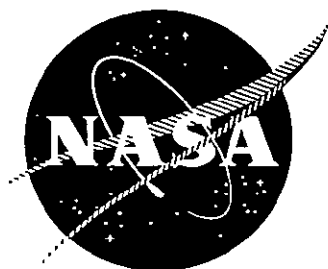


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QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE)

Over-the-Wing Engine Digital Control System Design Report

DECEMBER 1977

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EXPERIMENTAL ENGINE (QCSEE) OVER-THE-WING
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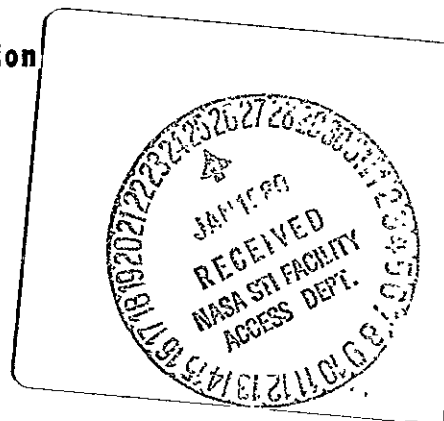
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16. Abstract A control system incorporating a digital electronic control is designed for the QCSEE Over-the-Wing engine. The digital electronic control serves as the primary controlling element for engine fuel flow and core compressor stator position. It also includes data monitoring capability, a unique failure indication and corrective action feature, and optional provisions for operating with a new type of servovalve designed to operate in response to a digital-type signal and to fail with its output device hydraulically locked into position.		
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1.0 SUMMARY

The QCSEE Program was established under NASA sponsorship to develop and demonstrate the technology required for propulsion systems for quiet, clean, economically viable, commercial short-haul aircraft. One element of the program has been to develop a digital electronic control system that provides a propulsion engine control in a manner which offers improvements in noise, pollution, thrust response, operational monitoring, and pilot workload, relative to current engines. This report describes the design of the control system for the second of the two engines in the QCSEE Program, the Over-the-Wing (OTW) engine.

The OTW experimental engine control system controls two variables: fuel flow and compressor stator angle. From a hardware viewpoint, the OTW system has been designed for maximum interchangeability with the UTW (Under-the-Wing) engine control system that preceded it. Both systems include a modified F101 hydromechanical fuel control and an engine-mounted digital electronic control specifically designed for QCSEE engines; however, the memory modules of each engine's respective digital computer are unique.

New technology features to be demonstrated on the OTW experimental engine control system are:

1. Full Authority Digital Control - The OTW digital control will be programmed to provide steady-state control, transient fuel schedules, core stator schedules, and limiting fuel-control functions, whereas the transient fuel schedules were performed hydromechanically on the UTW engine.
2. Failure Filter - A new Failure Identification and Corrective Action (FICA) scheme will be demonstrated on the OTW engine. The scheme employs a form of Kalman filtering in which a model of the engine is included in the digital control program to estimate the control system sensor outputs. Model inputs are control outputs and the control system sensor outputs. If the sensors are functioning properly, the model outputs will be corrected to reflect the actual sensor outputs. But if a large error occurs between a model-computed sensor value and the actual, sensed value, a failed sensor is indicated and that sensor is no longer used in the control. However, the engine operation will continue with only a slight reduction in control accuracy.
3. Fail-Fixed Servovalve - The OTW control system will demonstrate a two-stage electrohydraulic servovalve similar to current designs but modified so that the most likely electrical input signal failures (loss of signal or failure to full signal level) cause the device being controlled by the servovalve to be hydraulically locked at its existing position.

To implement the electrical compressor stator control, a new fuel-powered servovalve assembly (standard design) has been added to the control configuration, as well as an LVDT to sense core stator position. The torque motor and LVDT have been designed for compatibility with the digital control circuitry from the UTW configuration so that, from an interface viewpoint, the digital controls for UTW and OTW are interchangeable.

A control mode analysis was performed to identify the preferred method of automatic control of an OTW flight design which would require control of a variable area exhaust nozzle in addition to the two variables being controlled on the experimental engine. This analysis involved the use of a computer program that evaluated many potential control modes relative to the accuracy with which they maintain key engine variables when subjected to typical control and manufacturing tolerances, sensing tolerances, and hardware deterioration. Scheduling practicality, stability, and response were other factors evaluated in the analysis. The primary control mode chosen is one in which 1) fuel flow controls corrected fan rpm, 2) the compressor stators are scheduled as a function of corrected core rpm, and 3) the exhaust nozzle is scheduled as a function of power demand and/or flight condition. Since the experimental OTW engine will not have an operationally controllable exhaust nozzle, the latter function will not be demonstrated. The design of a nozzle actuation and control system for a flight-design engine can be extrapolated from current variable geometry actuation system design technology.

The system contains provisions for monitoring and displaying forty-eight engine and control variables, for detecting certain malfunctions, and for taking corrective action in the event of some critical malfunctions such as fan drive gear failure, high vibration, and certain digital computation faults.

An F101 fuel pump is utilized in the system for supplying fuel for engine operation, for operating servomechanisms in the hydromechanical control, and for providing a source of high-pressure fuel for operation of the actuators that position the core compressor stator vanes.

2.0 INTRODUCTION

The QCSEE Program is a program established by NASA to develop and demonstrate propulsion system technology for an advanced, short-haul, commercial aircraft having short-takeoff-or-landing (STOL) capability and producing less noise and atmospheric pollution than current aircraft. A number of specific technological objectives were established at the beginning of the program. One of these was to provide the digital electronic control technology required to accommodate certain specific QCSEE features that are not included in current commercial aircraft propulsion systems.

