64
251	(190.67)	1314.67	- .27	(5023.1)	2278.5	- .12	(2458.5)	1365.8	+ .50
254	(241.43)	1664.66	- .63	(7137.5)	3237.6	- 1.3	(2742.1)	1523.4	+ .07
256	--		--	(8536.1)	3872.0	- 2.4	(2869.0)	1593.9	-1.11
258	--		--	(9075.0)	4116.4	- 2.47	(2920.8)	1622.7	- .84

*FADEC T41 Calculation adjusted by 135 degrees to match test experience

**Single Annular Combustion

8.0 ICLS CONTROL SYSTEM PERFORMANCE

The ICLS control system with its new, engine-mounted FADEC, performed very well throughout the engine test program. Accurate, predictable, responsive control of all controlled variables was provided and flexibility incorporated in the system served well in accommodating unexpected differences from pretest predictions relative to transient fuel flow requirements and active clearance control system characteristics. There were no control system component failures.

Highlights of the control system operation are given below.

8.1 STARTING

The first eight starts were made by motoring to maximum motoring speed (i.e., setting starter air pressure at 380 kPa (55 psia) and holding until core speed stabilized), opening the stopcock until ignition occurred, and then manually increasing fuel flow until idle speed was achieved. Figure 65 shows a typical manual start.

All subsequent starts (9 through 28) were made with automatic scheduling of fuel flow. Automatic starts were made with progressive fuel enrichment, ultimately using a schedule that was higher than the design schedule by approximately 70% at cranking speed and by 50% near ground idle. There was no evidence of compressor stall during any engine start.

Figures 66 and 67 are two successive starts which demonstrate the potential for a 44-second start. Figure 66 is a start with normal stopcock opening (20% PCHHR - approximately 2500 RPM at these inlet conditions). Figure 67 is the maximum enriched start. Stopcock opening was delayed here because of a false indication of high engine vibrations but if it had been opened at 20% PCNHR, time for the start would have been 44 seconds.

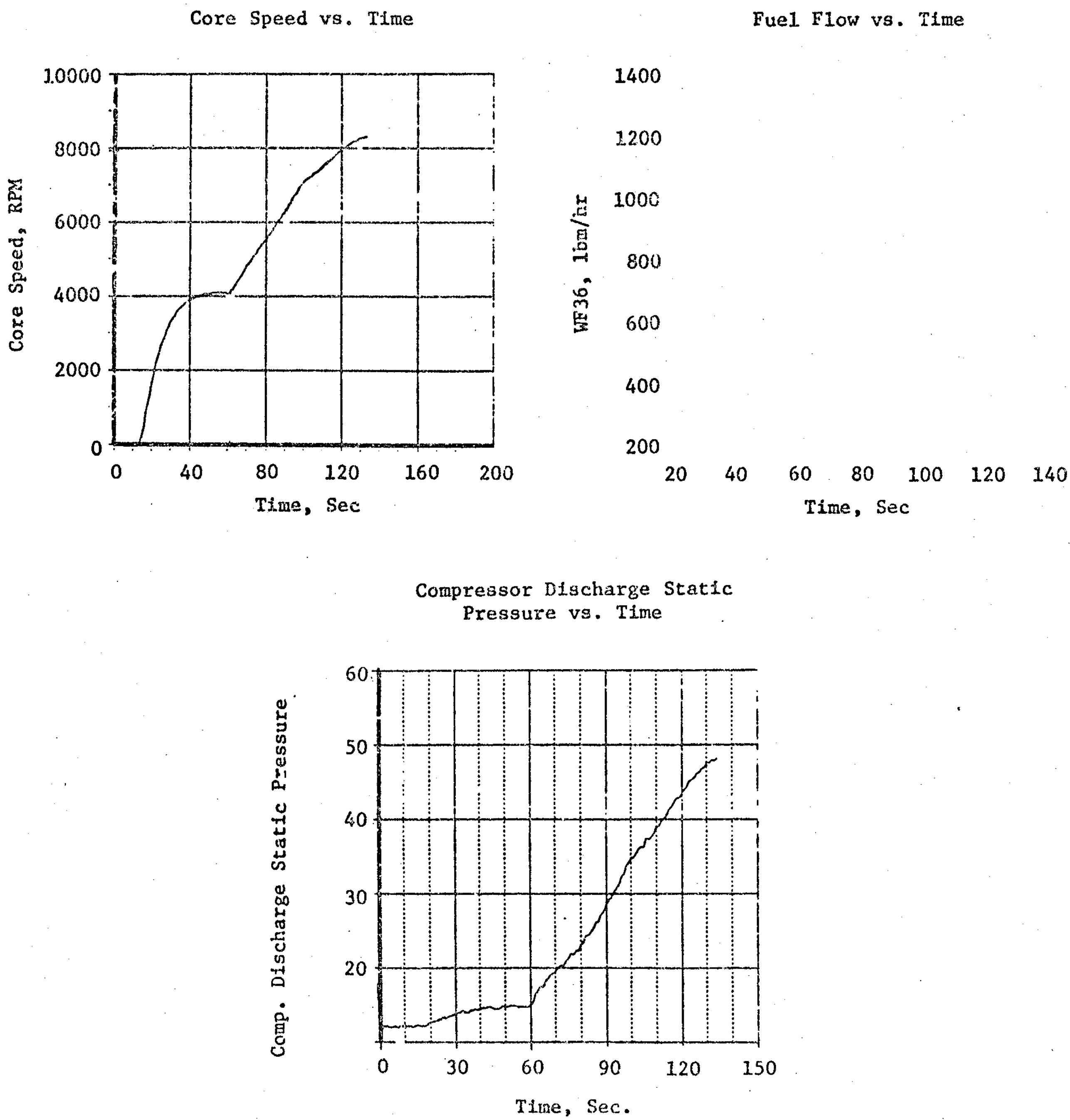

Figure 65. Typical Manual Start.

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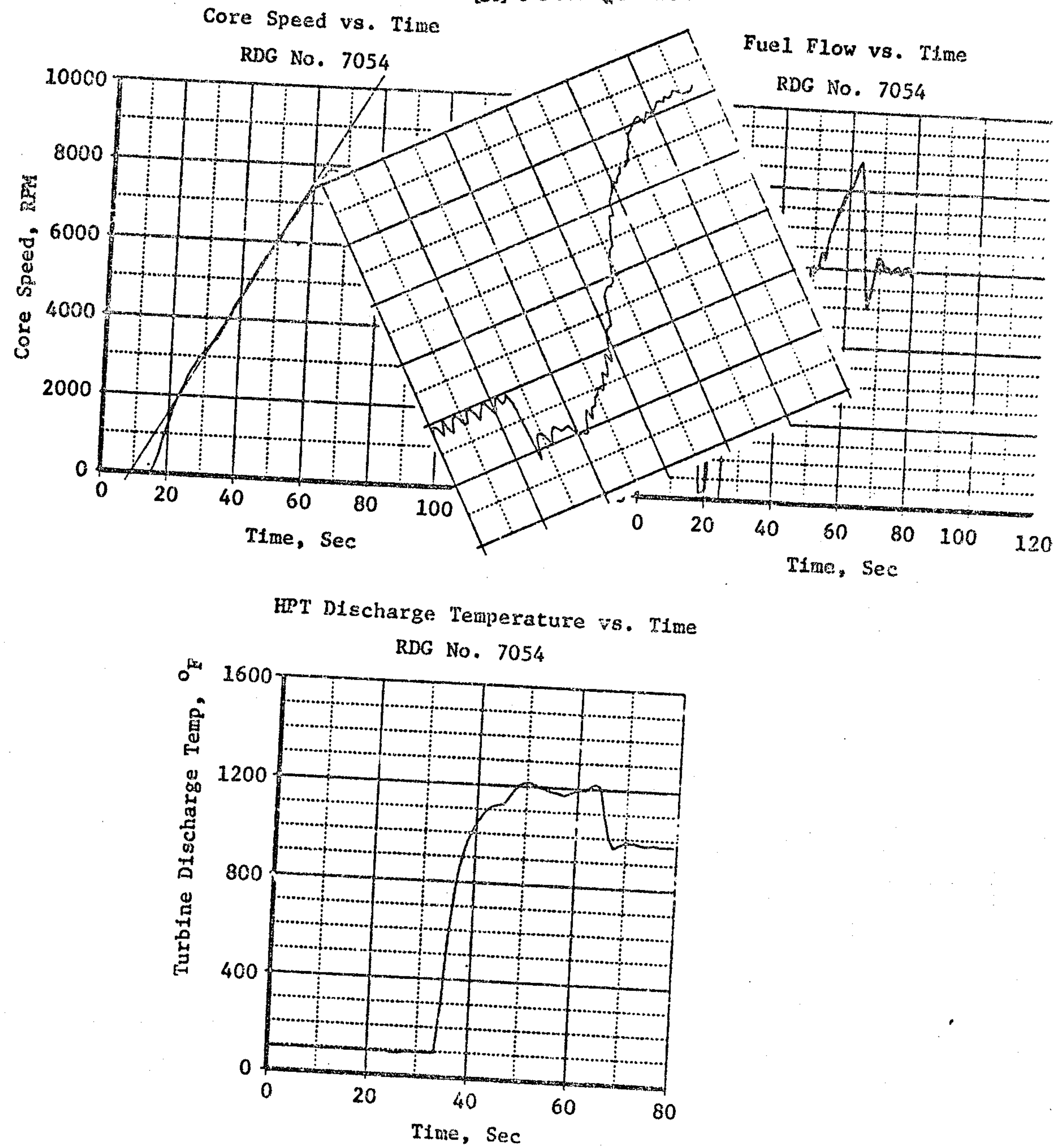


Figure 66. Start with Normal Stopcock Opening.

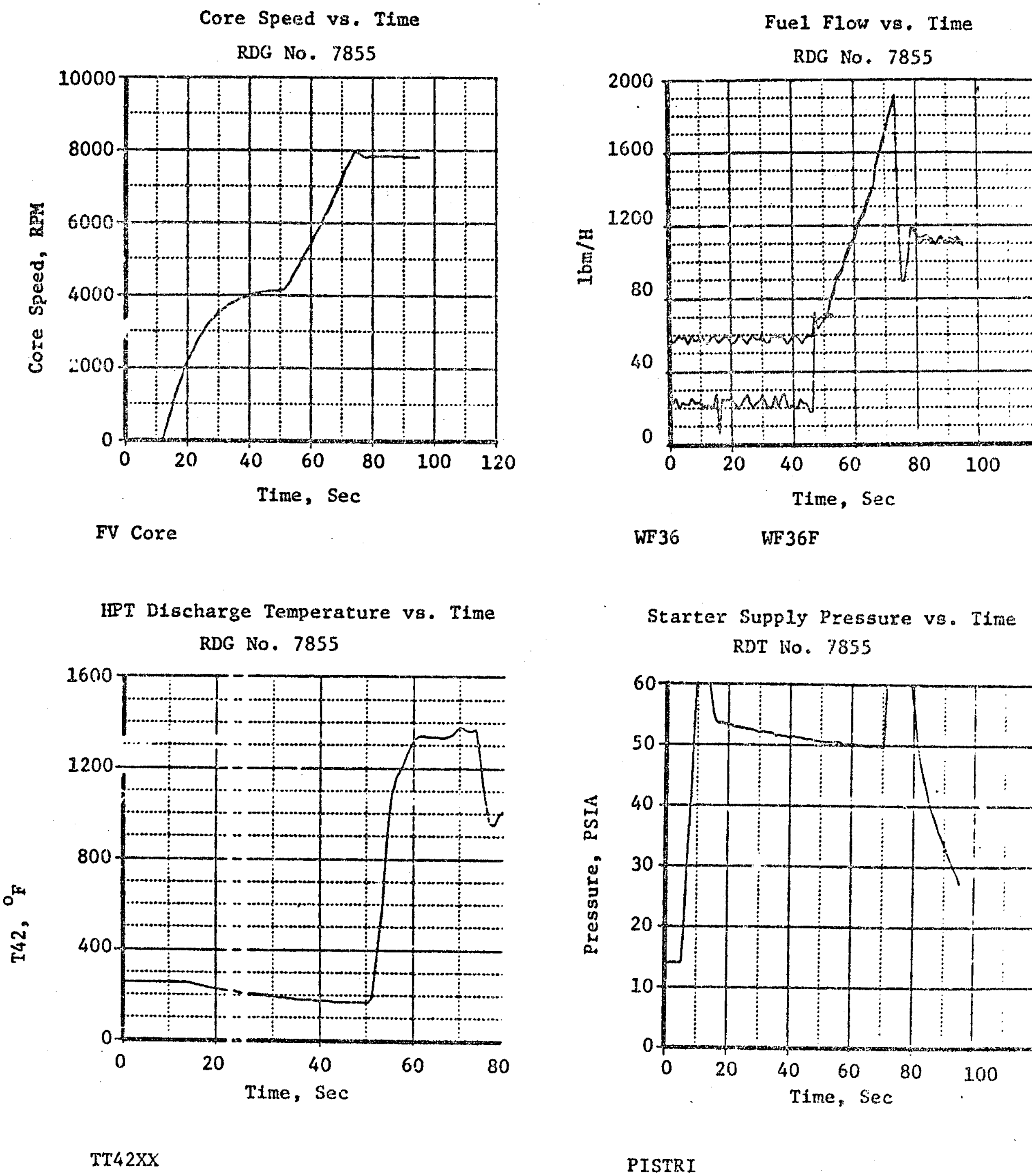


Figure 67. Maximum Enriched Fuel Schedule Start (Delayed Stopcock Opening).

Data from these starts was combined with engine motoring data and past test starter calibration data to define the general characteristics of the engine in the start range. Figure 68 is both a corrected and uncorrected plot of torque characteristics for the two enriched starts of Figures 66 and 67. Figure 68 also shows calculated torque at the highest steady state speed attained while motoring the engine with the starter as well as the torque calculated from an engine coastdown. The difference between the indicated coastdown torque and the other torque data is attributed mainly to the fact that the engine was warm during the coastdown with lower viscosity oil and different internal clearances. Figure 69 also illustrates those torque differences. Note the differences in time required to start a hot engine and cold engine. Start No. 15 was made immediately after a shutdown and start No. 16 was made after a four (4) hour shutdown. Both starts were made using the same accel schedule enrichment.

8.2 SPEED GOVERNING (CORE & FAN)

For most ICLS testing, the power lever angle (PLA) schedules for fan speed and core speed were adjusted so that the core speed schedule was in effect from idle to approximately 30% thrust and the fan speed schedule was in effect above that. Figure 70 shows steady state operation at low power and Figure 71 shows steady state operation on fan speed control at high power. Figure 72 is a steady state plot of switching from core speed to fan speed control. The trace of the mode signal is obscured because signal excursions were limited by recorder response.

These plots demonstrate the excellent speed holding capability of the FADEC and also verify that switchover between speed control modes was smooth.

8.3 FUEL FLOW LIMITS

Limits were imposed on the basic core rotor and fan speed schedules to prevent excessive HPT inlet temperature (calculated), excessive LPT inlet temperature (T42), and excessive compressor discharge pressure (PS3). These limits were combined in a selection network which established priorities and assured smooth transition between control modes.

Net Torque - Calculated from Measured Acceleration Rate and Calculated HP Rotor Polar Moment of Inertia

Starter Torque - Calculated from Measured Starter Inlet Conditions and Calibrated Starter Data Defined by Hamilton Standard on the Starter used (8/5/83)

Engine Torque - Calculated by Subtracting Starter Torque from Net Torque

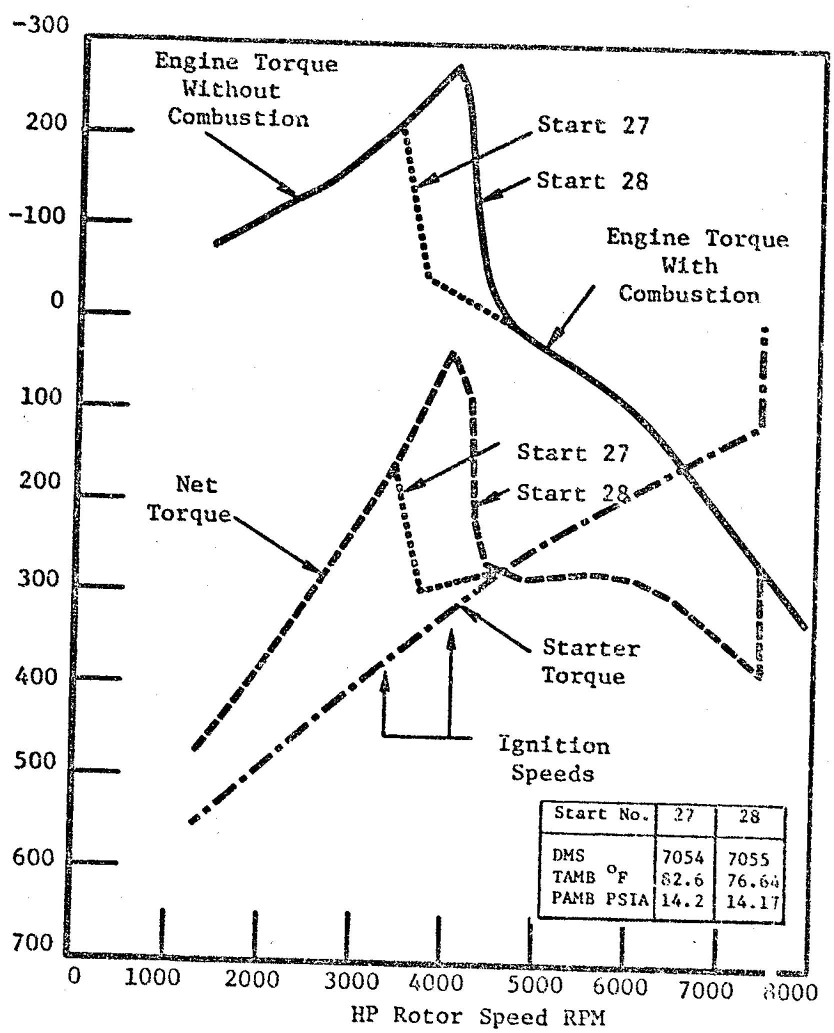


Figure 68. Engine Torque Data Maximum Enrichment (Sheet 1 of 2)

A. Start No. 28 (Ambient Engine) DMS 7055-Engine Shutdown Approx. 3 Hours Prior to Start No. 28
B. Stabilized Maximum Motoring Speed Point (Ambient Engine) DMS 23 Maximum Motoring Made Prior to the First Start of the Day (Calibrated Starter Data Used for A and B and D Calculations)
C. Engine Coastdown from Idle After Fuel Shut-off (Hot Engine) (DMS 7026)
D. Start No. 27 (Ambient Engine) DMS 7054 First Start of the Day