Control systems for current commercial aircraft turbine engines, most of which have only one or two controlled variables, use primarily hydraulic and mechanical computing elements. This combination has generally proven adequate, though recently there has been a move toward adding limited-authority electronic trim of the hydromechanical controls to provide more automatic control of thrust and thus reduce pilot workload.

The QCSEE Program definitely requires engine control system capability beyond that provided on current commercial engines - even those incorporating limited electronic trims. The main reasons are:

- More variables must be controlled.
- Automatic responsive engine and aircraft control coordination is required for STOL operation near the ground, where the engines provide lift-assist as well as thrust.
- Automatic thrust control throughout the flight envelope is desired, to reduce pilot workload.
- Engine and control data transmittal to the aircraft are desired for operational and engine health monitoring.
- Automatic failure detection and corrective action are desired for certain key control system sensors.

Consideration of these new functional requirements, in conjunction with the recognition of the trend toward using digital computation in aircraft control and indication systems, led to the QCSEE Program objective stated above; namely, that digital electronic technology be developed for incorporation into the QCSEE control system. This report describes in detail how this is being done and how the digital electronic elements are mated with the more traditional engine control elements to comprise the QCSEE OTW control system.

The following section outlines the basic system design requirements and gives an overall description of the design. Analytical background material follows this. The rest of the report gives design details of the individual system components.

3.0 ENGINE CONTROL SYSTEM

3.1 DESIGN REQUIREMENTS AND CRITERIA

The QCSEE OTW control system design is based on requirements and design criteria established by the QCSEE Program contract and by the nature of the OTW engine, a cross section of which is shown in Figure 1. The major requirements are outlined below.

General System Design - Design a digital control system for controlling the OTW engine, utilizing existing controls and accessories (where applicable) supplemented by digital electronics to perform most major functions and to provide a flexible interface with a powered lift aircraft.

Operating Regime - Design for ground static, wind tunnel, and altitude chamber operation. The flight envelope is to be as shown on Figure 2.

Flight Design - Design for flight operation (i.e., flight weight, performance) except for designated exceptions made for cost purposes. Control system-related exceptions include: accessories and accessory gearbox, heat exchangers, piping, wiring, drains, vents, and the auxiliary power supply. Analyses shall be performed on all nonflight hardware to provide flight weight and performance predictions considering flight design life requirements.

Variables To Be Controlled - The QCSEE OTW experimental engine requires control of two variables: the fuel flow and the compressor stator angle. For a flight design, the exhaust nozzle area would also be controlled.

Experimental Engine Flexibility - The system shall include a way to make adjustments in the control strategy without changing the hardware. The digital control shall be designed for easy replacement of its law memory modules.

Control Capability - The system shall be capable of coordinated control variables so that STOL aircraft propulsion test investigations can be performed that would try to achieve:

- Thrust control throughout the specified flight map with minimum pilot workload.
- Fast thrust response: 62 to 95% forward thrust in one second.

Engine Protection - The system shall protect the engine from rotor overspeeds, turbine overtemperature, and excessive compressor or fan pressure.

Bleed and Power Extraction - The system shall be compatible 1) with air bleed of up to 13% core airflow, and 2) with power extraction up to 2.2 hp per 450 kg (1000 lb) of installed thrust, for aircraft use. Neither will be demonstrated in the initial QCSEE Program.

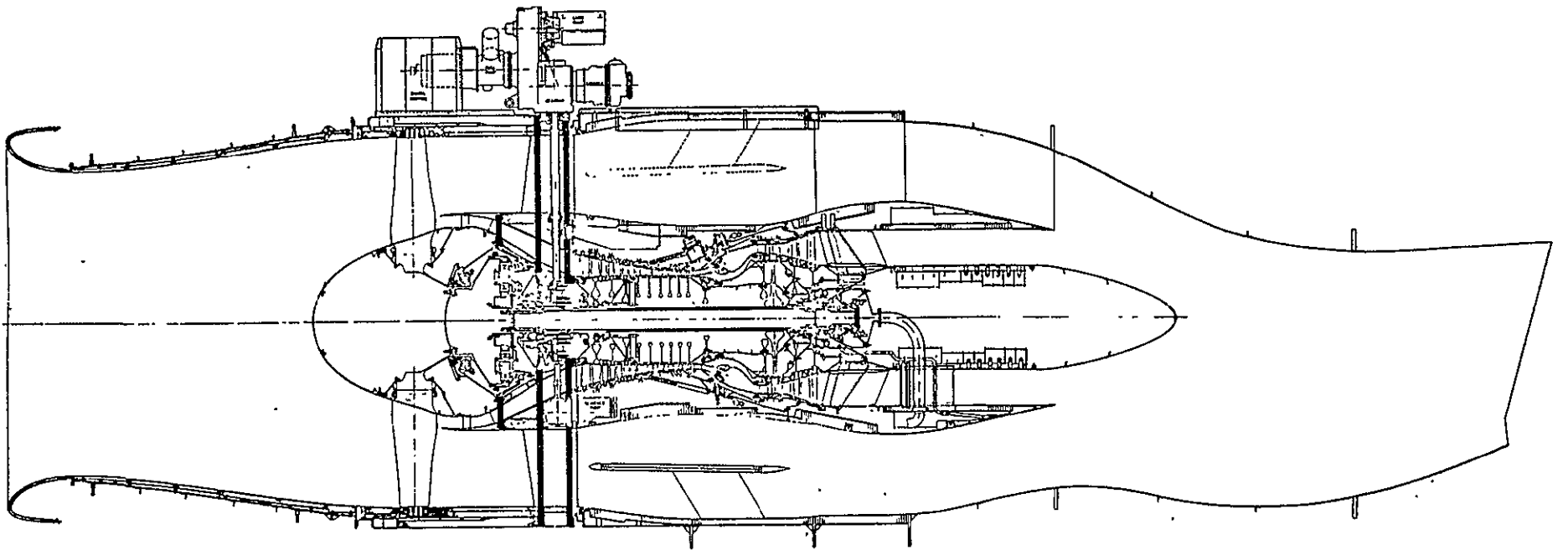


Figure 1. OTW Experimental Propulsion System.