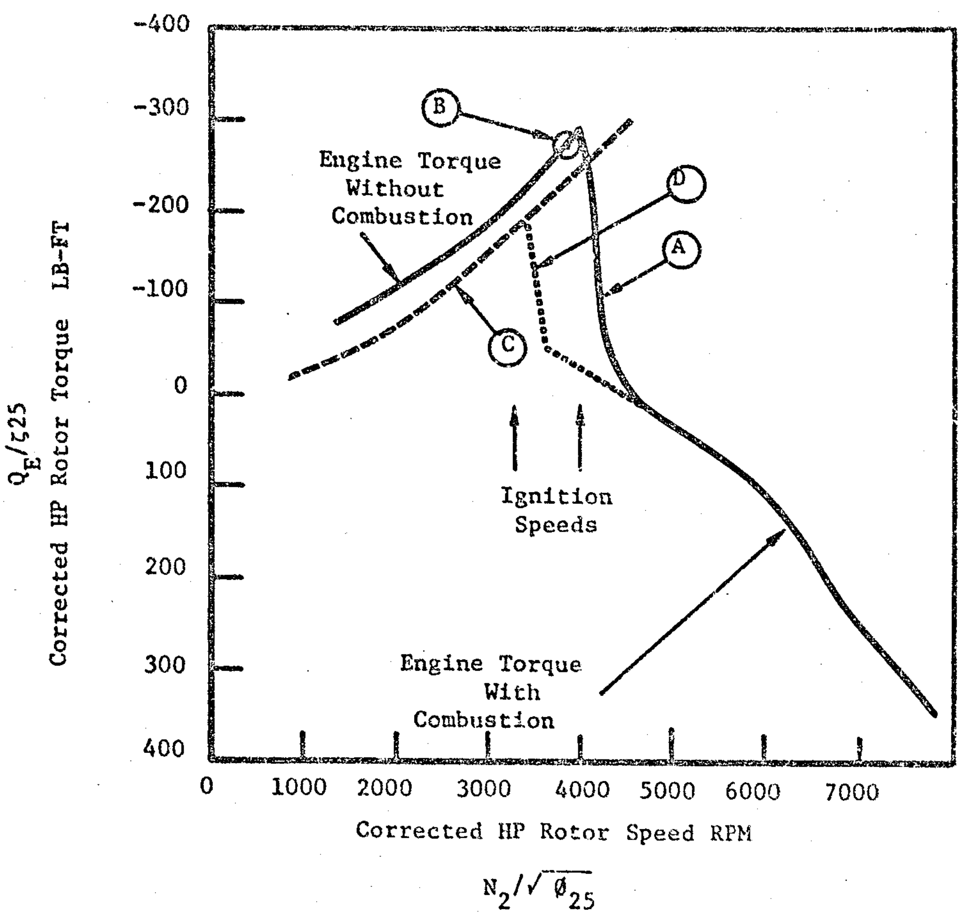
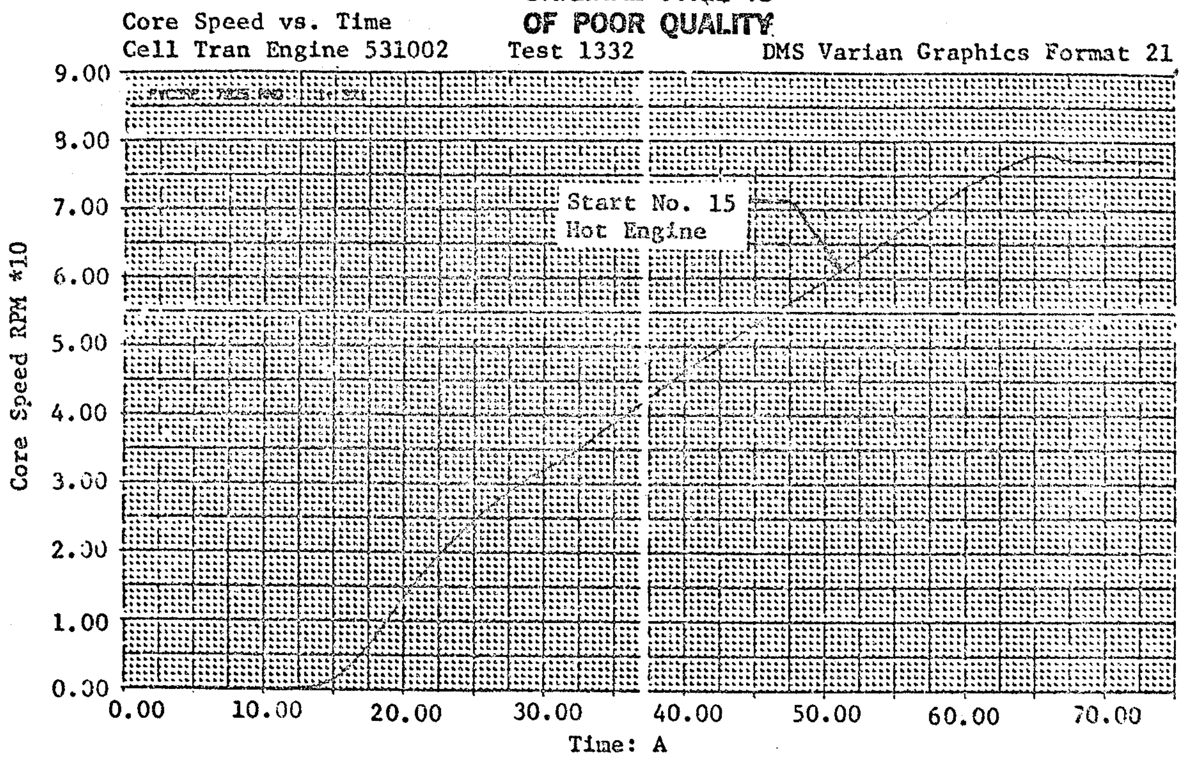


Figure 68. Engine Torque Data Maximum Enrichment (Sheet 2 of 2)



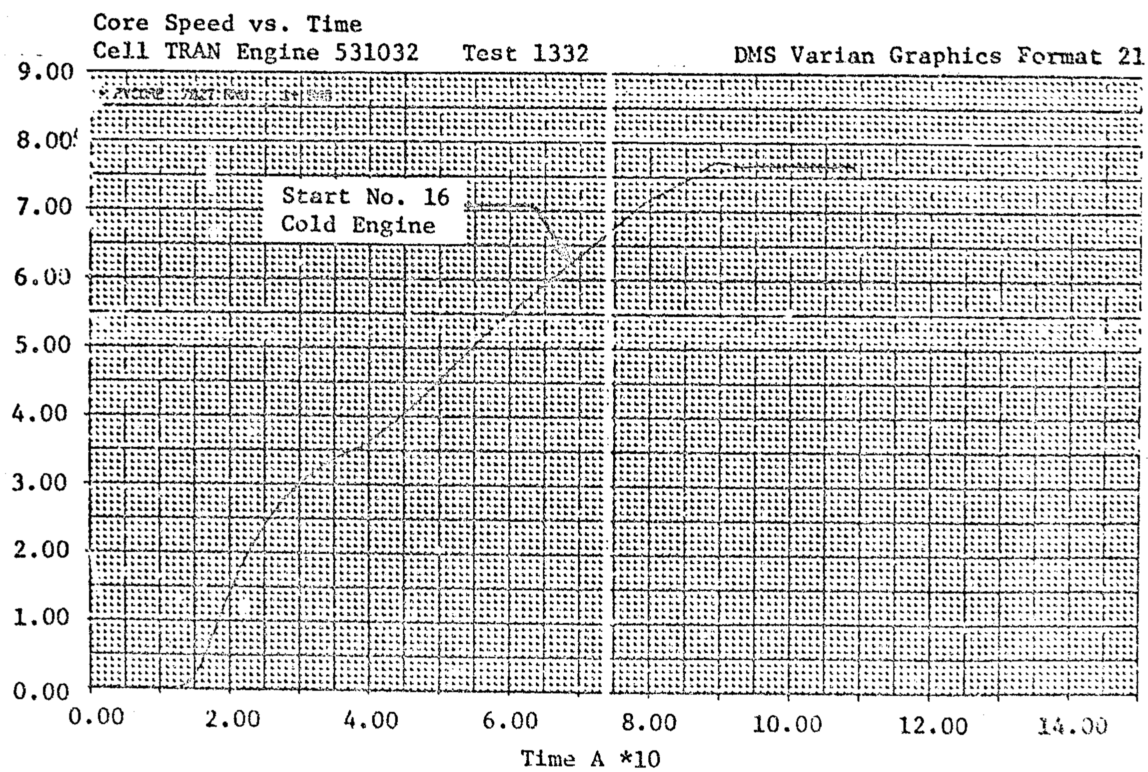


Figure 69. Starting - Hot Engine vs. Cold Engine.

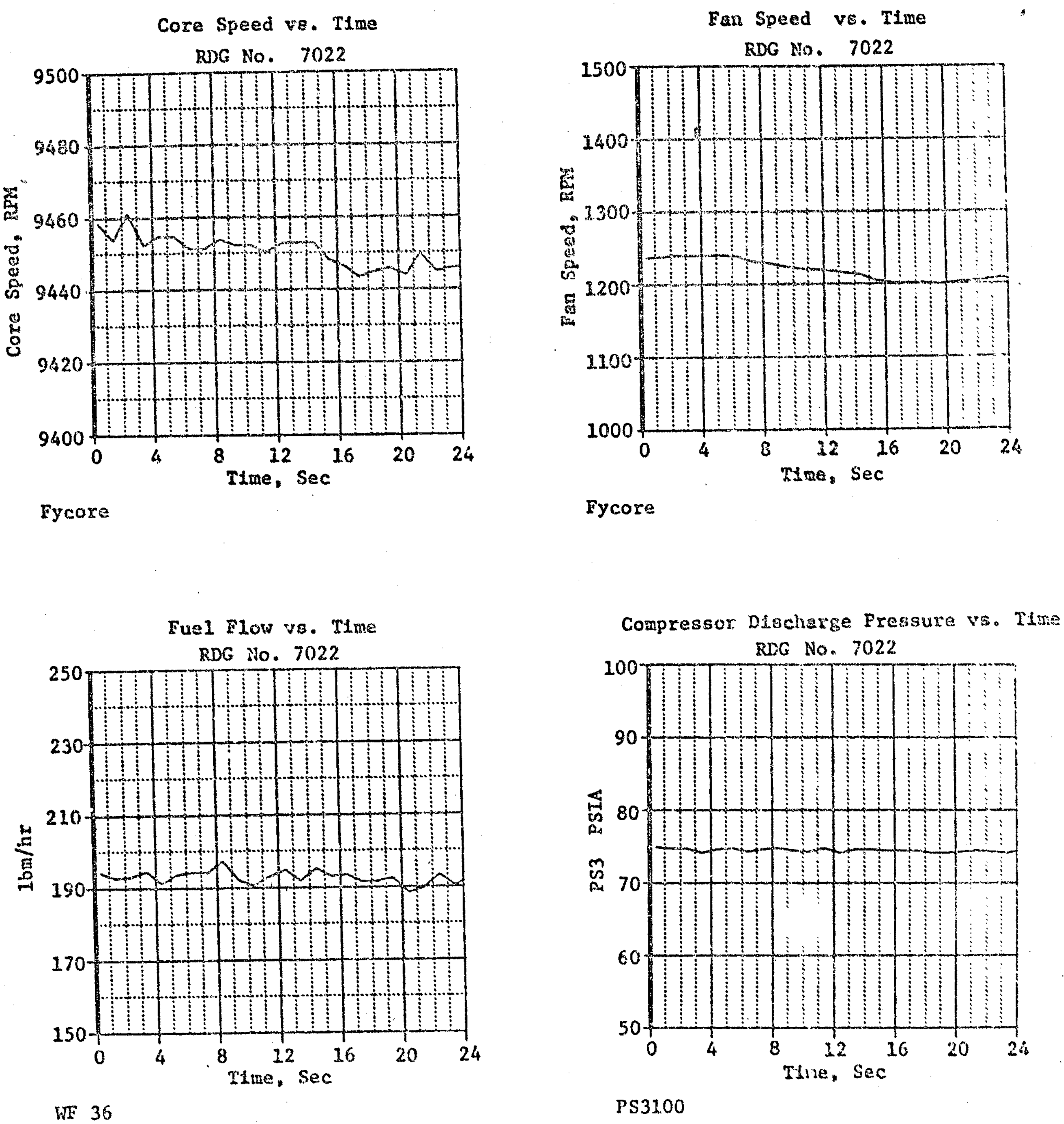


Figure 70. Core Rotor Speed Control at Low Power.

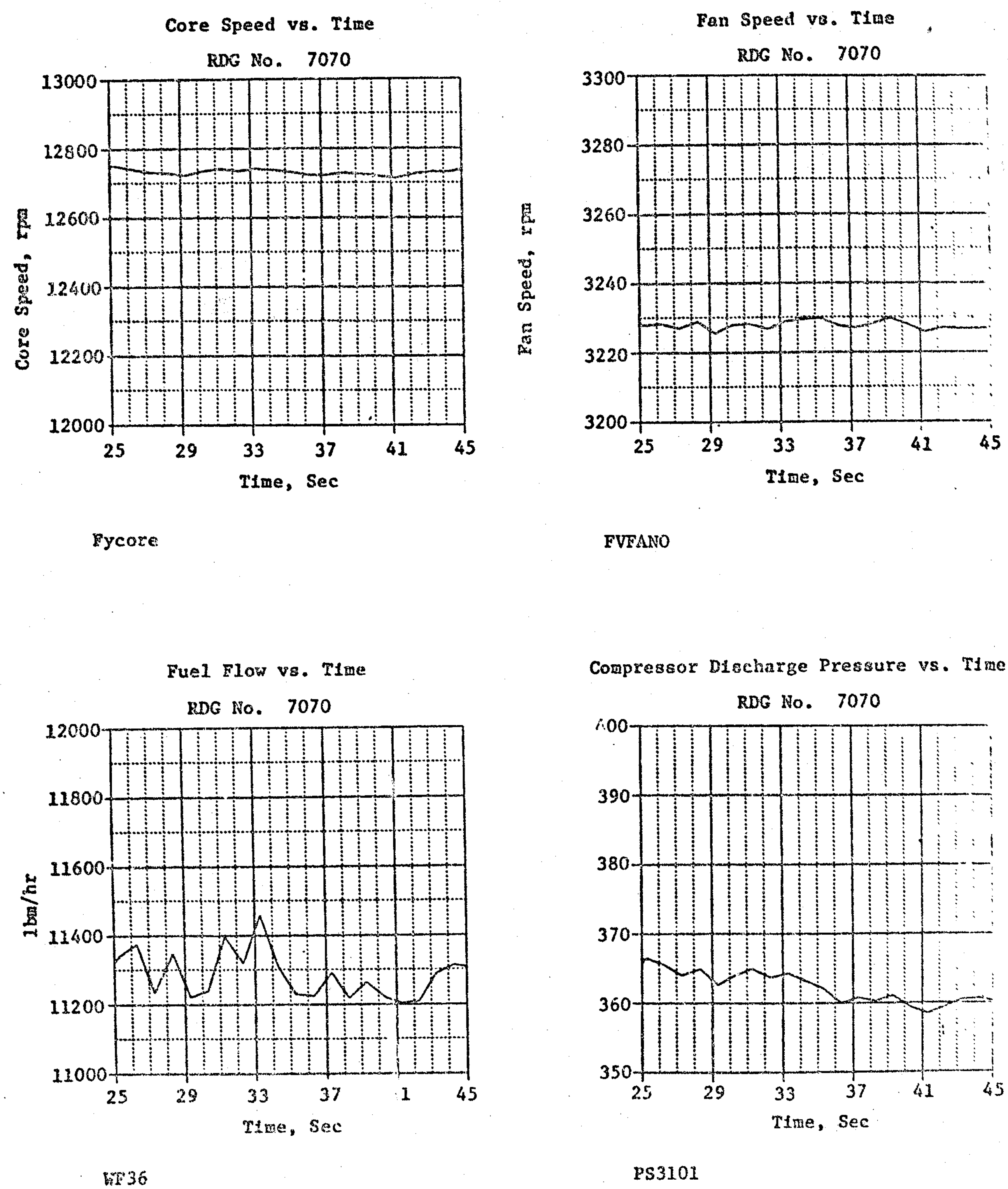


Figure 71. Fan Speed Control at High Power.

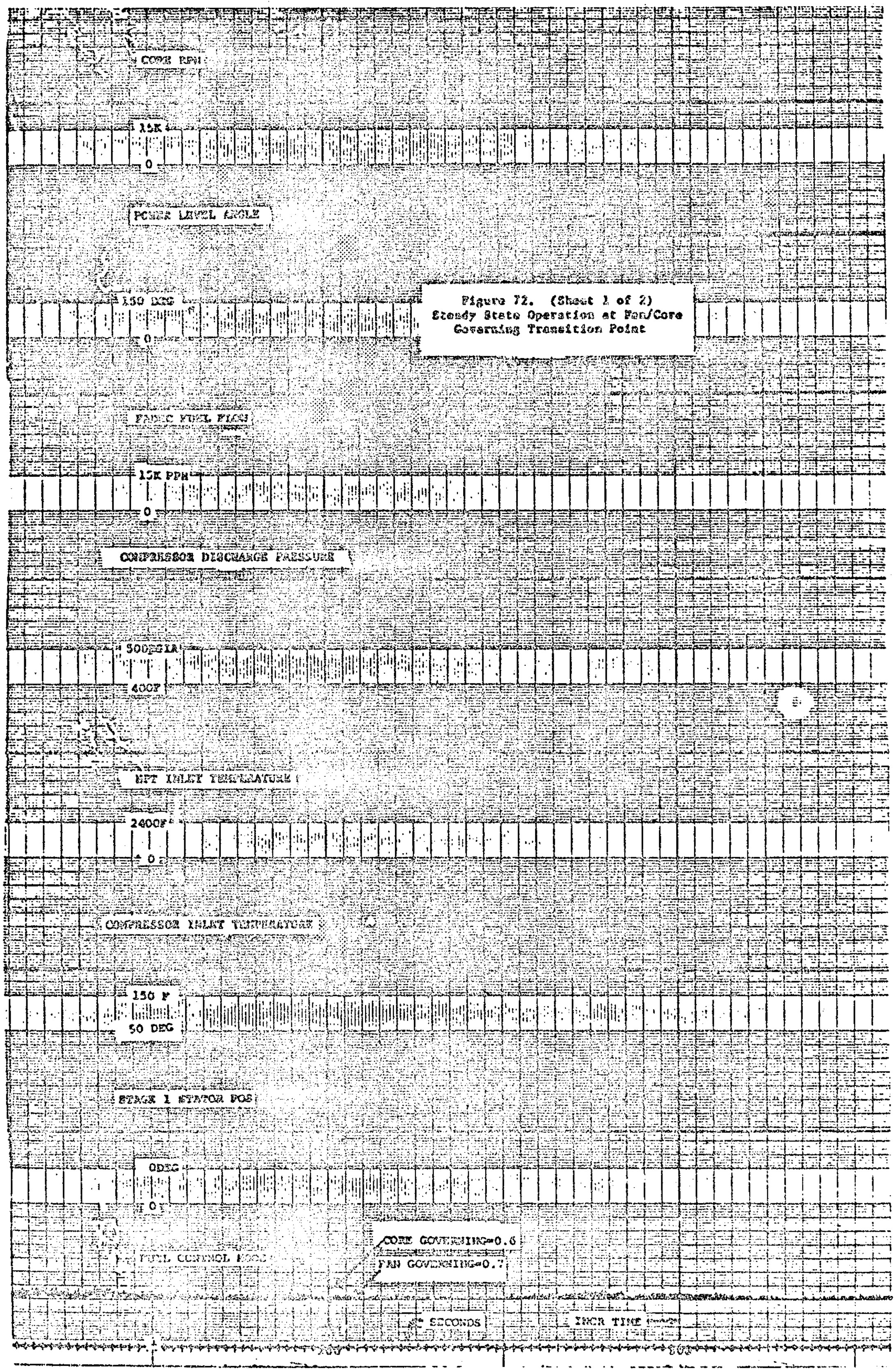


Figure 72. (Sheet 1 of 2) Steady State Operation at Fan/Core Governing Transition Point

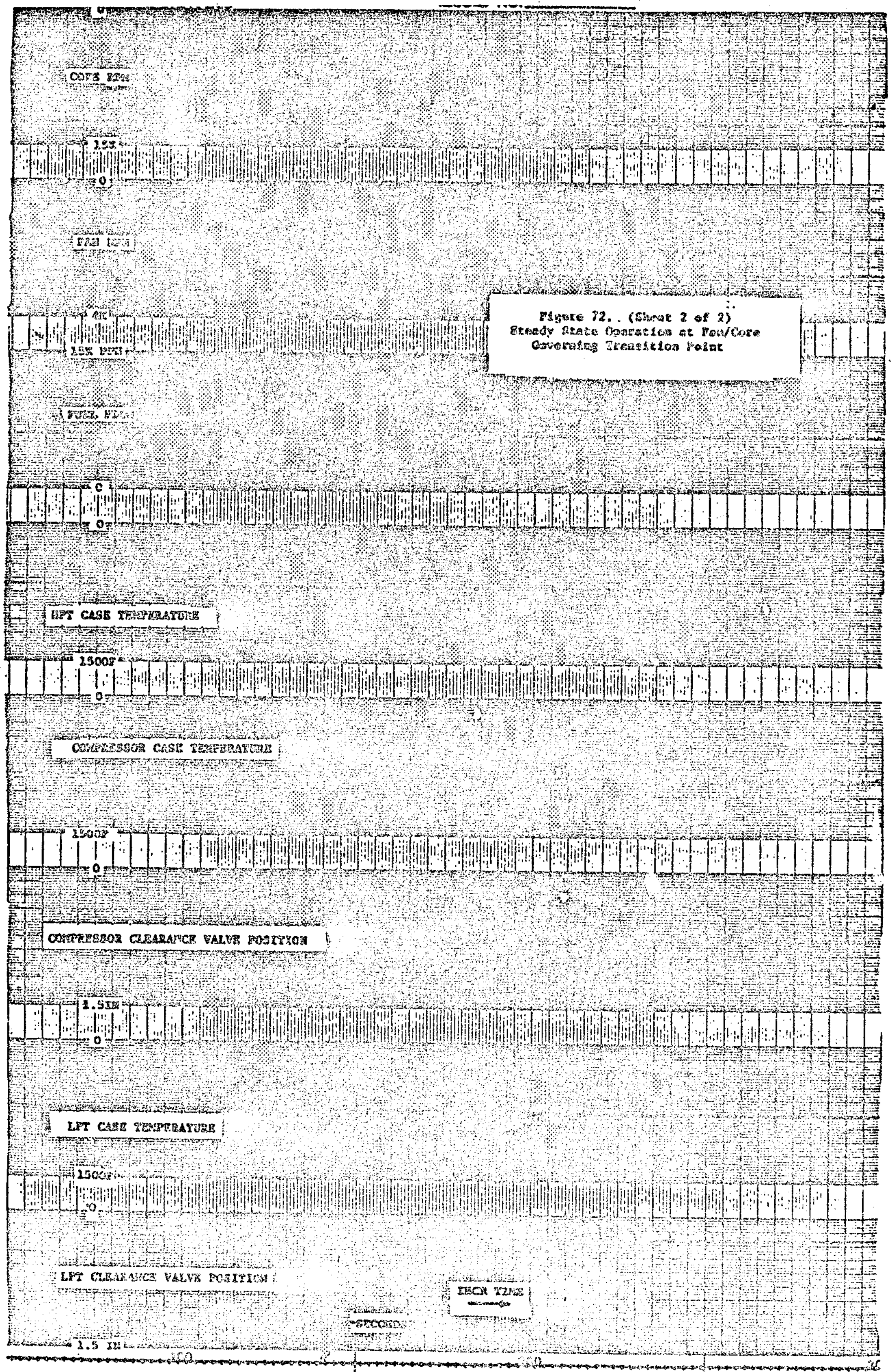


Figure 72. (Sheet 2 of 2)
Steady State Operation at Fan/Core
Governing Transition Point

A slow accel was made onto each limit to demonstrate transition onto the limit and steady state operation on the limits. Figures 73, 74 and 75 are slow accelerations from fan speed control onto the T42, PS3, and T41C (calculated HPT inlet temperature) limits respectively. Operation was satisfactory on each limit. (NOTE: T41C was not recorded transiently but the PS5 and fuel flow traces shown on Figure 75 was equivalent because these are the two main factors in the T41C calculations)

8.4 T3 SENSING ERROR

Early in the ICLS test it was discovered that the compressor discharge temperature (T3) signal to the FADEC was erroneously low by increasing amounts as ambient temperature in the core cowl area increased. Limited investigation on the engine indicated the presence of an extra thermocouple junction at the T3 sensing lead connection in the core cowl area, suggesting the use of incorrect material in the lead and/or the connector pins. Because this lead pressed through a crowded fan frame vane and was difficult to remove and re-install, it was not replaced and steps were taken to minimize the effect of the error. By routing some instrumentation cooling water near the suspect connector and making FADEC adjustments, it was possible to use the T3 signal. T3 is a factor in the T41C limit, the compressor clearance control automatic control strategy, and the sensor failure indicator and corrective action (FICA) feature.

A resistance test of the T3 lead after test completion revealved that the chomel and alumel wires were reversed. This created extra sensing functions at both ends of the lead and explains why the T5 signal decreased as the temperature in the core cowl area increased.

8.5 STATOR SCHEDULING

The conventional practice of scheduling compressor stator angles as a function of rpm and inlet temperature was used for ICLS testing. Steady state stator positioning accuracy and stability was excellent throughout the test. Figure 76 is a plot of steady state DMS data points of stage 1 angle versus corrected core speed with the schedule line shown for reference purpose.

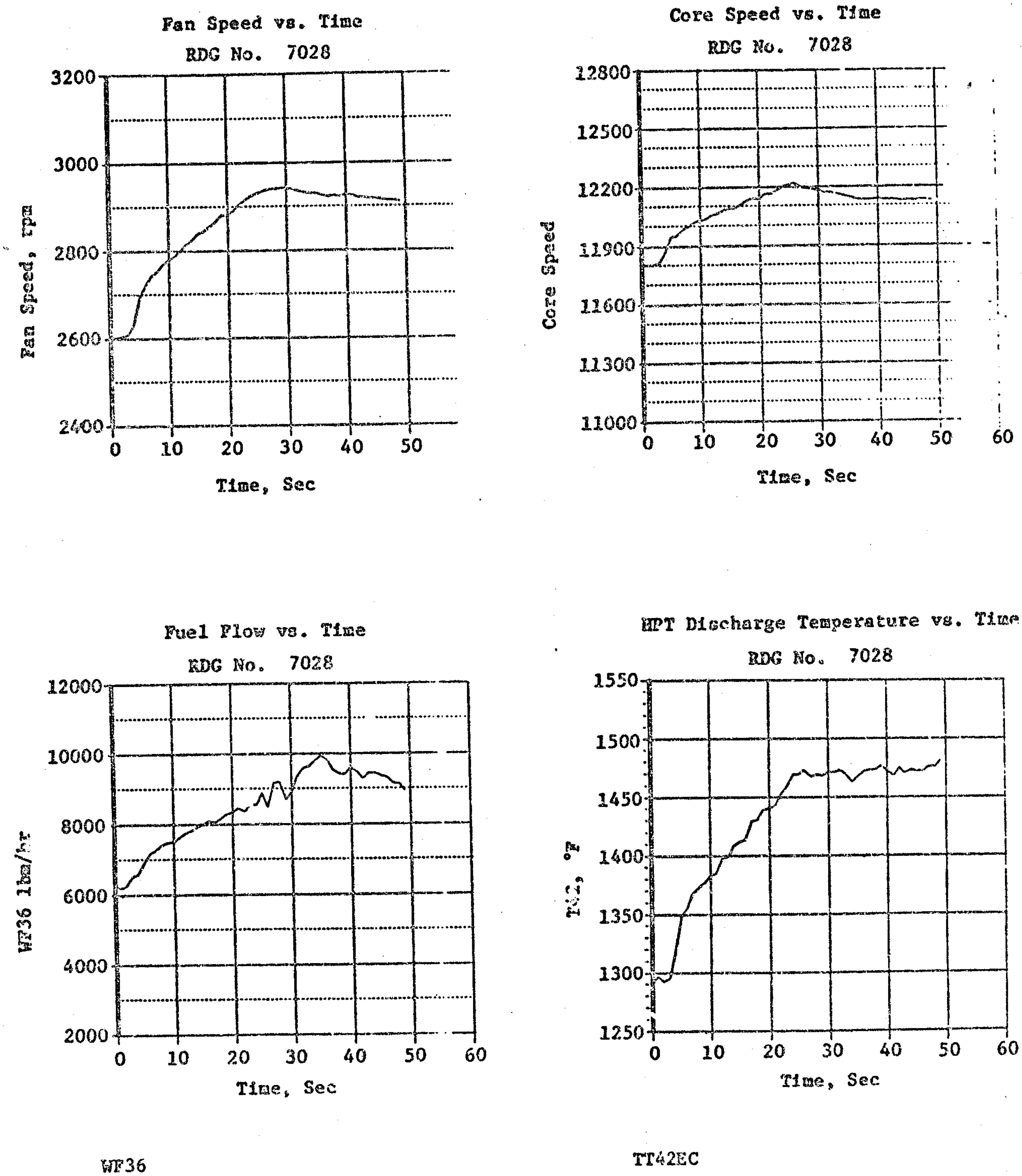


Figure 73. Acceleration to T42 Limit.

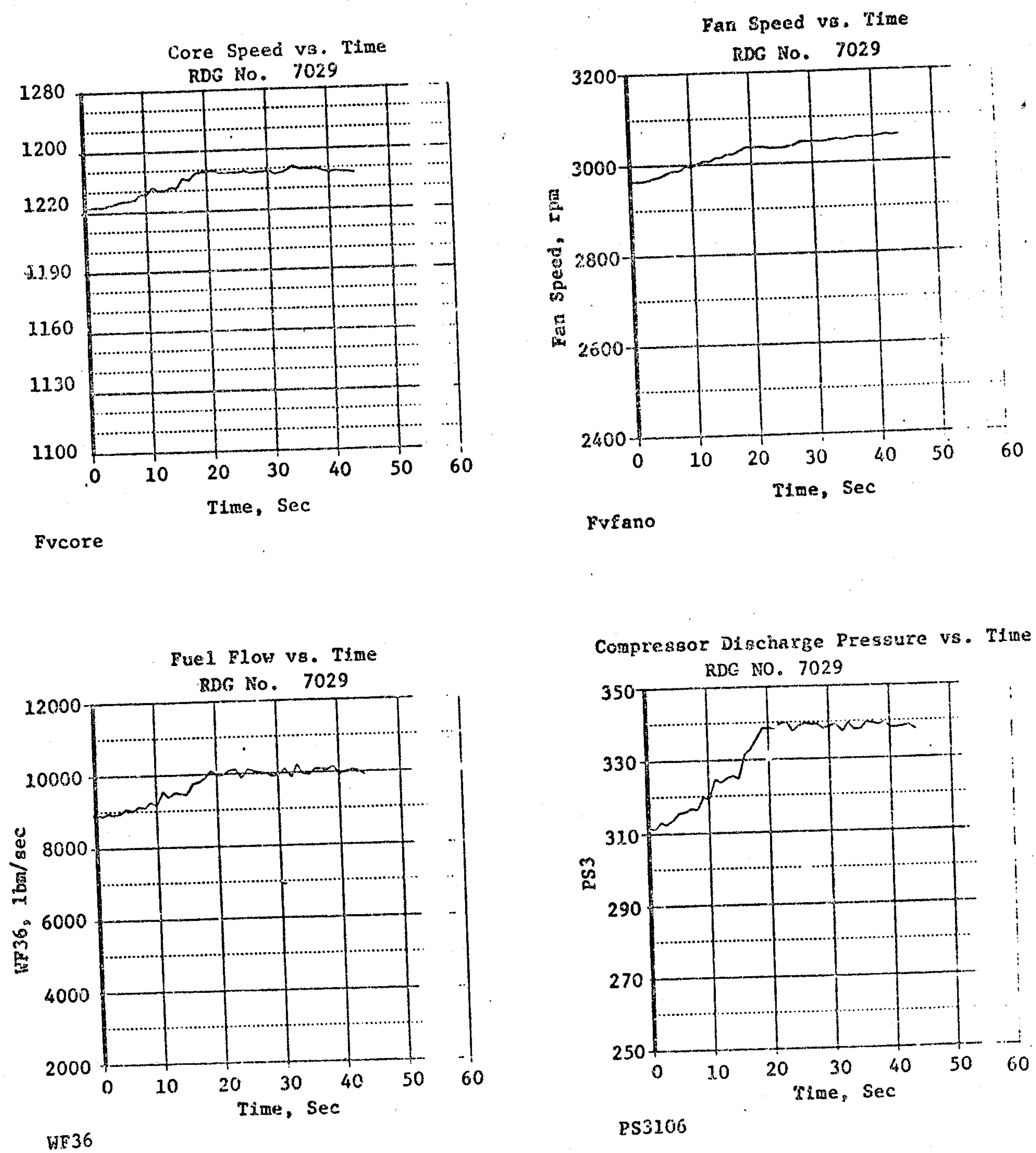


Figure 74. Acceleration to PS3 Limit.

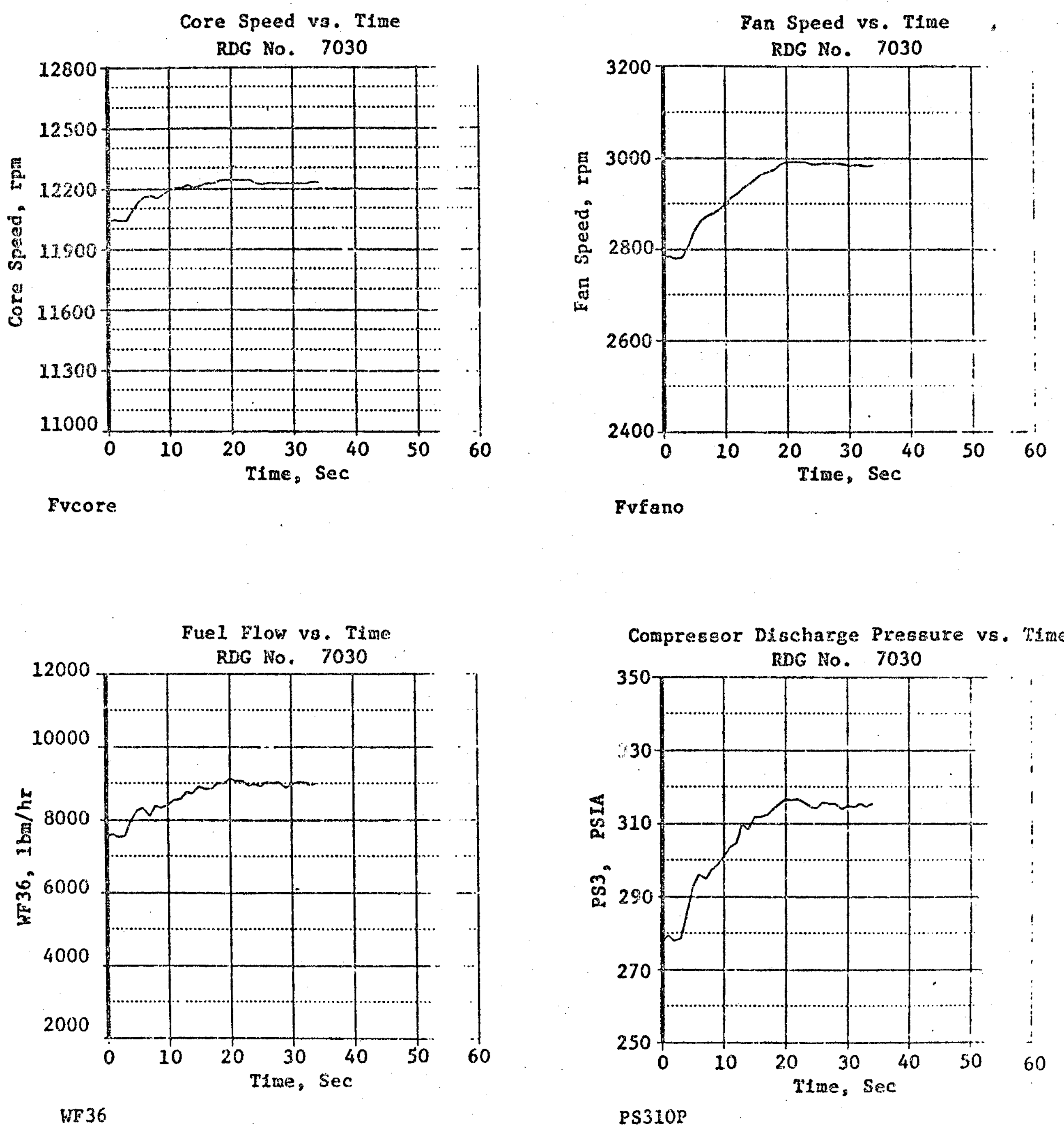


Figure 75. Acceleration to T41C Limit.