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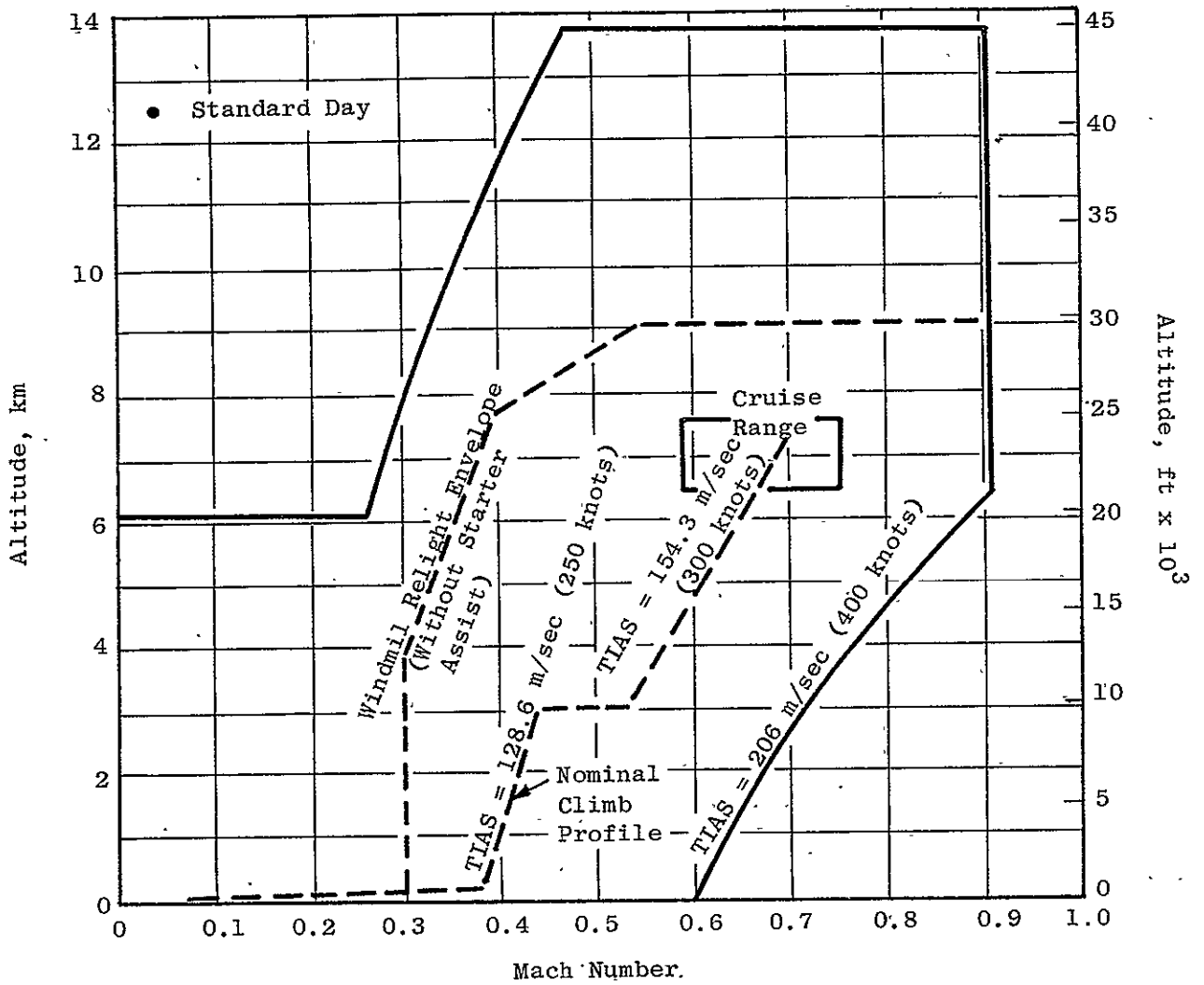


Figure 2. QCSEE OTW Operating Envelope.

Starter - Design for use of a typical, current, commercial transport starter.

Altitude Starts - Capability the same as present commercial transports as shown on Figure 2.

Overboard Drainage - There shall be no overboard fluid leakage during normal operation.

Maintainability - The system shall be compatible with the following engine maintainability goals:

- The engine shall be easily removable from the nacelle without requiring removal of the fan exhaust duct once the engine is installed.
- The engine shall be capable of being trimmed on a test stand, with no additional trimming required if installed on an aircraft.
- Accessories shall be located for easy inspection.
- Access to borescope ports shall be provided without requiring removal of any engine component.
- Any propulsion system accessory shall be replaceable in 45 minutes.
- Modular construction is desired to facilitate maintenance.