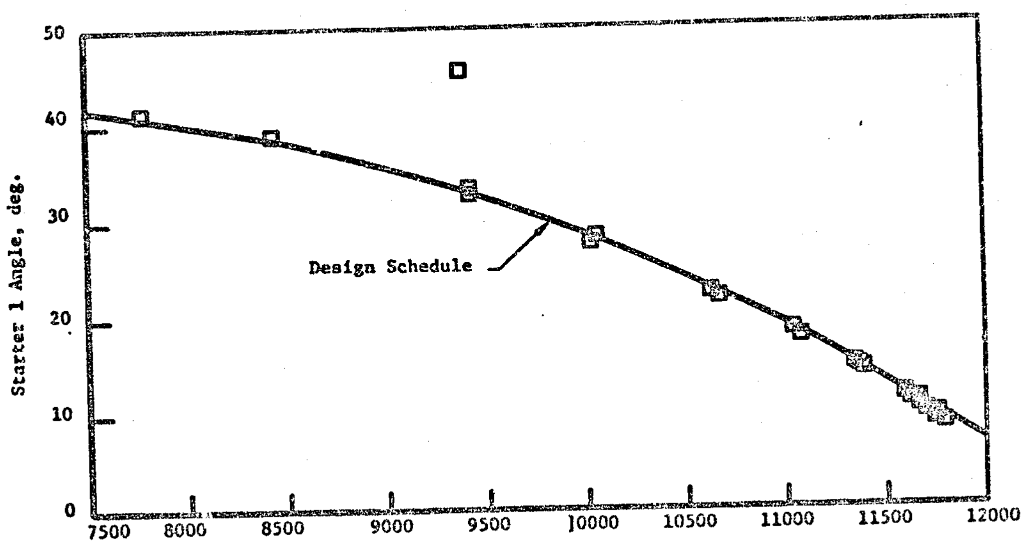


Figure 76. Steady State Stator Tracking.

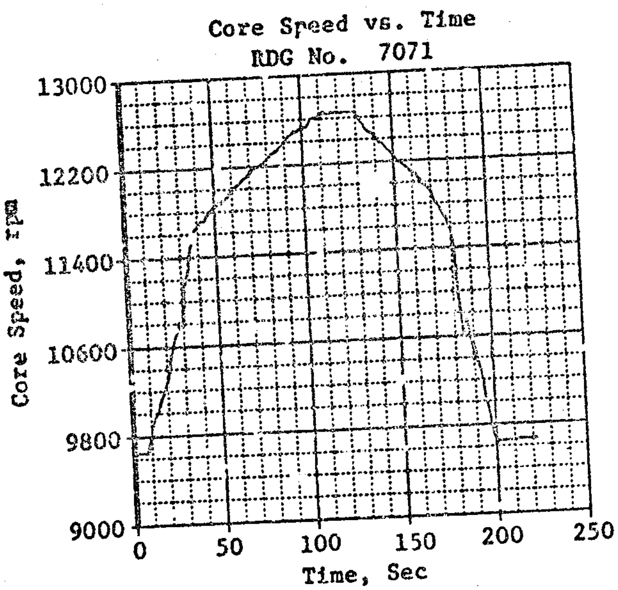
Transient stator accuracy is difficult to assess precisely because of the transient lag inherent in measuring compressor inlet temperature. A fairly good assessment is possible, however, by comparing the slow and fast accel/decel transients shown in Figure 77 and 78. This comparisor indicates a maximum deviation of ±0.5 degrees for the fast transient as compared to the slow, essentially steady state, transients.

8.6 ACTIVE CLEARANCE CONTROL

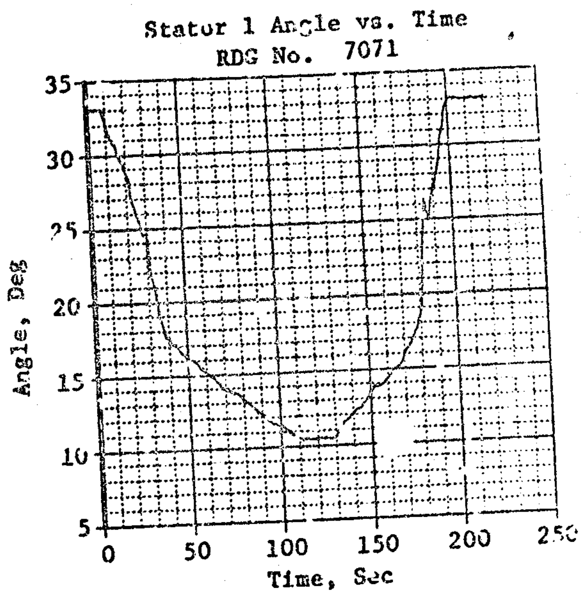
The active clearance control concept which uses closed loop control of casing temperatures was demonstrated for the first time on the ICLS engine. Air valve modulation in both the compressor and LP turbine clearance control systems was successfully used to set casing temperatures as a function of rotor speeds and inlet temperatures. The casing temperature control mode was not demonstrated on the HP turbine because an unexpected out-of-roundness condition on the engine made it necessary to shutoff the clearance control air manifold in the vicinity of the casing thermodouple used for control feedback.

Figure 79 is a data trace showing compressor and LP turbine clearance control mode changes from manual to automatic at 80% fan corrected speed. The compressor system mode change was made first and it was done from a condition at which the compressor clearance control valve was in the minimum casing cooling position and casing temperature was higher than the schedule. The valve first moved to the high cooling region, then gradually moved to the midstroke region as casing temperature decreased to the schedule, and finally began modulating in that region to maintain the scheduled temperature. The response and stability during and after the transition into the automatic mode are considered to be quite satisfactory.

The LP turbine system mode change was made with the air valve partially open in the manual mode and casing temperature near the scheduled level. The system becomes somewhat unstable with casing temperature oscillating approximately 50F at 0.25 Hertz. This amount of oscillation is undersirable but the unexpectedly high frequency of the oscillation suggests that the casing thermocouple response is faster than anticipated. This was primarily due to the thermocouple responding to cooling air flow rather than casing temperature. A standard instrumentation-type thermocouple was used here and



Fvcore



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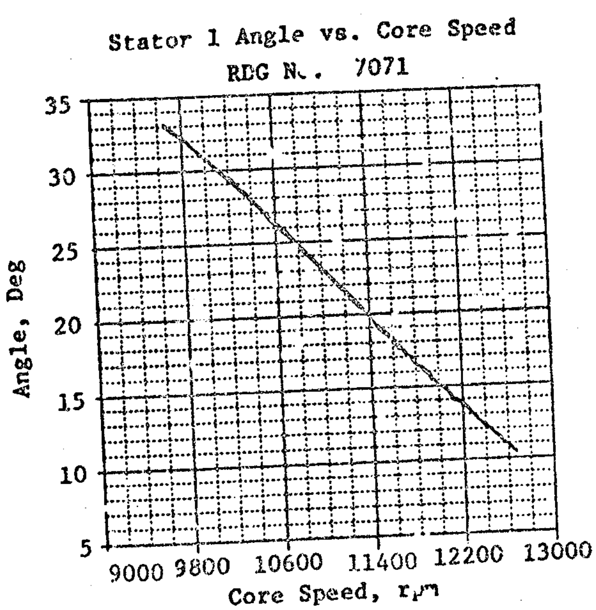

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Figure 77. Slow Acceleration & Deceleration Stator Tracking.

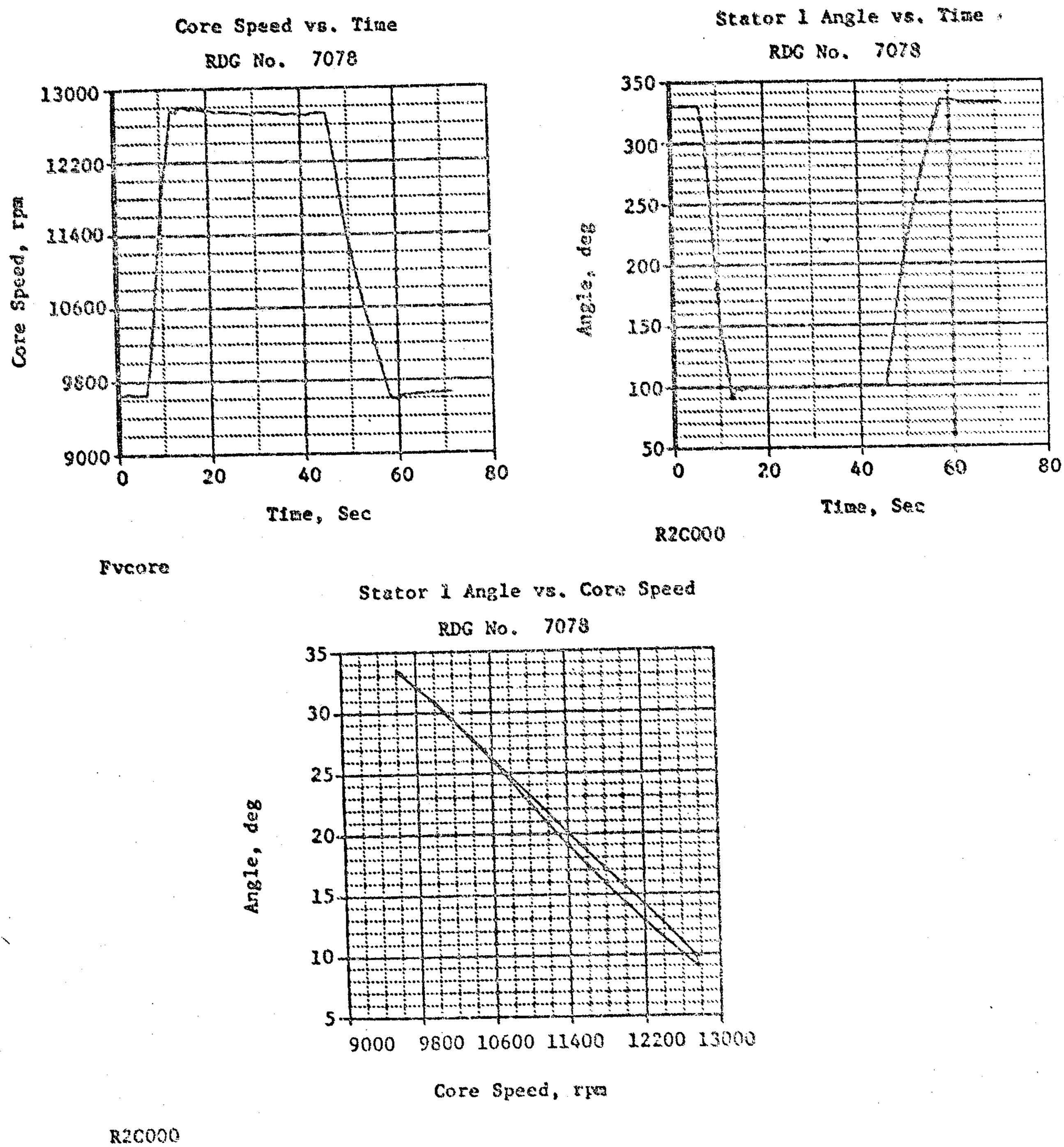

Figure 78. Rapid Acceleration & Deceleration Stator Tracking.

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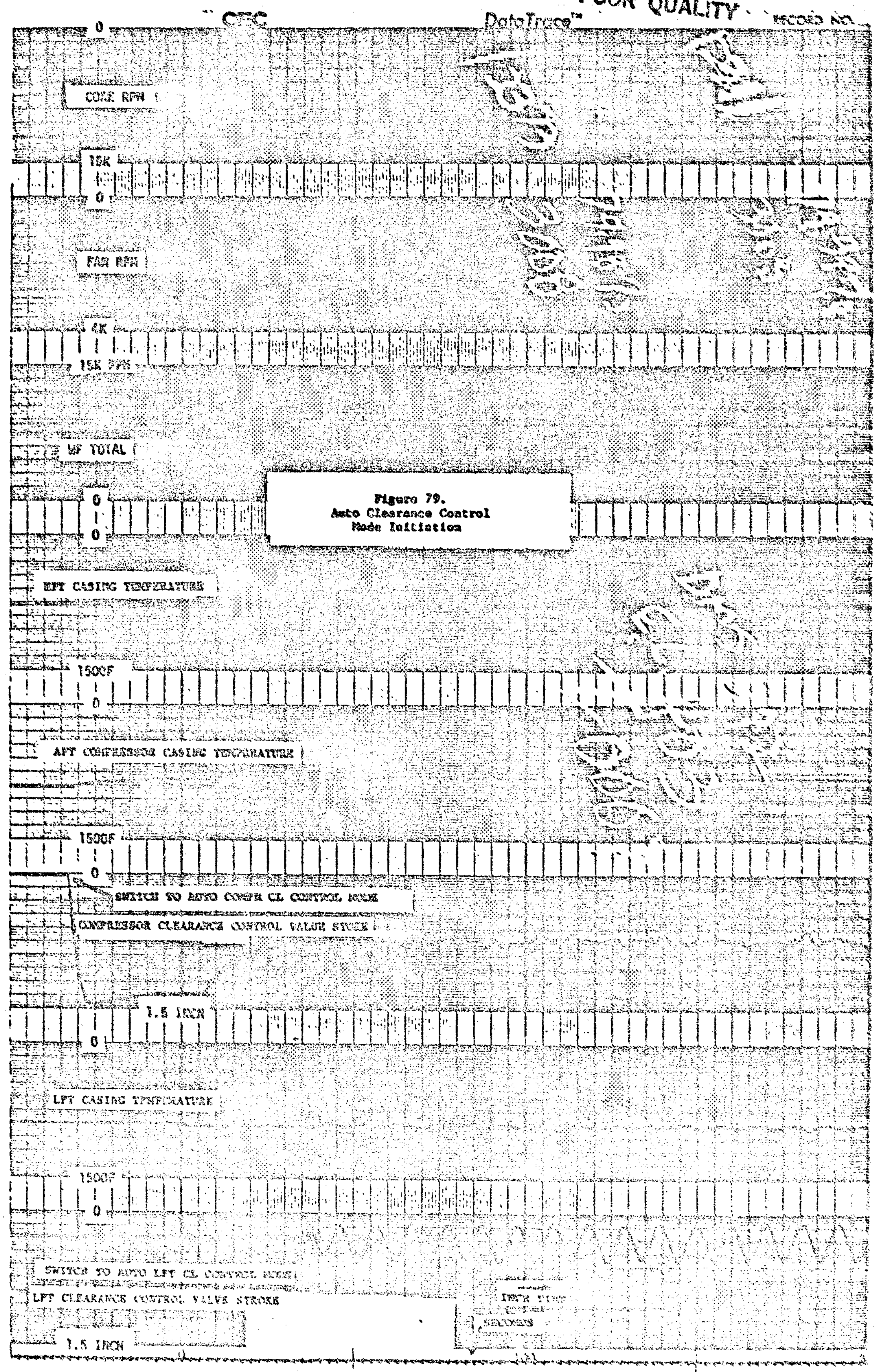

Figure 79.
Auto Clearance Control
Mode Initiation

it was attached to the casing using an electrically non-conductive, ceramic-based cement which reduced casing-to-thermocouple thermal conductivity. For any future application a sturdy probe or set of probes would be designed that would provide a better measure of casing temperature.

Figure 80 shows a deceleration of 40% corrected fan speed from the condition shown in the previous figure at a rate below that which would trigger the air valve decel shutoff function. The casing temperature characteristics proved to be such that both casings became hotter than scheduled during the decel but the compressor casing later dropped below the schedule and remained there even with no cooling while the LP turbine returned to the temperature modulating condition.

Figure 81 is a similar deceleration except that the deceleration rate was increased enough near the end of it to cause the air valve decel shutoff function to operate. Both of the active clearance control valves closed as they should under these conditions.

The manual clearance control modes were used to explore the steady state characteristics of the clearance control systems. The resulting data are plotted on Figure 82 in terms of the directly controlled parameters (casing temperatures). Corresponding clearance characteristics are discussed in sections of this report that relate to compressor and turbine mechanical performance.

8.7 COMBUSTOR TRANSITION

Initial transitions from single annular to double annular combustion were made in the manual mode to determine the necessary FADEC adjustment settings for fill volume (flow area set during main zone manifold filling) and fill time (time required to fill main zone manifold). These settings were then made on the engineering operator panel and all subsequent transitions were made in the automatic mode. Figure 83 is a slow accel showing the action of the main zone and pilot zone valves in the automatic mode during transition. To successfully transition from single annular to double annular burning, it was necessary to:

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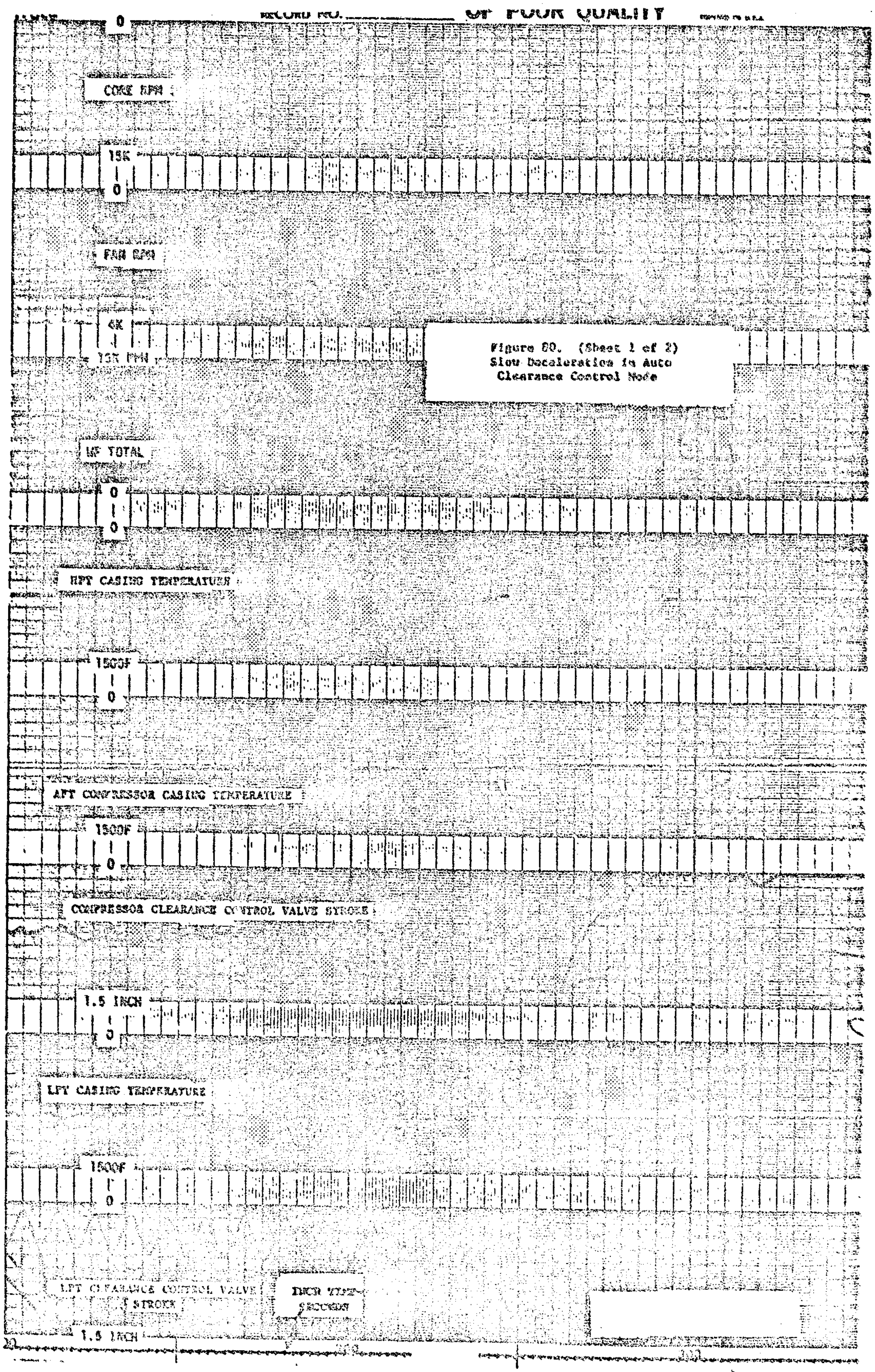

Figure 80. (Sheet 1 of 2)
Slow Deceleration in Auto
Clearance Control Mode

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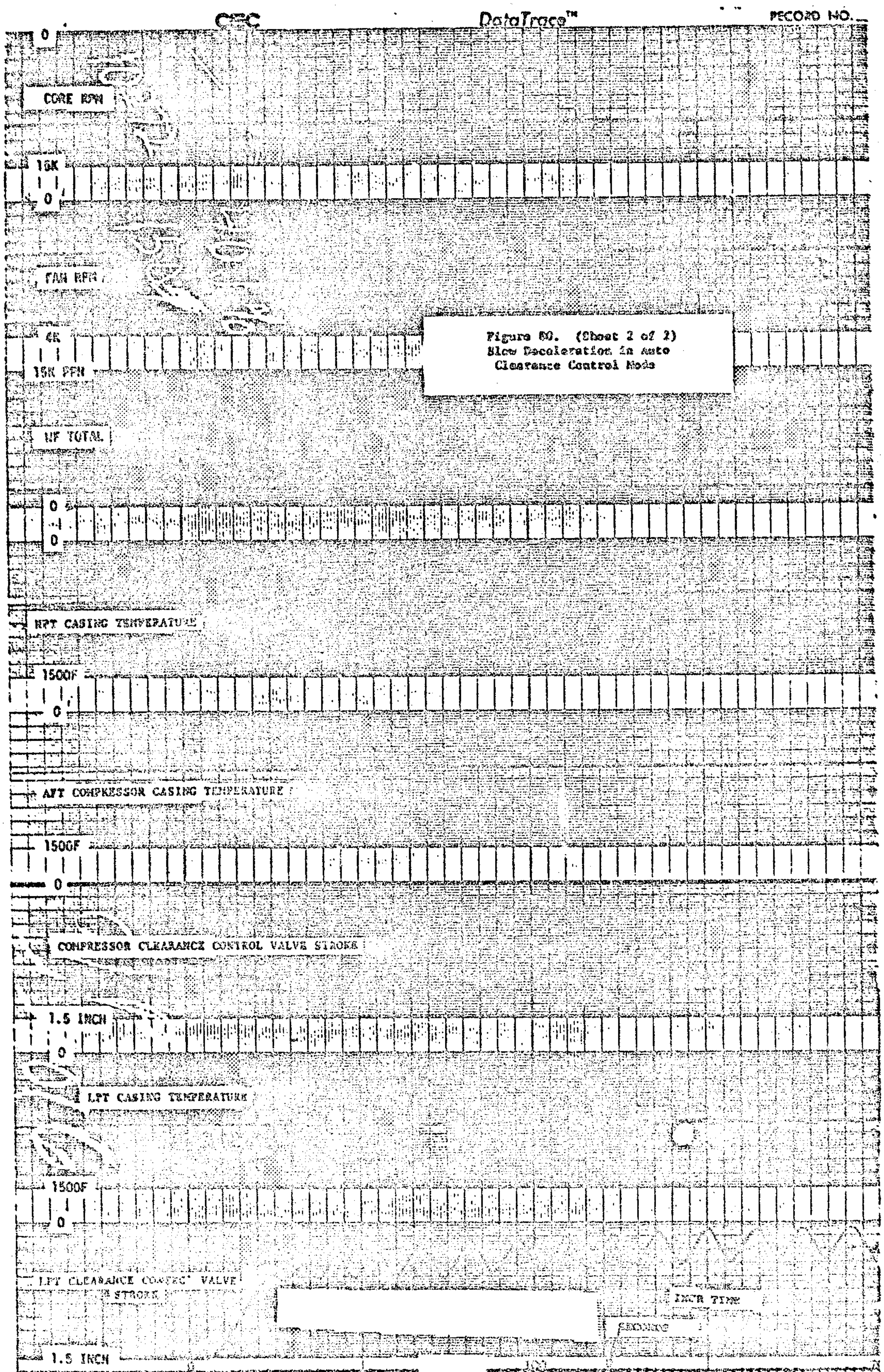


Figure 60. (Sheet 2 of 2) Slow Deceleration in Auto Clearance Control Mode

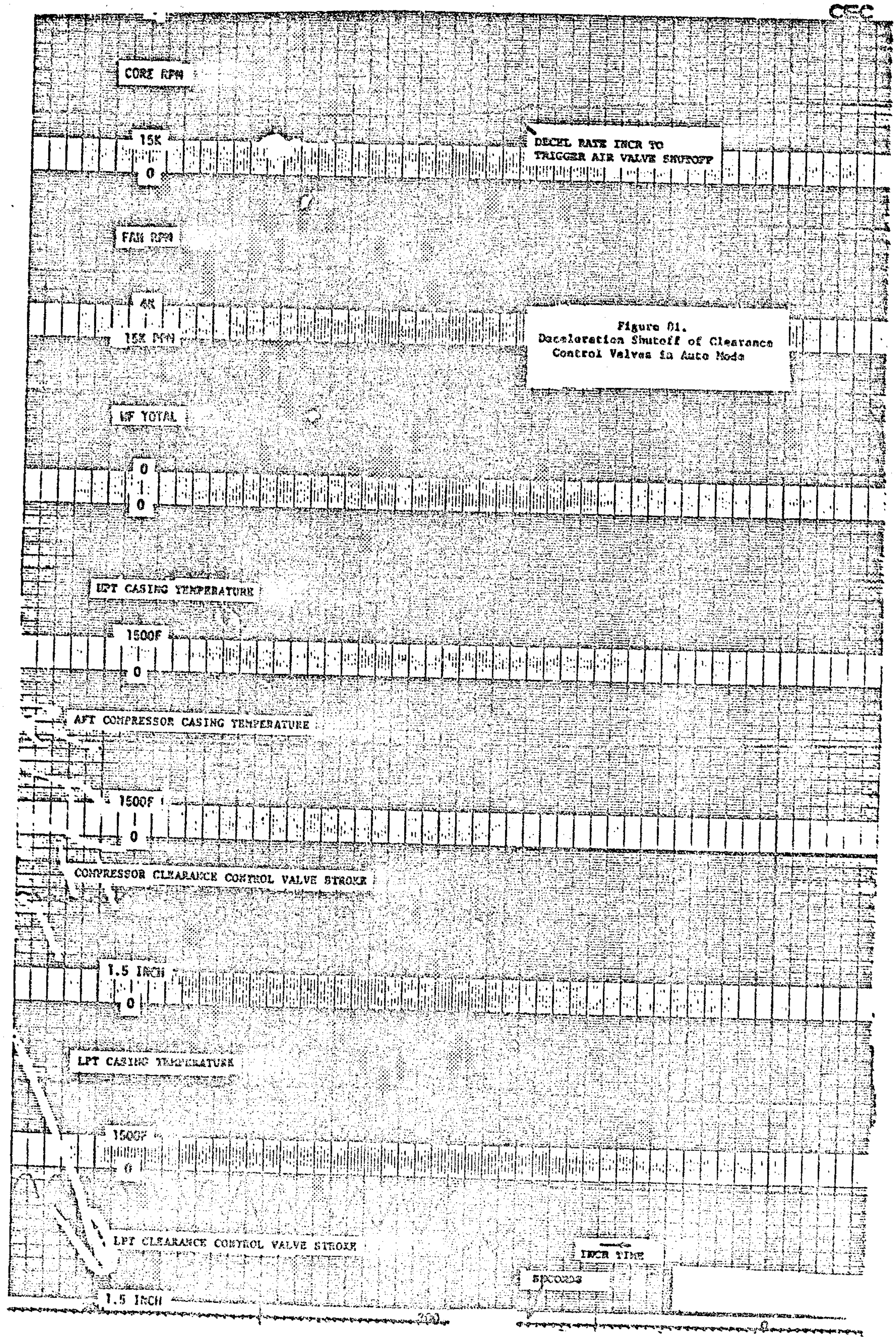


Figure 81.
Deceleration Shutoff of Clearance Control Valves in Auto Mode

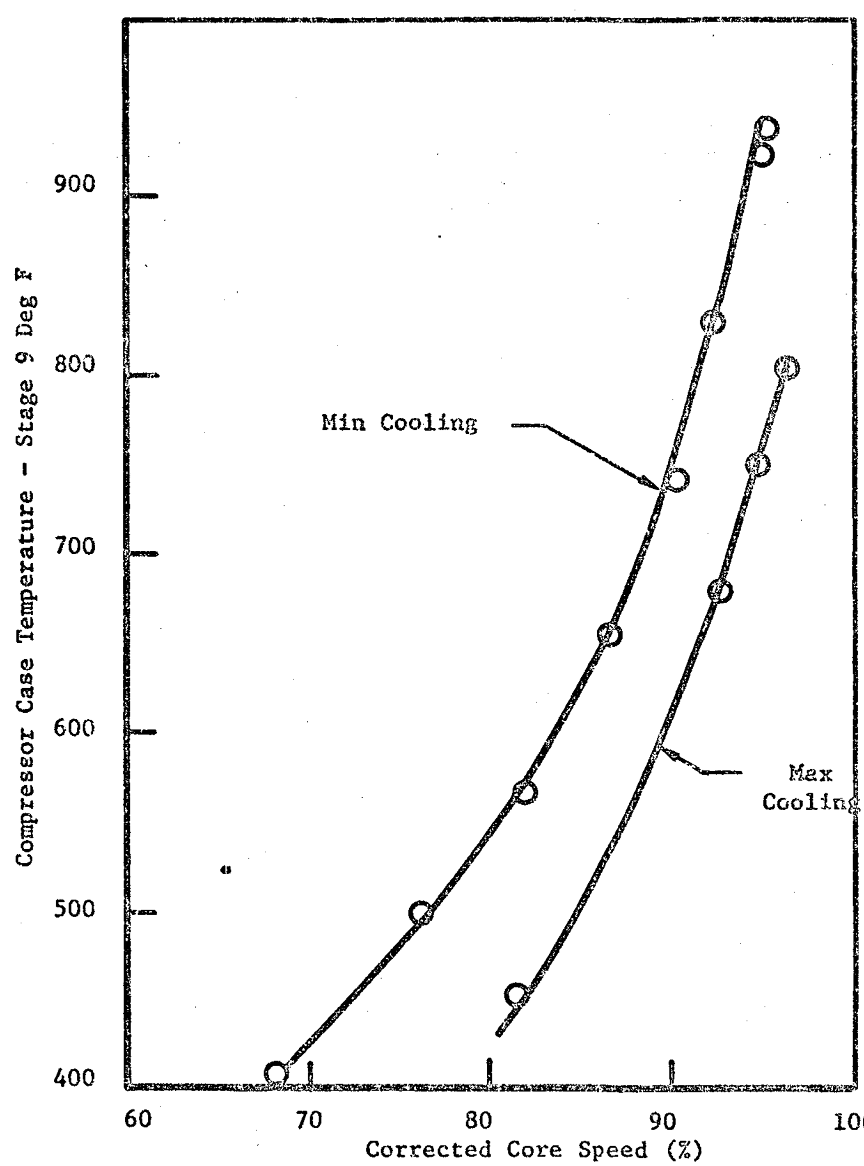


Figure 82. Steady State Case Temperatures.
(Sheet 1 of 3)

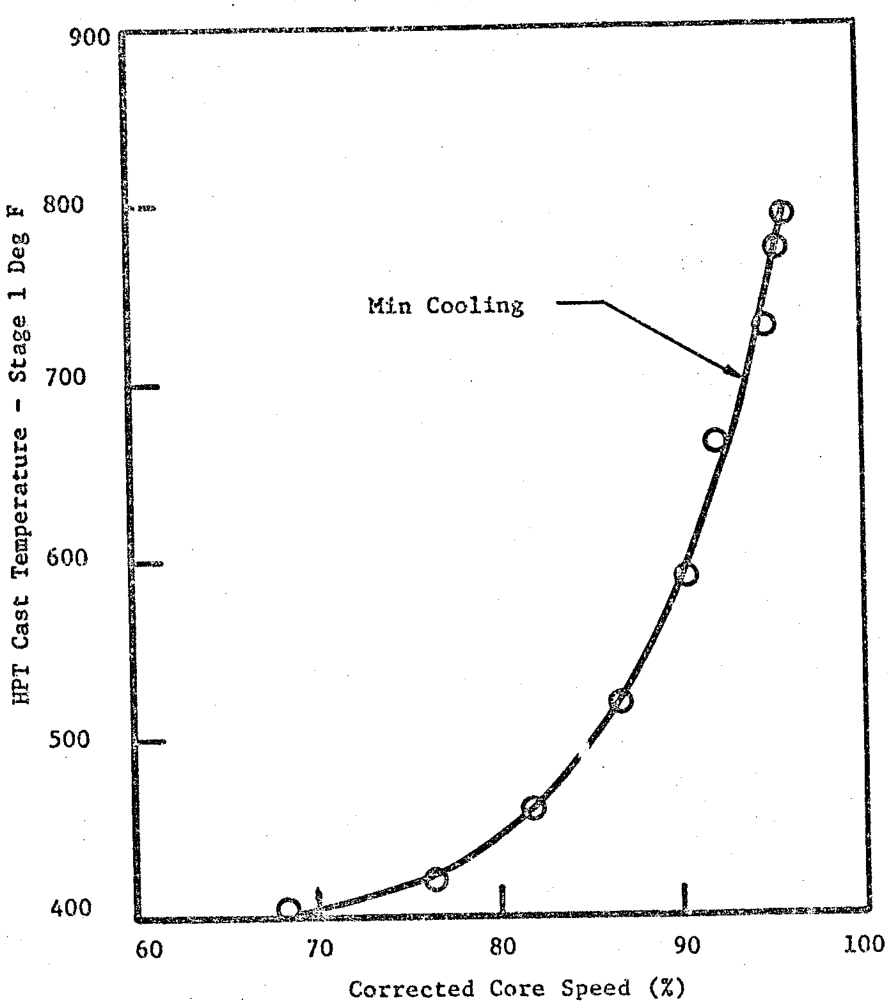


Figure 82. Steady State Case Temperature.
(Sheet 2 of 3)

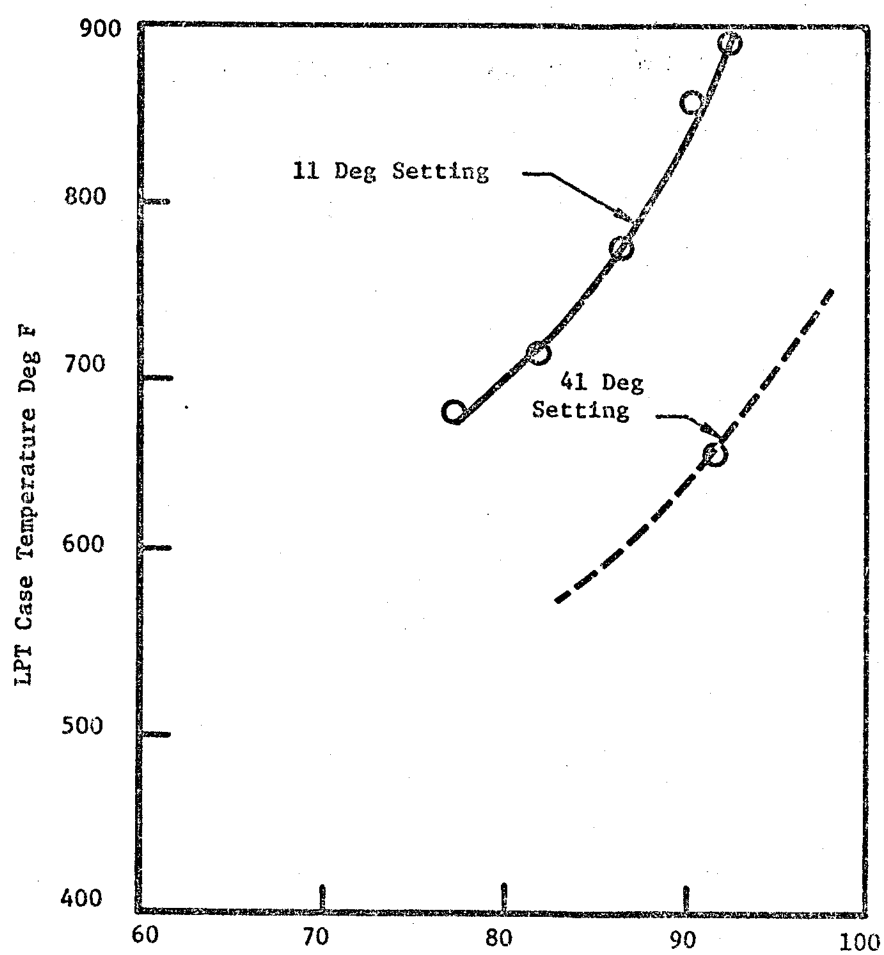


Figure 82. Steady State Case Temperature.
(Sheet 3 of 3)