Supplementing the requirements and design criteria outlined above, a set of aircraft-oriented general principles for automatic control of the QCSEE engine was established early in the program based on coordination with NASA, McDonnell Douglas, and Boeing. These principles are:

1. A separate power lever link is assumed from the aircraft to the engine, to be used as an enable and for backup fuel control only.
2. A digital electrical signal is assumed from the aircraft computer to the engine digital control, demanding percent of available thrust.
3. A digital electrical mode signal is assumed from the aircraft computer to the engine digital control to select between available operating modes such as takeoff, climb, cruise, etc.
4. The engine digital control shall compute maximum rated thrust at all flight conditions and shall be capable of setting this thrust, or any portion of it, as a function of a single aircraft thrust demand signal (unless some safety limit such as rotor speed or gas temperature prevents attainment of full thrust).
5. The engine control system shall provide selected engine safety limits that protect against rotor overspeeds, fan or compressor stall, turbine overtemperature, and compressor discharge overpressure.

6. Manual control of thrust via the throttle shall be maintainable within safe limits if the engine digital control and/or aircraft digital control fails.
7. It is desirable that no throttle or thrust demand changes be required during takeoff except in the event of an abort.

3.2 GENERAL SYSTEM DESCRIPTION

A schematic diagram of the QCSEE OTW Control System is shown in Figure 3. The digital electronic control is the heart of the system, and controls the manipulated variables in response to commands representing those that would be received from an aircraft propulsion system's computer. The system includes an existing (F101) hydromechanical control, as called for in the program requirements. This control includes an electrohydraulic torque motor servovalve (TM) through which the digital control maintains primary control of fuel flow. A separate electrohydraulic servovalve controls the flow of compressor stator actuation fuel in response to a control signal from the digital control. A fuel-operated servomechanism in the hydromechanical control serves as a backup core speed governor.

The hydromechanical control is mounted on an F101 fuel pump, which is a centrifugally boosted, positive displacement, vane pump. Pump discharge flow is delivered to the control through the mounting interface; the control returns excess fuel to the vane element inlet through a similar channel.

The fuel system includes an eductor to evacuate interstage seal cavities within fuel-handling components and thus reduce the possibility of external fuel leakage.

In order to achieve the operational flexibility required by the QCSEE Program, the commands to the digital electronic control are being introduced through the control room elements shown on Figure 4. The interconnect unit, operator panel, and engineering panel are actually peripheral elements of the digital control. They provide the means for the engine operators to introduce commands; to adjust various control constants, and to monitor control and engine data. The remote computer is a separate digital computer system supplied by NASA to represent a typical aircraft computer.

In addition to these digital commands from the control room, the system also receives a mechanical input in the form of a power lever angle (PLA) transmitted to the hydromechanical control. This serves as an input to the backup core-speed governor and operates a positive fuel shutoff valve in the control.

A number of control and engine variables are sensed by the control system. These are shown schematically in Figure 5 and discussed briefly below.

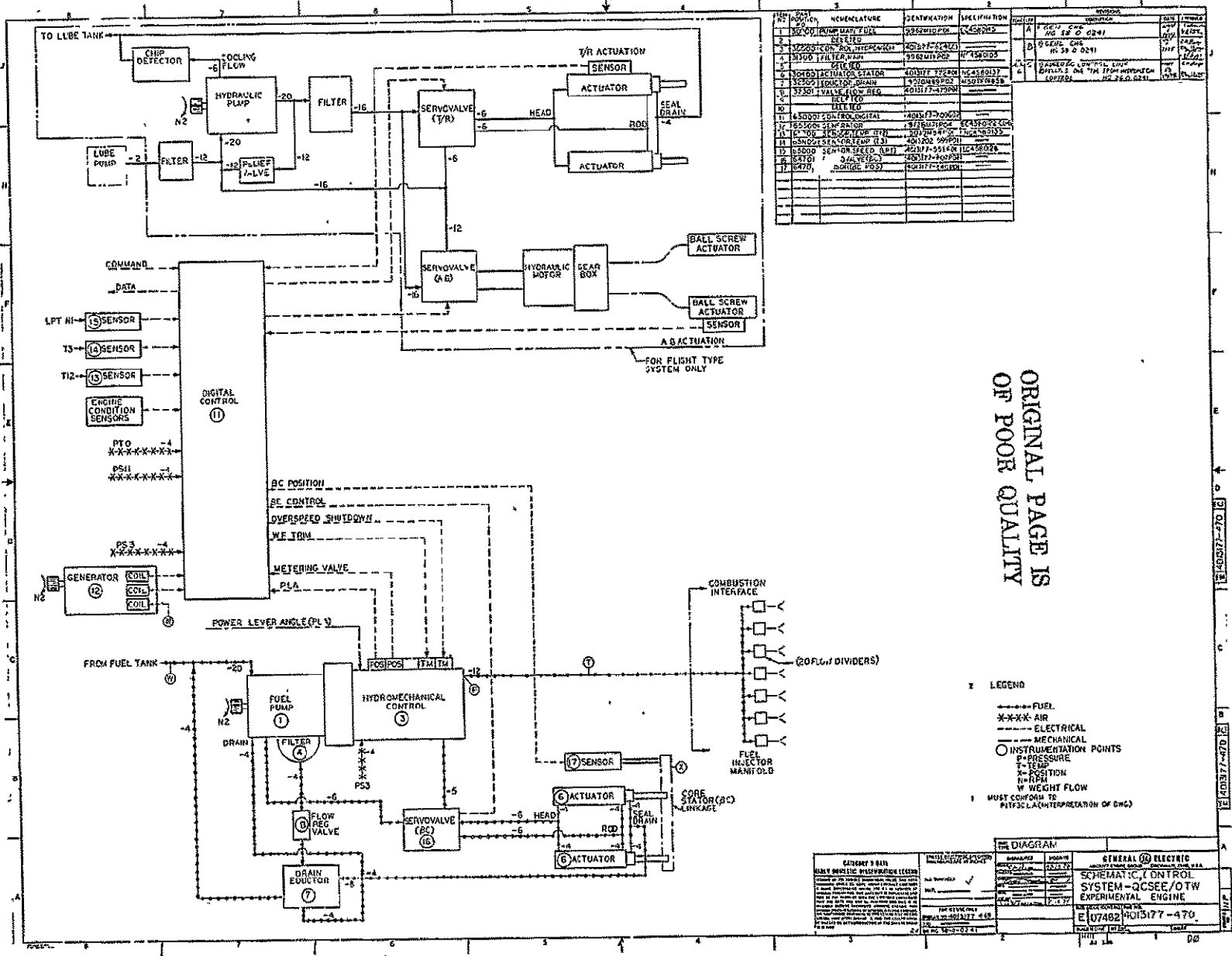


Figure 3. System Schematic.