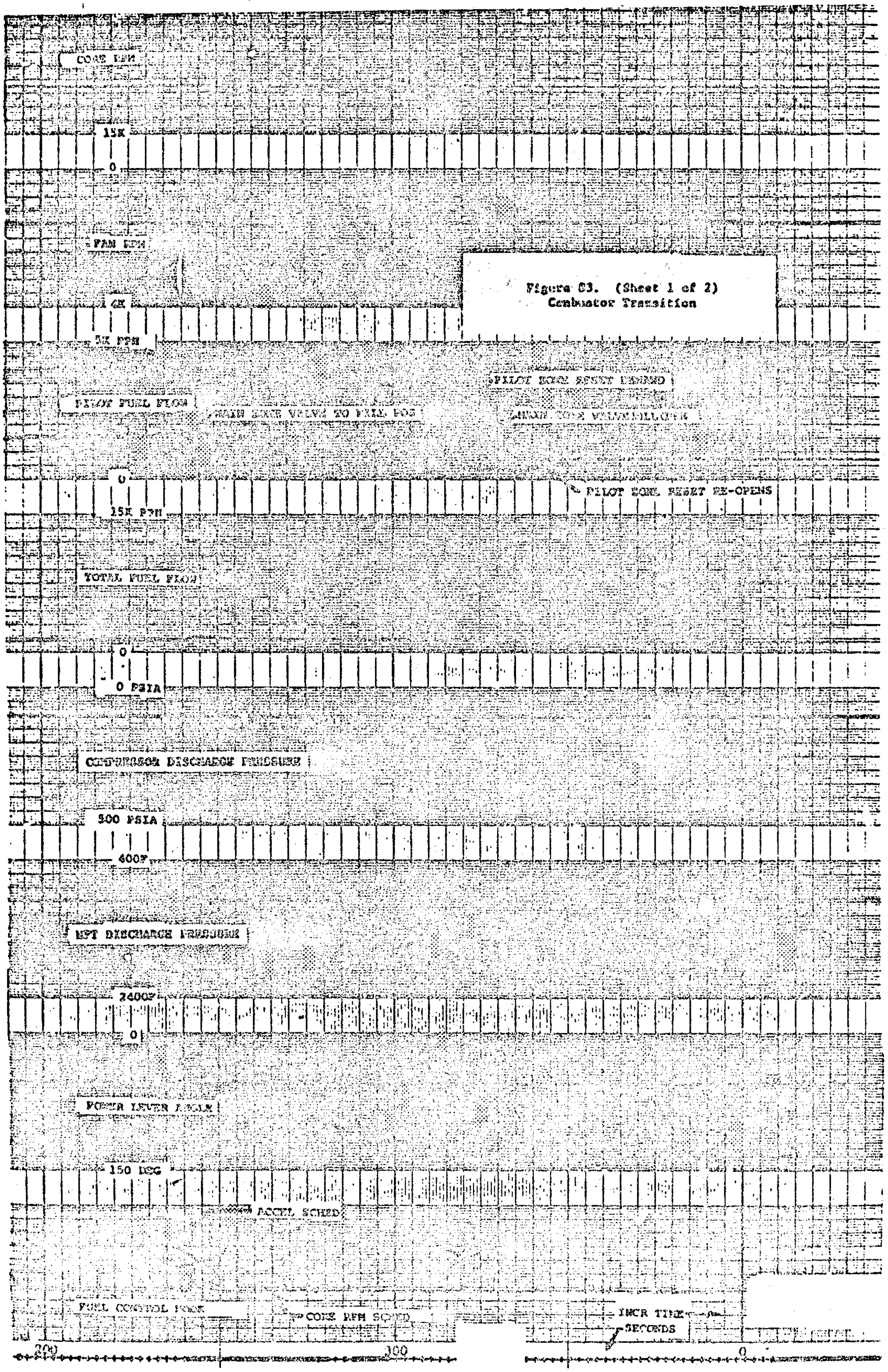


Figure 83. (Sheet 1 of 2)
Combustor Transition

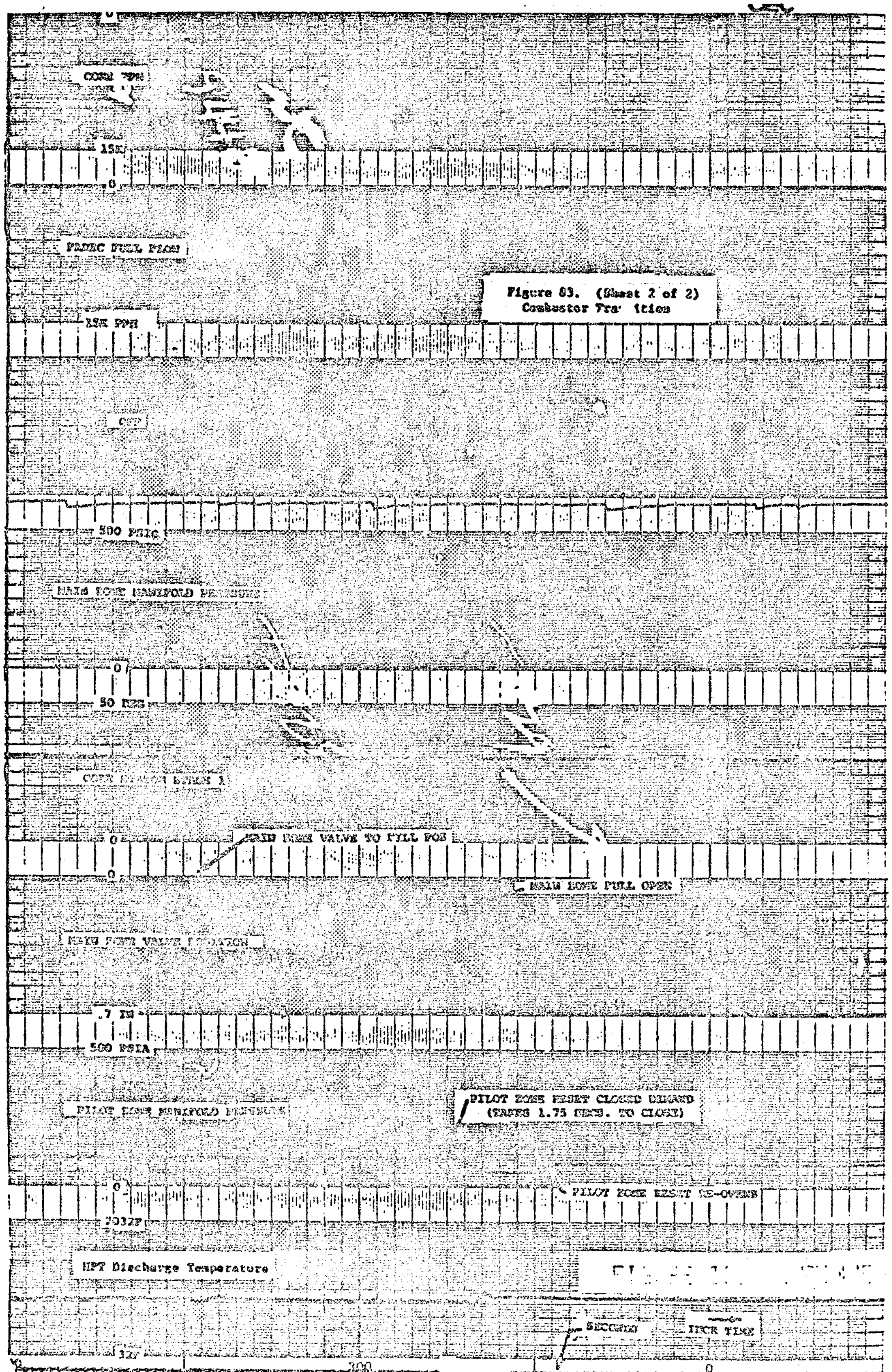


Figure 83. (Sheet 2 of 2)
Combustor Tra ition

a. Fill the main zone manifold and nozzles. For this, the fill volume adjustment was set so that the engine did not decelerate during filling and the fill time was set at 30 seconds.

b. Close the pilot zone reset to enrich the main zone to allow the main burner to light. Note that the pilot zone reset valve is signaled closed 1.75 seconds before the main zone goes fully open. This is a slow (.25 gpm servovalve) system and takes that long to close.

c. Open the main zone as the pilot zone reset is going fully closed.

d. Reopen the pilot zone reset after transition to double annular.

Transition to single annular from double annular was accomplished simply by closing the main zone valve.

8.8 ACCEL/DECEL TRANSIENTS

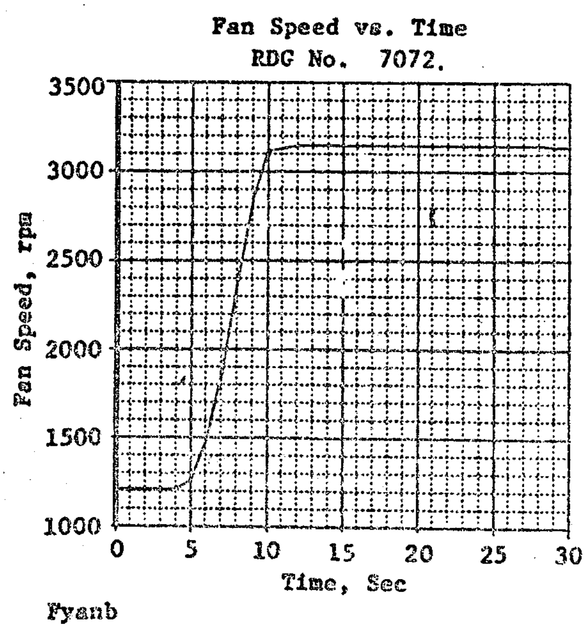
A series of throttle burst were made, first with the nominal accel schedule and then with gradually enriched schedules. Minimum demonstrated time from Flight Idle to 90% net thrust was approximately 5.5 seconds, where core physical rpm limits (based on the maximum speed proven safe in core testing) were reached. The maximum design core rpm was not reached because lack of airfoil instrumentation during ICLS testing made it prudent not to run "blind" at unexplored speeds. Figure 84 is a plot of core speed, fan speed, fuel flow, and stage 1 core stator angle versus time for this accel.

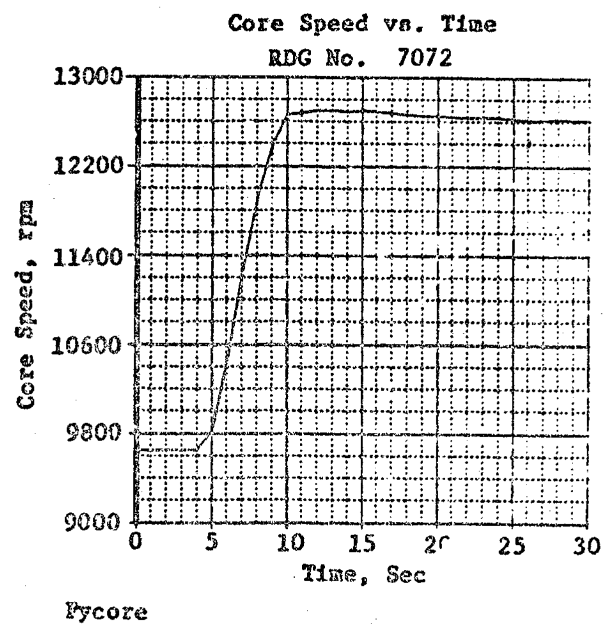
Figure 85 shows a 12-second chop from 90% net thrust to 12% net thrust.

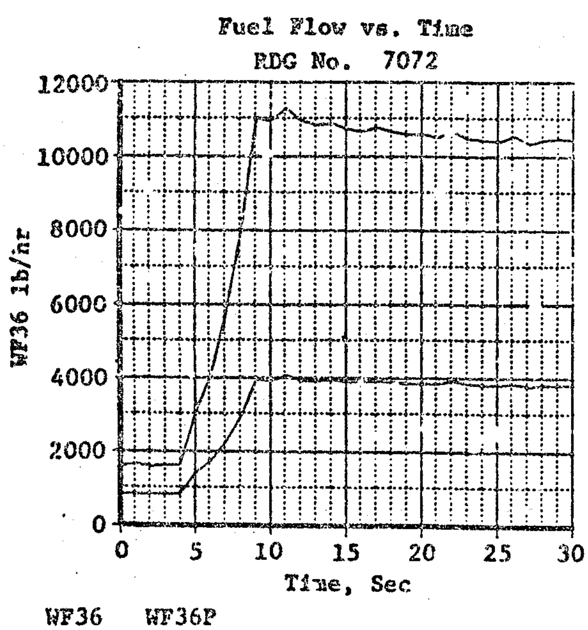
No stalls or blowouts were encountered during the transient testing.

8.9 FAILURE INDICATION AND CORRECTIVE ACTION (FICA)

For FICA demonstration purposes, the ICLS control strategy incorporated a feature to simulate sensor failures for each FICA substituted variable (fan speed XNL, core speed XNH, compressor inlet temperature T25, HP turbine







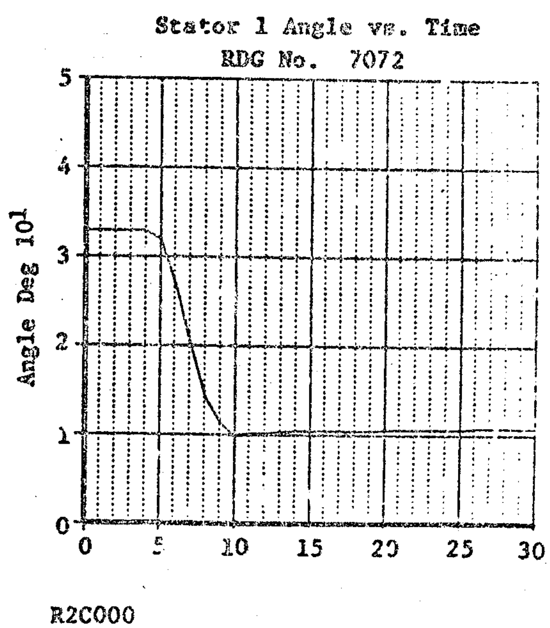


Figure 84. Throttle Burst - Maximum Fuel Schedule

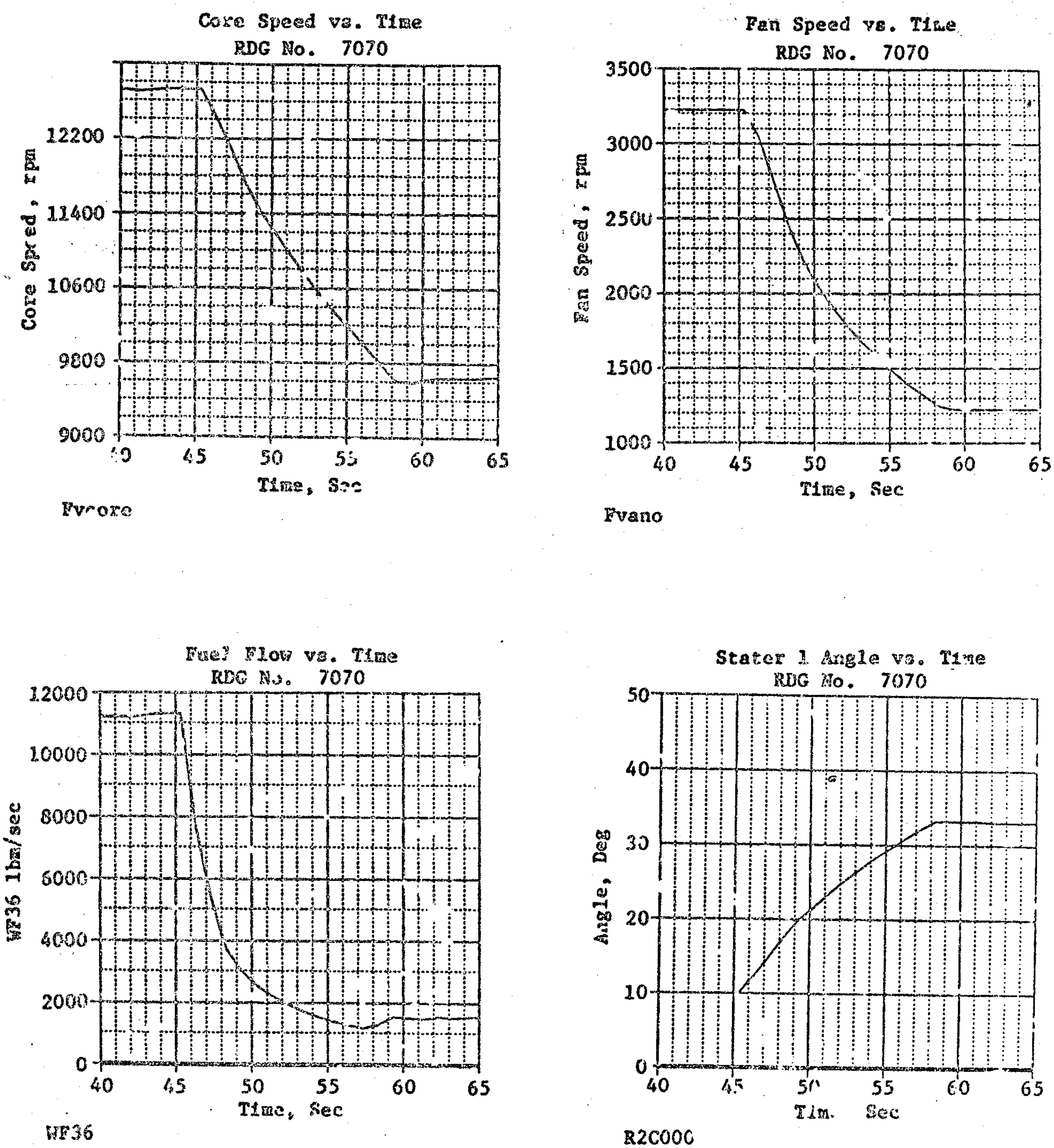


Figure 85. Typical Deceleration Transient

discharge temperature T42, and compressor discharge pressure PS3). Each sensor was multiplied by an engineering operator panel potentiometer which was scaled from .5 to 1.5 (nominal value is 1.0). A switch on the engineering operator panel was used to enable the multipliers.

To induce a simulated sensor failure, the potentiometer associated with the sensor to be failed was adjusted to a value beyond the FICA tolerance and the switch was then activated to create a step change in the sensor value as seen by the control strategy. The FICA then substituted the estimated value for the sensed value. This method was used to demonstrated single and double sensor failures.

The table below summarizes the simulated sensor failures demonstrated. (NOTE: PCNLR refers to percent fan corrected speed.)

Simulated Sensor Failure(s)	Range Tested	Comments
Compressor Discharge Temp. (T3)	40% PCNLR to Max T42	Normal system operation
HPT Discharge Temp. (T42)	40% PCNLR to Max T42	Normal system operation
Compressor Inlet Temp. (T25)	40% PCNLR to Max T42	Normal system operation
Fan Speed (XNL)	40% PCNLR to Max T42	Normal system operation
Core Speed (XNH)	40% PCNLR to 60% PCNLR	Marginally acceptable system operation
Compressor Discharge Static Pressure (PS3)	40% PCNLR	Normal system operation
XNL & T3	40% PCNLR to Max T42	Normal system operation
XNL & T42	40% PCNLR to Max T42	Normal system operation
XNL & T25	40% PCNLR to Max T42	Normal system operation

All simulated sensor failures except core speed produced normal operation both steady state and transiently. A typical transient with one simulated sensor failure is shown on Figure 86 and a similar transient with two simulated sensor failures is shown on Figure 87.