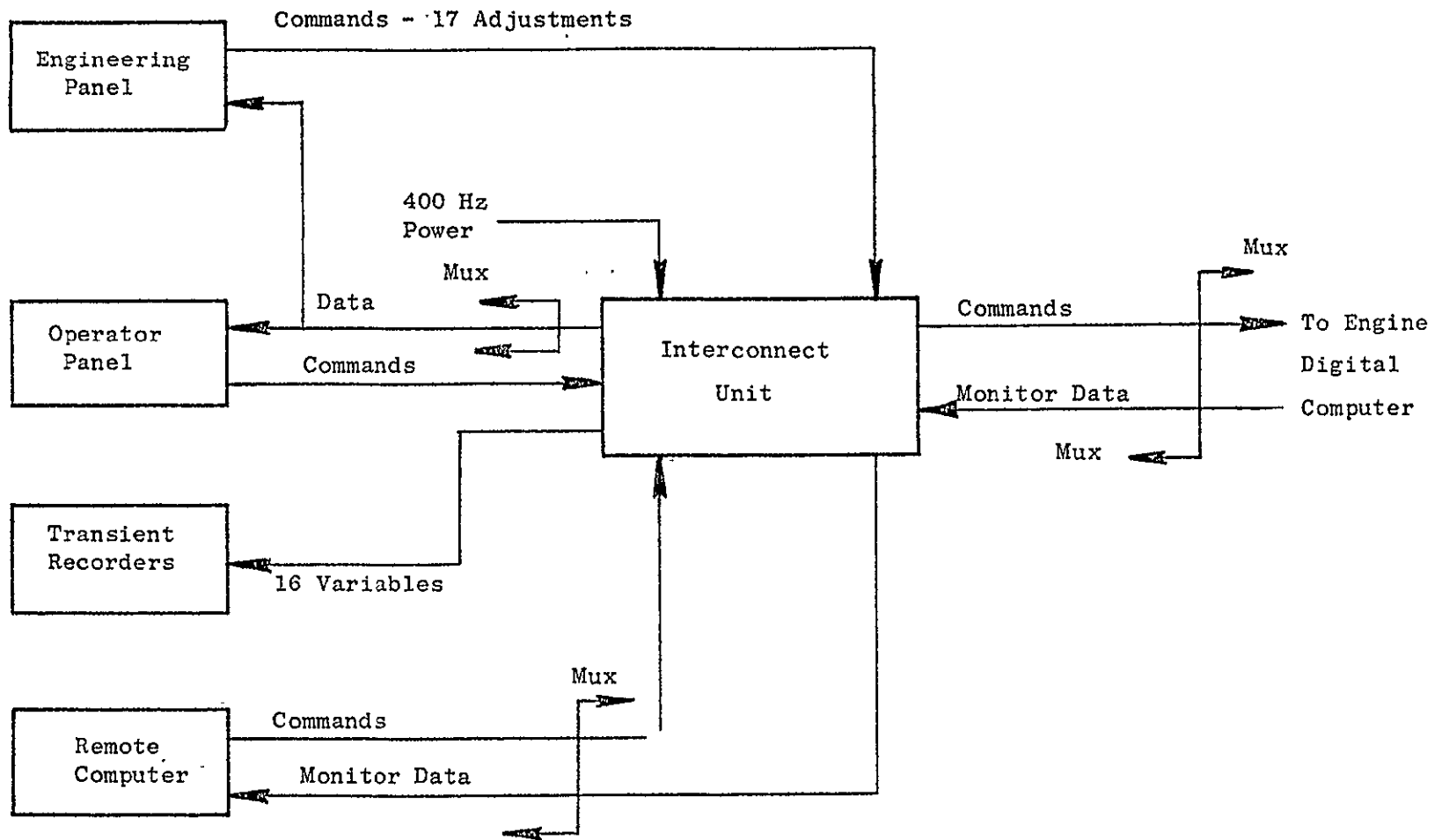


Figure 4. Control Room Elements of QCSEE Digital Control.