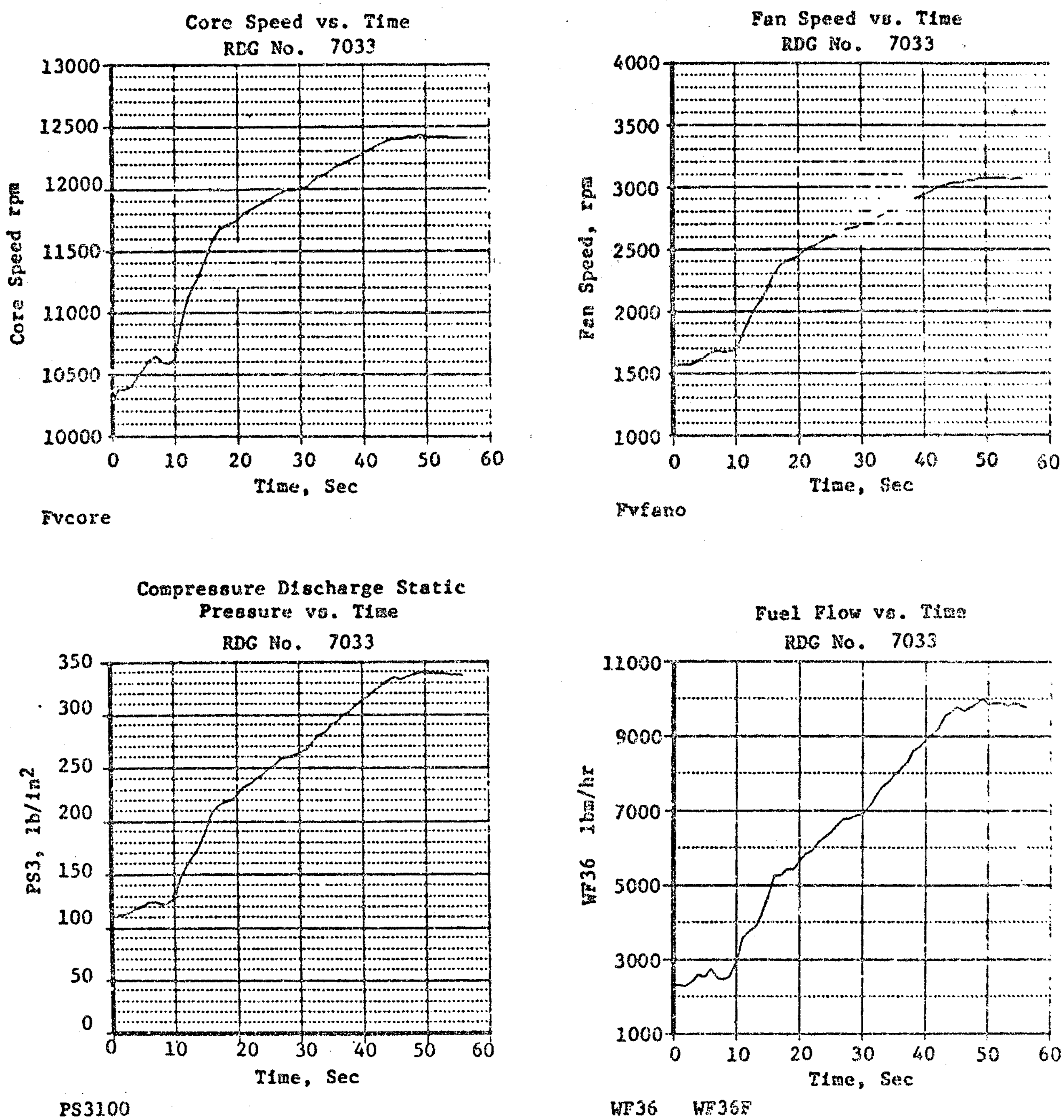
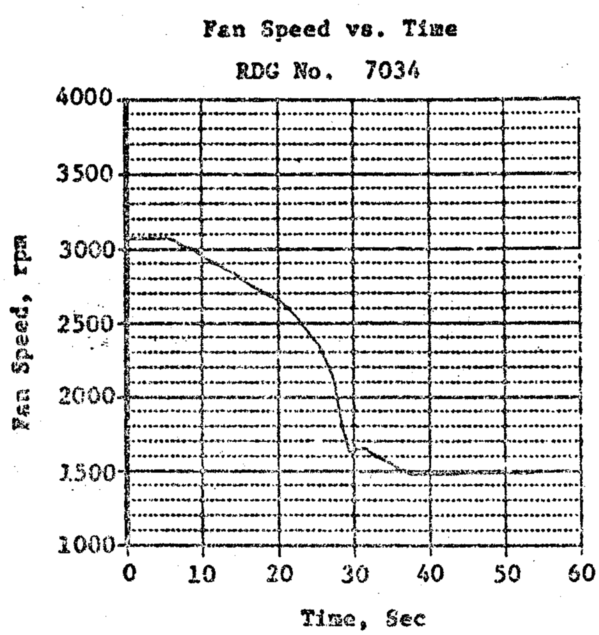
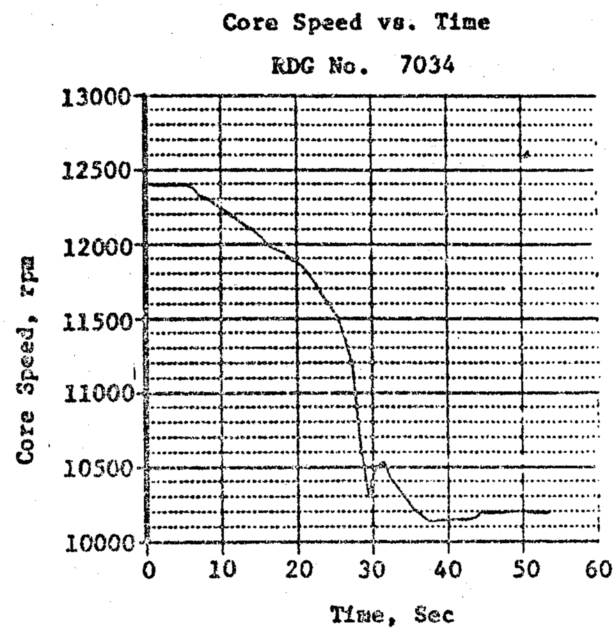


Figure 86. FICA Acceleration & Deceleration with T3 Failed (Sheet 1 of 2)





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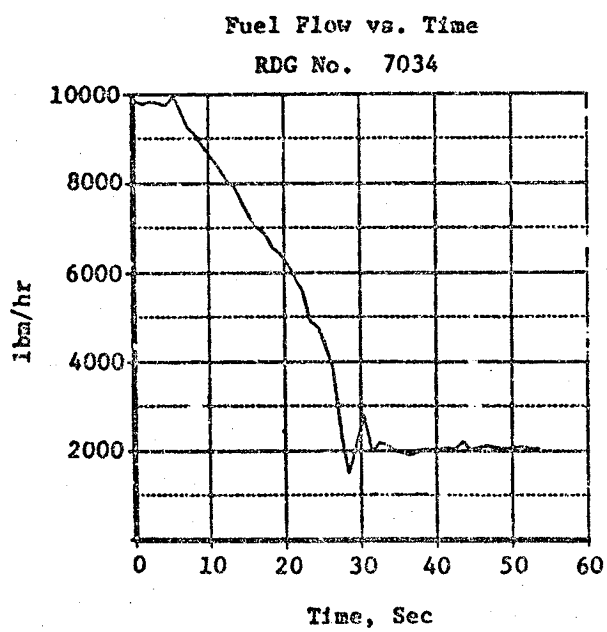

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Figure 86. FICA Acceleration and Deceleration with T3 Failed (Sheet 2 of 2)

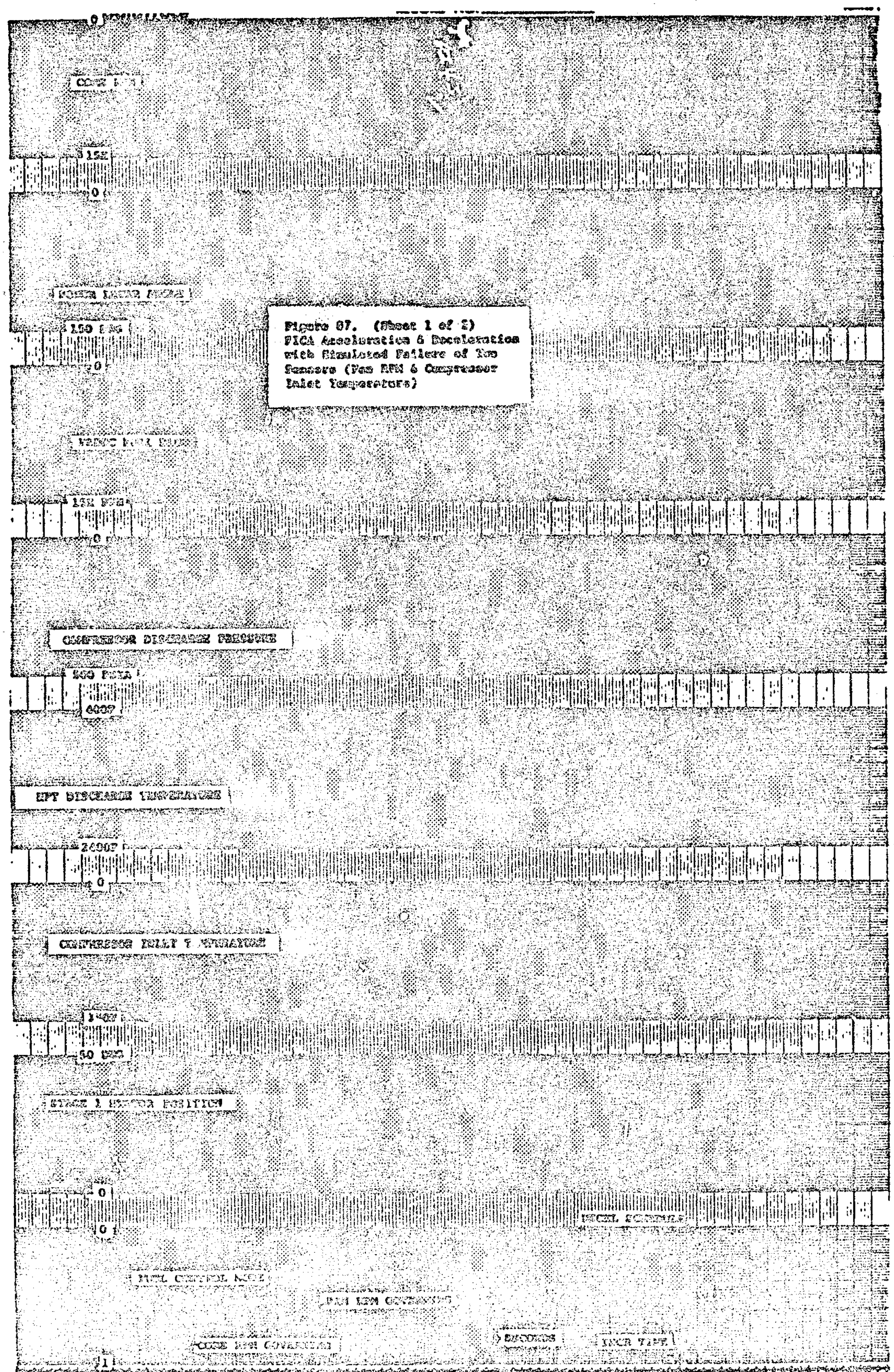

Figure 87. (Sheet 1 of 2) FICA Acceleration & Deceleration with Simulated Failure of Two Sensors (Fan RPM & Compressor Inlet Temperature)

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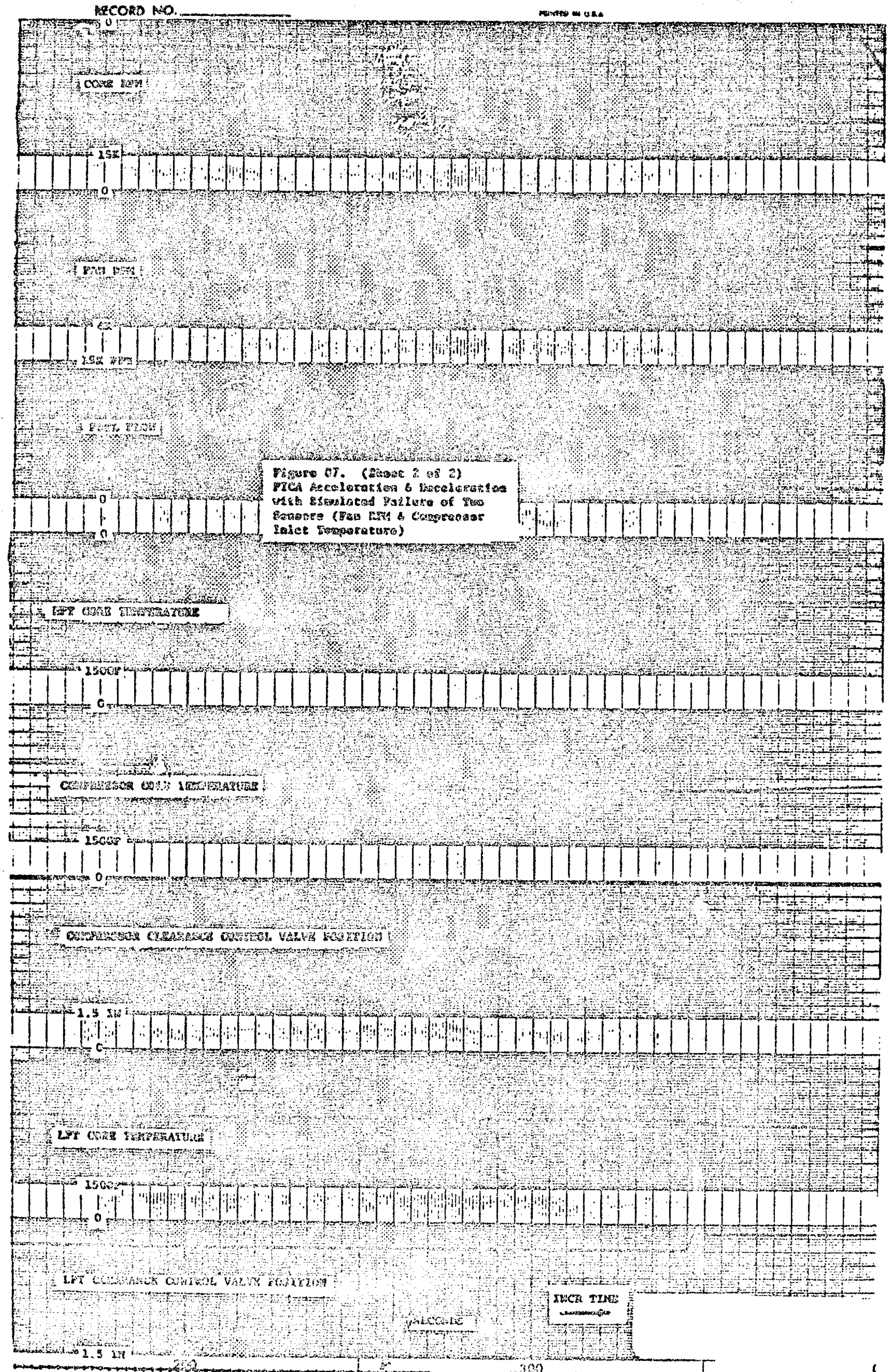

Figure 87. (Sheet 2 of 2) FICA Acceleration & Deceleration with Simulated Failure of Two Sensors (Fan RPM & Compressor Inlet Temperature)

Simulation of a core speed sensor failure produced marginally stable results. The first attempt was made with the engine on core speed control at just under 20 percent thrust. An instant after the simulated failure, substituted core speed from the FICA model jumped to a level above actual core speed causing the control to reduce fuel flow and open the core stators a small amount. The combined effect was a fuel-air ratio reduction of sufficient magnitude to cause loss of combustion and engine shutdown.

A second attempt was made at the same thrust level but with the PLA schedule adjusted so that fuel flow was under fan speed rather than core speed control. Simulation of a core speed sensor failure caused the engine to break into an oscillation as shown on Figure 88. Adjustment of the PLA schedule to re-establish core speed control of fuel flow caused the amplitude of the oscillations to increase.

Preliminary analysis of this second attempt indicated that the oscillation was aggravated by the core stator effect on air flow through fan and core speed. In an attempt to reduce this effect the servovalve null shift compensation in the stator control loop was deleted and a third simulation of a core speed sensor failure was made at the same conditions as in the previous attempt. As shown on Figure 89, this again produced an oscillation but it was smaller in amplitude than in the previous case. A slow acceleration to 40 percent thrust caused no increase in the oscillation but an attempt to re-establish core speed control of fuel flow by PLA schedule adjustment had to be abandoned because it produced excessive oscillation amplitude.

Time did not permit more extensive investigation relative to FICA core speed sensing substitutions. A further investigation should evaluate potential improvements such as the incorporation of core stator effects in the FICA model and the modification of Update Matrix coefficients after sensor substitution.

Overall, the ICLS FICA testing was a worthwhile step forward in the evolution of this processing concept for improving future engine control system operation reliability without added hardware. Simple FICA implementations have been tested in the past but the ICLS FICA brought together an engine model based on component equations and a multiple-element

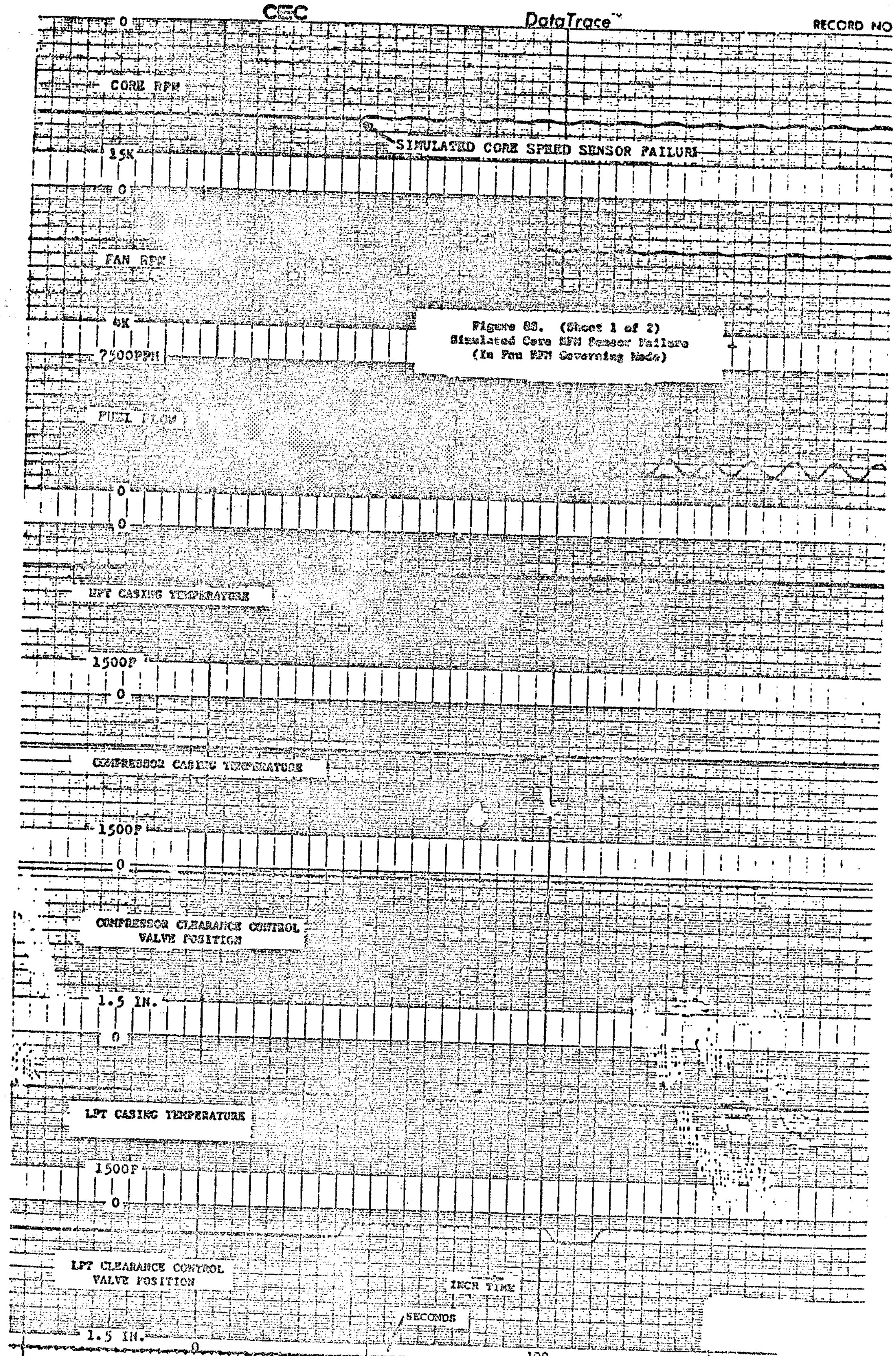

Figure 83. (Sheet 1 of 2)
Simulated Core RPM Sensor Failure
(In Fan RPM Governing Mode)