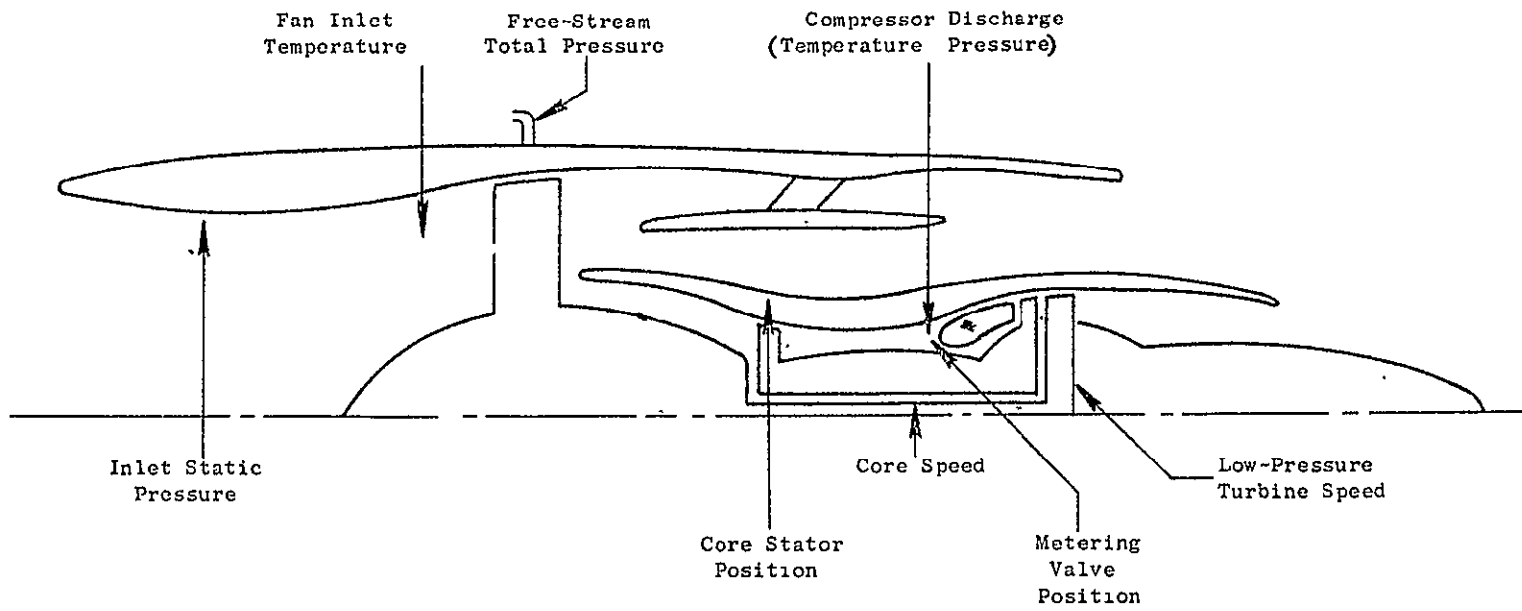


Figure 5. Sensed Engine and Control Variables.

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Core Speed - This speed is sensed electrically by measuring the output frequency of the generator that powers the digital control computer, and is sensed mechanically by a rotational input from the accessory gearbox to the hydromechanical control.

Low-Pressure Turbine Speed - This speed, which is proportional to fan speed, is sensed by a stationary magnetic pickup located near a multi-toothed disk that rotates with the turbine shaft. A turbine speed signal is preferred to a fan speed signal because, first; it is mechanically simpler to acquire, and second, it remains available to begin the correcting of a turbine overspeed, which might result from a fan or fan gearing failure.

Core Stator Angle - This is sensed by means of electrical position transducers (linear differential transformers) in the core stator actuation system. Because core stator angle is crucial to satisfactory engine operation, two sensors are used. They are averaged by the digital control and protection is provided against failures of either unit as described in Section 3.3.3.

Compressor Discharge Pressure - This is sensed through a static pressure tap in the entrance to the engine combustor and piped to a pressure-to-electrical transducer in the digital control.

Compressor Discharge Temperature - This is sensed by a chromel-alumel thermocouple at the entrance to the core combustor.

Metering Valve Position - This is used as a measure of fuel flow in the digital control and is sensed with a transducer (rotary differential transformer) in the hydromechanical control.

Engine Inlet Static Pressure - This is sensed through two static taps in the inlet duct wall and piped to one side of a differential pressure transducer in the digital control. The taps are on the inlet horizontal centerline and are diametrically opposed to minimize angle-of-attack and crosswind effects. They are located in a position near the inlet throat - a position which NASA model data indicates will give the most consistent pressure reading (Reference Paragraph 4.9).

Fan Inlet Temperature - This is sensed by an electrical resistance temperature detector protruding through the inlet wall into the airstream.

Free-Stream Total Pressure - This is sensed by means of a total-pressure probe on the bottom centerline of the nacelle extending into the external airstream. This pressure is actually used as a measure of engine inlet total pressure but is sensed outside where the probe will not be affected by the aerodynamic distortions that can exist inside the inlet, and will thus give a more consistent indication of average inlet total pressure.

3.3 SYSTEM OPERATION

The OTW experimental engine control system has one basic mode of operation with several optional operational features, any of which can be turned on or off by switches in the control room. In the basic operating mode, fuel flow is manipulated to control corrected fan rpm, and the core compressor stator angles are scheduled as a function of corrected core rpm. Details of this operating mode and the optional features are given below.

3.3.1 Control of Fuel Flow

A simplified schematic of the fuel control system is shown in Figure 6. (Detailed block diagrams of the digital portion of this schematic are included in Appendix B.) A fan speed (N_1) demand is computed as a function of a digital power setting input from the control room and T_{12} . N_1 demand and actual N_1 are compared and any difference generates a fuel metering valve rate demand. Metering valve rate demand is compared with actual metering valve rate to generate a signal to the servovalve, which positions the metering valve in the fuel control. The inner rate loop is employed to provide stable, responsive control of the fuel metering section. The system includes a number of limits which can override the N_1 error signal and limit fuel flow to prevent engine damage or unsatisfactory operation. These are listed below.

T41 Limit - Turbine inlet gas temperature (T_{41}) is calculated in the digital control from compressor discharge temperature (T_3), fuel flow, and compressor discharge pressure. Fuel flow is limited to prevent this calculated T_{41} from exceeding a predetermined limit.

Acceleration Limit - An acceleration fuel schedule that is a function of core rpm, core compressor inlet temperature, and core compressor discharge pressure is used in the digital control program, and fuel flow is prevented from exceeding this schedule. The schedule is designed to provide satisfactory starts and rapid acceleration without core compressor stall or excessive turbine temperature transients.

Deceleration Limit - To prevent loss of combustion during rapid thrust reductions, a function in the digital control prevents WF/PS₃ from dropping below a prescribed minimum limit.

Fan Speed Limit (Normal) - The digital control limits fuel flow to prevent exceeding a predetermined normal fan speed (LP turbine) limit.

Maximum Core Speed Limit - The digital control and hydromechanical control both include functions for limiting fuel flow to prevent core overspeed.

Backup Core-Speed Governor - This governor in the hydromechanical control can reduce fuel flow and speed in response to the mechanical power lever input in the event of an electrical malfunction.

Minimum Idle Speed - The digital control limits fuel flow in the downward direction to prevent idle speed from dropping below an allowable minimum (an experimental engine limit only - related to lube sump pressurization).

Fault Correction - Fuel flow is moreover limited by several fault detection and correction features in the system, which are described in Section 3.3.3.

3.3.2 Control of Core Compressor Stators

A simplified schematic of the core compressor stator control is shown in Figure 7. (Detailed block diagrams of the digital portion of this schematic are included in Appendix B.) The stators are basically scheduled as a function of core-corrected speed. Core inlet temperature, T25, is calculated in the digital control as a function of fan inlet temperature.. (T12) and fan rpm (N_1). This eliminates the need for a separate T25 sensor.

One of the major requirements for this engine is to provide rapid thrust response during the approach phase of the flight profile. This will be accomplished through the use of stator reset logic as shown in Figure 8. When the reset is activated, the reset schedule will cause the stators to close as the power setting is reduced. This schedule is designed to maintain core speed at or near takeoff speed. Therefore, when the rapid thrust response is desired, only the fan will have to be appreciably accelerated because the core will already be near full speed. Also the core will be in a better condition to provide fan acceleration energy. This is one of the optional operational features and can be deactivated by a switch on the engineering control panel in the control room.

3.3.3 Failure Detection and Correction

One objective of the QCSEE Program digital control technology development is to harness the inherent abilities of digital computation to record and compare large amounts of data for engine condition monitoring and fault correction.

There are two distinct failure detection and correction features in the OTW control system. One of these is termed FICA (Failure Identification and Corrective Action). FICA employs a form of Kalman filtering in which a simplified engine model is included in the digital control program to estimate control system sensor outputs. Control and control system sensor outputs serve as inputs to this model. If the sensors are operating properly, the model outputs will be adjusted to reflect actual sensor outputs. However, if a large error occurs between a model-computed sensor value and the actual sensed value, a failed sensor is indicated and the computed value is substituted for the actual value as an input to the control system. Engine operation will continue with only a slight reduction in control accuracy. A more detailed description of FICA is given in Section 5.0.

Switches on the engineering panel allow FICA to be partially activated (model-computing; computed outputs observable but not available for control) or fully activated.