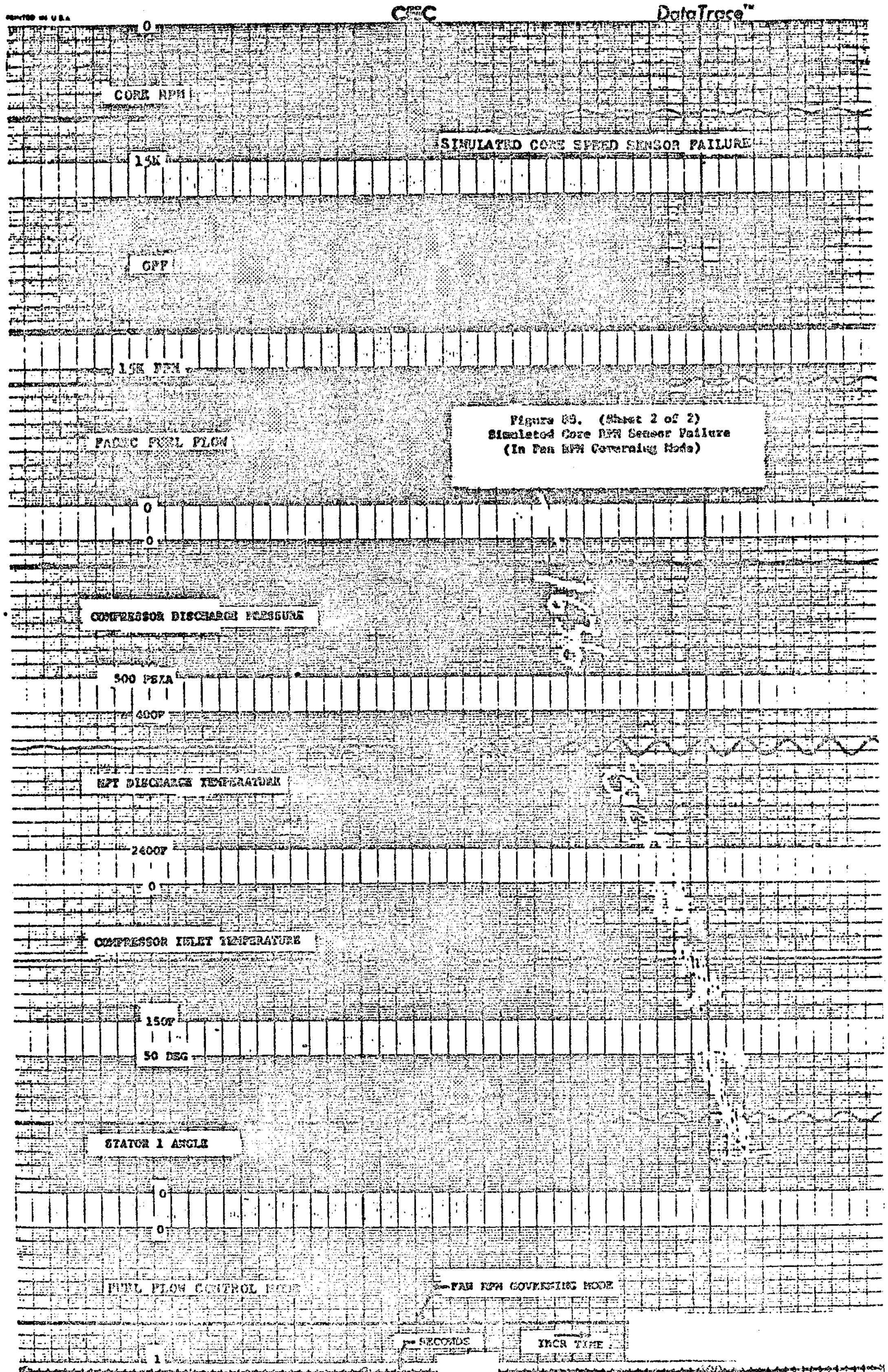

Figure 89. (Sheet 2 of 2)
Simulated Core RPM Sensor Failure
(In Fan RPM Governing Mode)

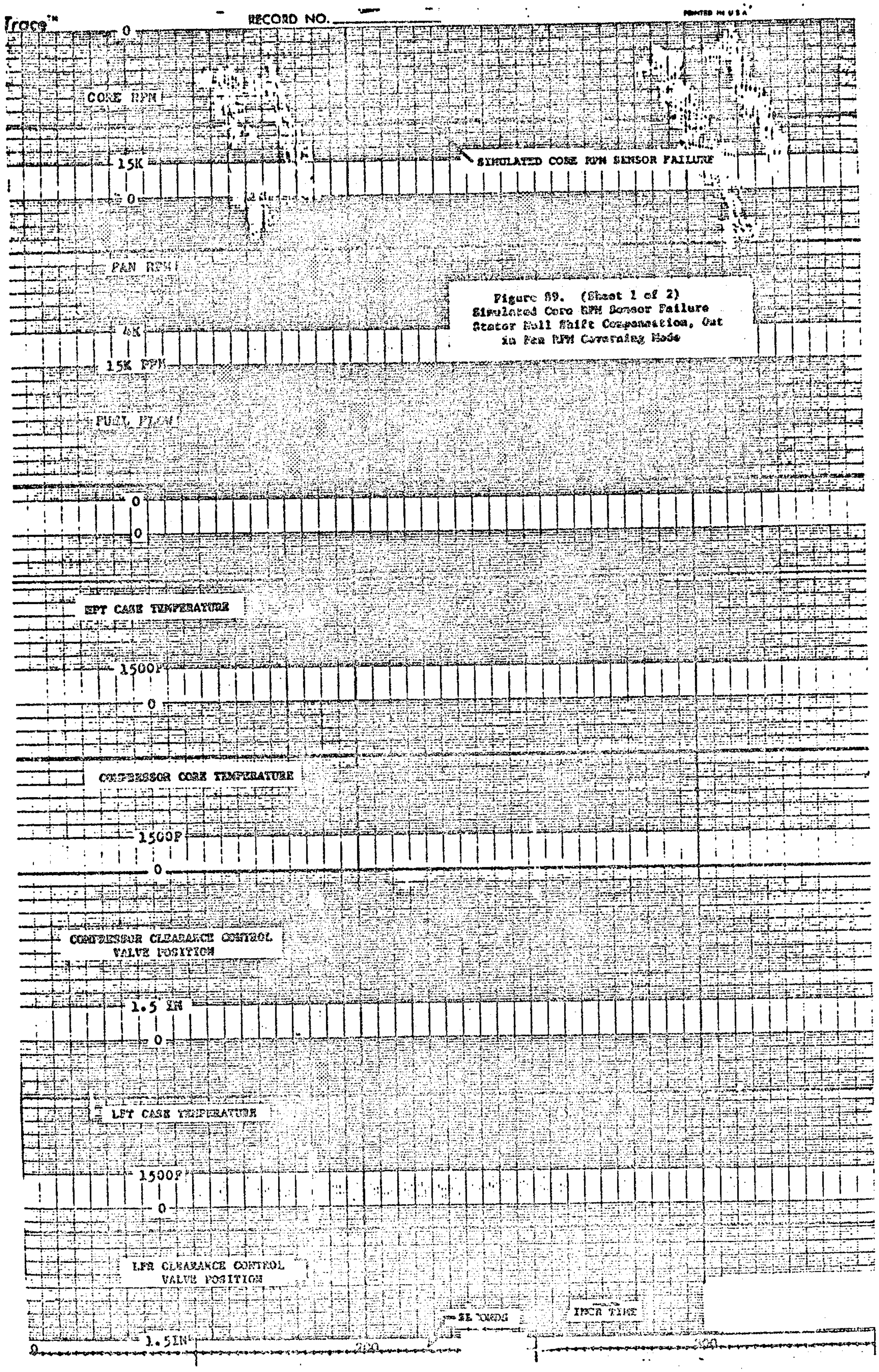

Figure 89. (Sheet 1 of 2)
Simulated Core RPM Sensor Failure
Stator Null Shift Compensation, Out
in Fan RPM Governing Mode

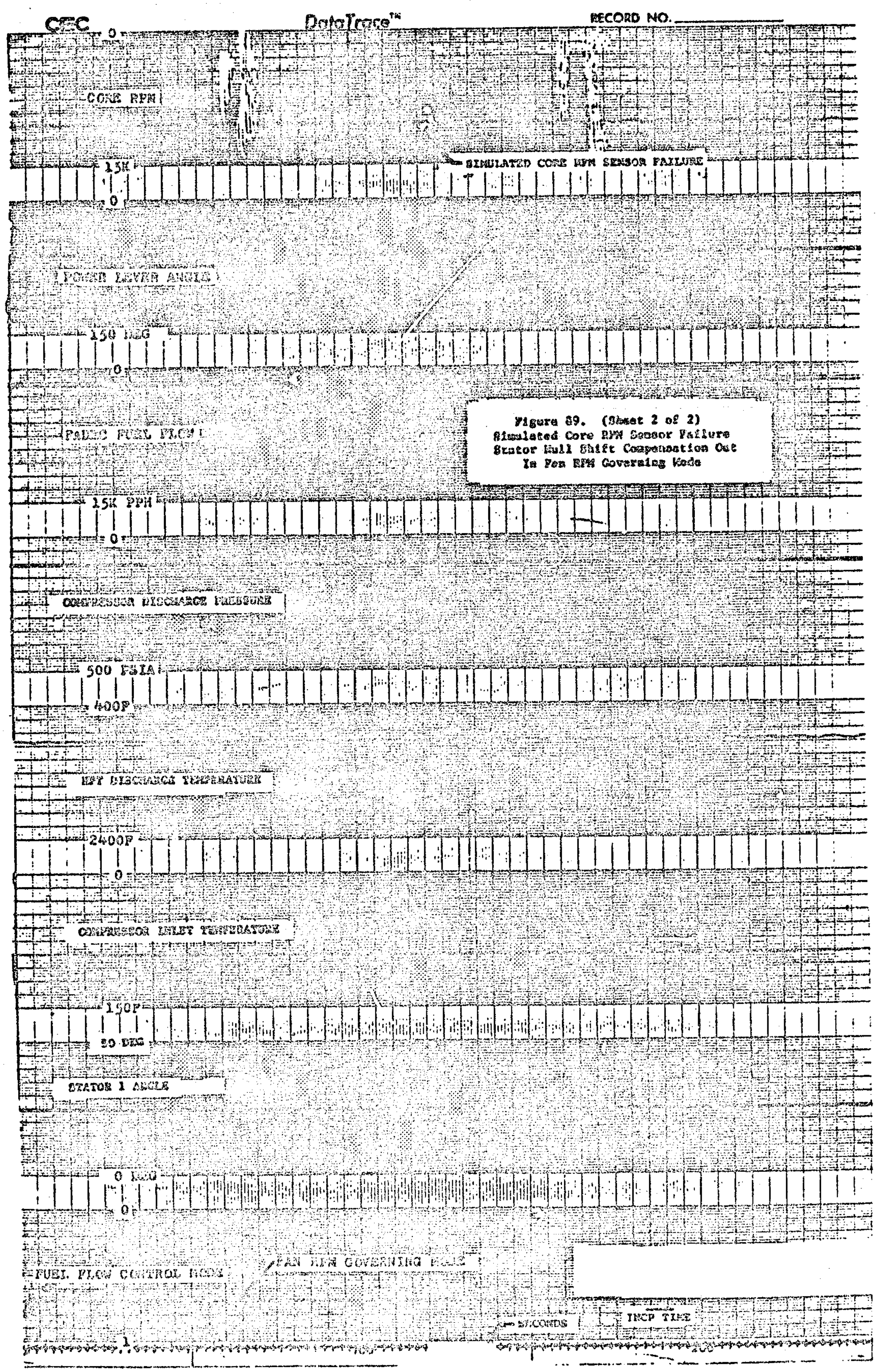

Figure 89. (Sheet 2 of 2)
Simulated Core RPM Sensor Failure
Stator Null Shift Compensation Out
In Fan RPM Governing Mode

Model Update Matrix that, in combination, offer improved potential for full flight map suitability. The ICLS testing showed this combination to be generally satisfactory and identified potential improvements for future evaluation as noted above.

8.10 FADEC OPERATING CONDITIONS

The on-engine FADEC operated satisfactorily throughout the ICLS test. It was mounted on the outside of the fan frame at the 3 o'clock position (aft looking forward) using four soft isolation mount elements. Vibration characteristics in this vicinity were recorded and are discussed in the Engine Dynamics section of Reference 3.

FADEC cooling air was supplied from the test facility at approximately 172.4 kPa (25 psia) and at essentially ambient temperature. Calculated airflow at these conditions is 0.011 kg/sec (0.024 lbs/sec) as limited by the 0.9525 cm (3/8 inch) inlet fitting on the FADEC cooling manifold. Internal temperature of the FADEC ran 6°C to 11°C (10°F to 20°F) above ambient temperature with the maximum differential when the FADEC was in direct sunlight and the minimum differential at night.

8.11 SWITCH TO BACK-UP

For safety reasons, an F101 hydromechanical fuel control was included as a fuel and stator backup for the single channel FADEC. Because of excellent FADEC operation, the backup was not needed at any point in the test program but an intentional switchover to the backup mode proved the suitability of this design as shown in Figure 90.

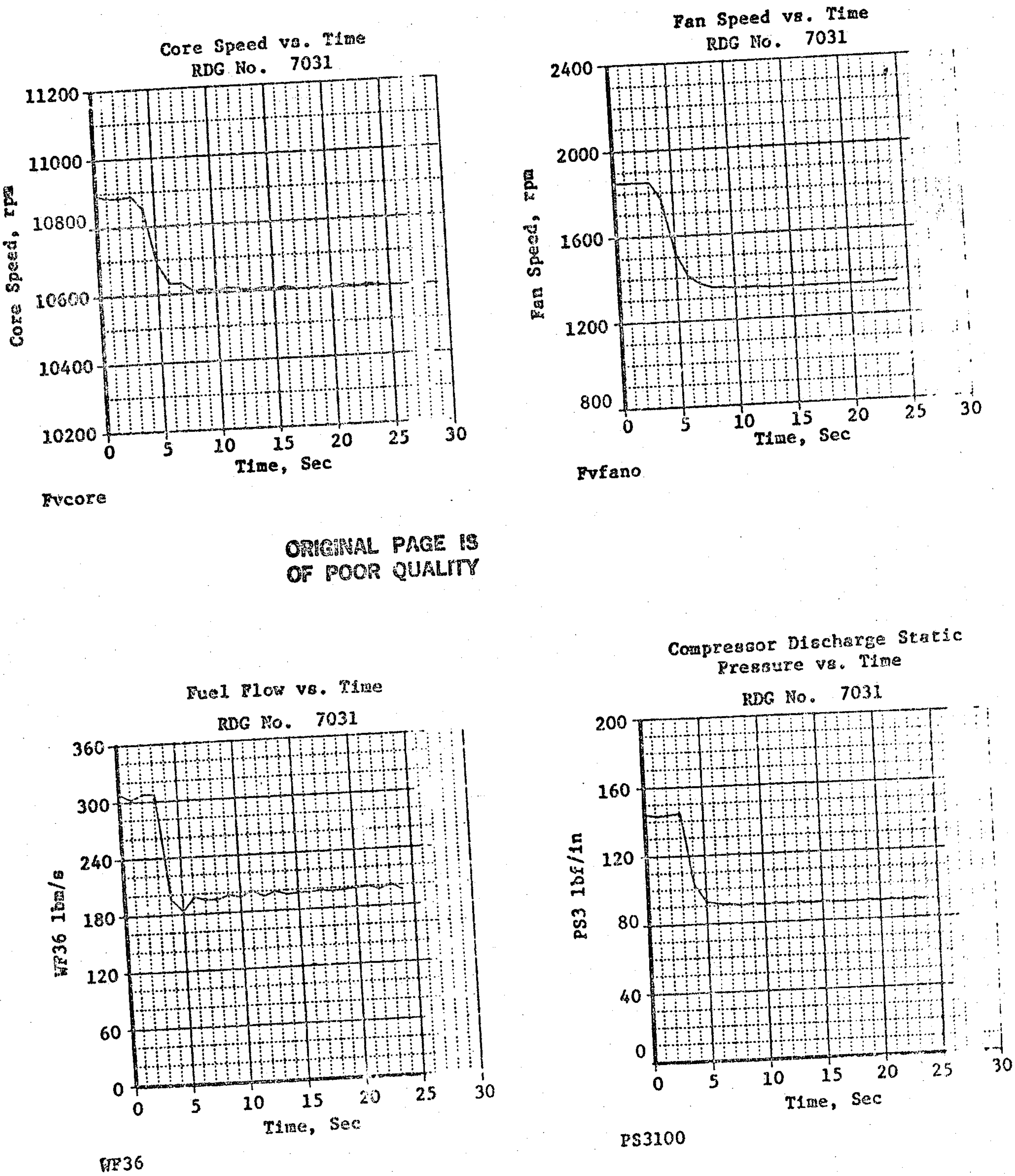

Figure 90. Trip to Backup Control

9.0 REFERENCES

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2. Bennett, G.W., "ICLS Control System Test Memo", General Electric Report No. R83AEB215, 1983.

3. Stearns, E.M. and Davis, D.Y. "Integrated Core/Low Spool (ICLS) Test Vehicle Design and Performance Report", NASA Report No. CR168211, 1984.

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16. Abstract

An Energy Efficient Engine (E^3) program was established to develop technology for improving the energy efficiency of future commercial transport aircraft engines. As part of this program, General Electric designed and tested a new engine. This report summarizes the design, fabrication, bench and engine testing of the Full Authority Digital Electronic Control (FADEC) system used for controlling the E^3 Demonstrator Engine. The system design was based on many of the proven concepts and component designs used on the General Electric family of engines. One significant difference is the use of the FADEC in place of hydromechanical computation currently used.

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