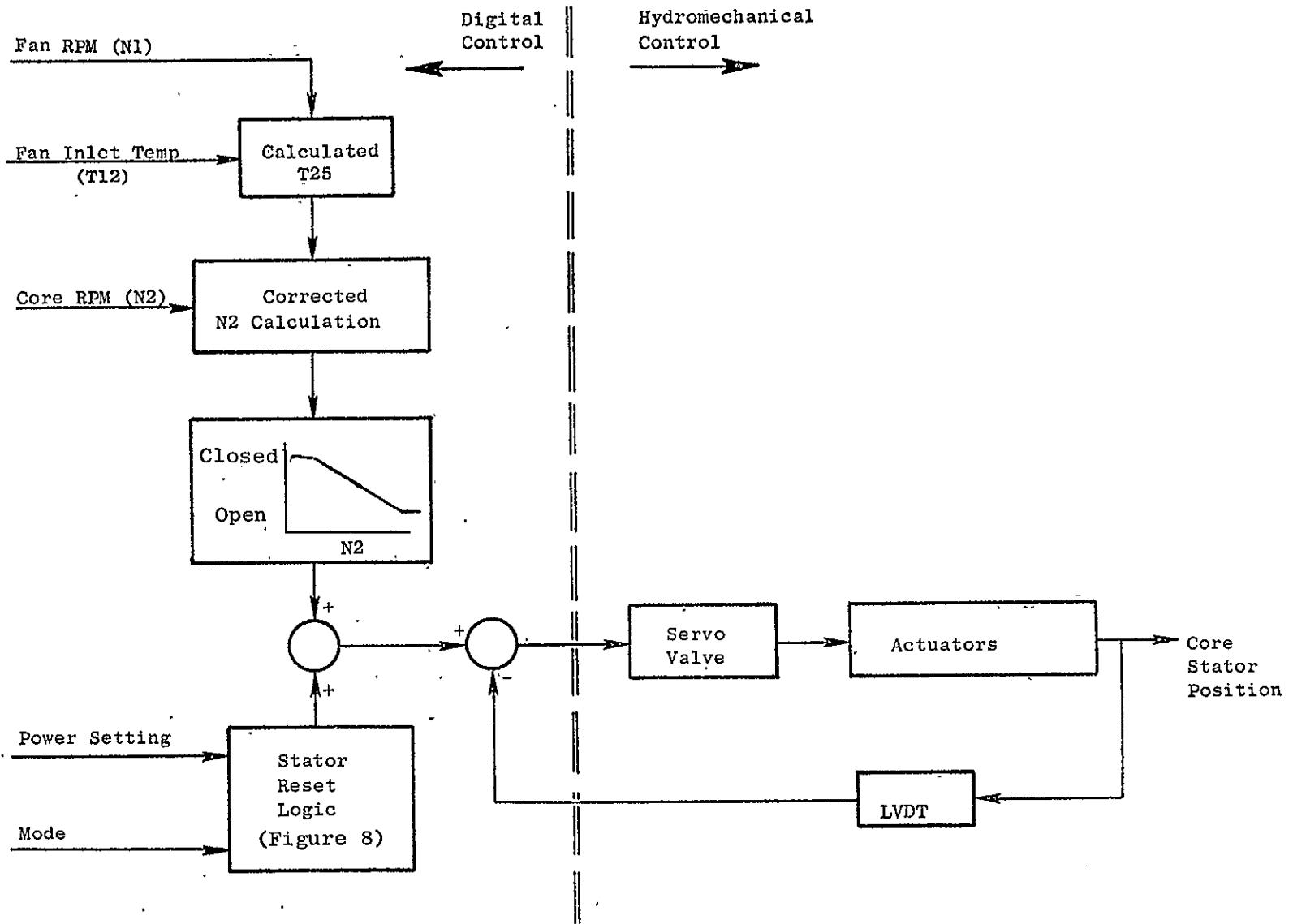


Figure 7. OTW Core Stator Control.

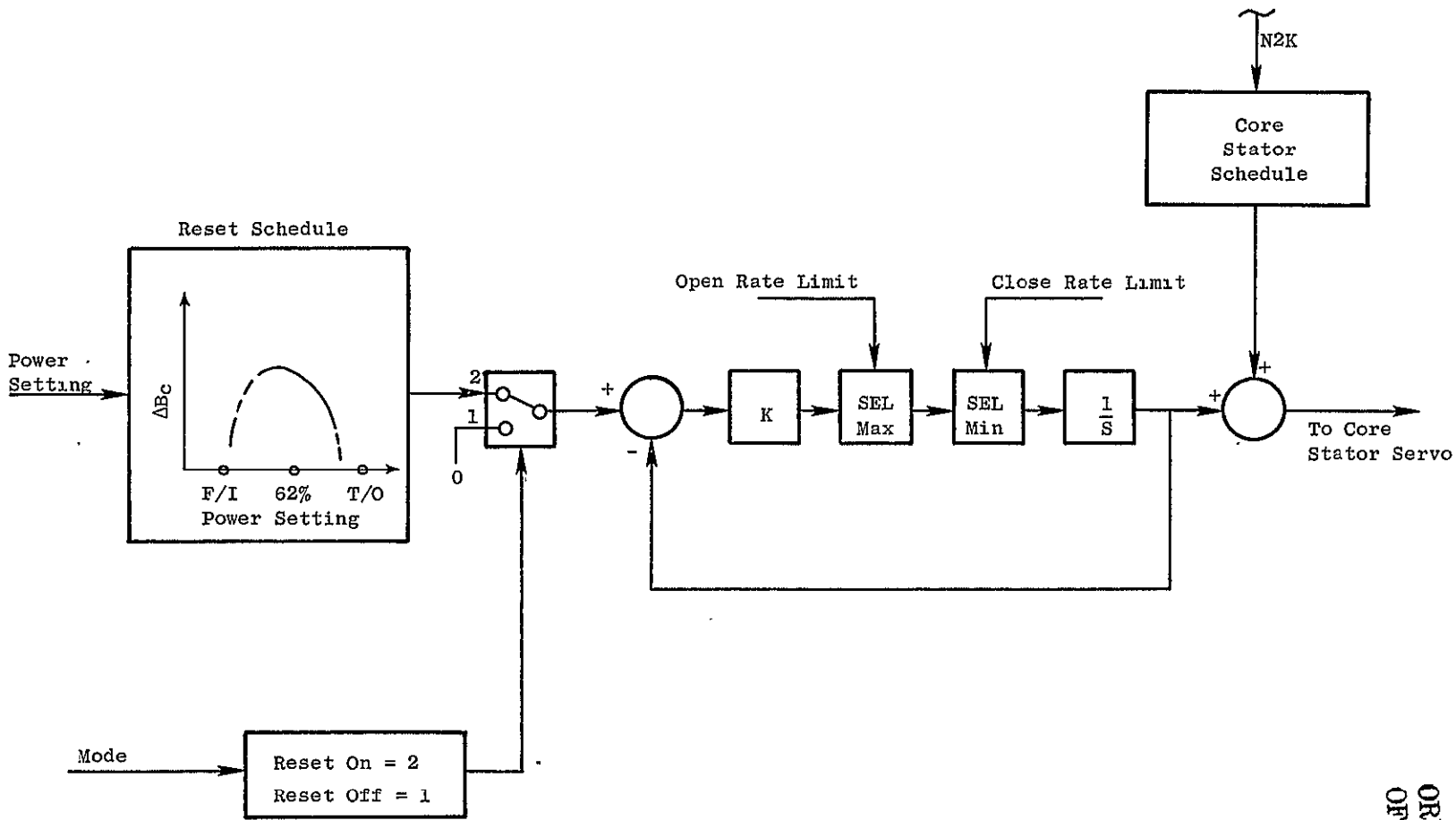


Figure 8. Core Stator Reset Logic.

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In addition to FICA the OTW Control System incorporates several active fault detection and correction features, which are listed below. A fault light on the operator panel indicates when one or more of the faults has occurred, and a digital indicator on the engineering panel identifies the fault or faults. A switch is available on the engineering panel to deactivate each of the features except the fan overspeed emergency shutdown.

Engine Vibration - Engine horizontal and vertical vibrations are sensed: if both exceed 40 mils, fuel flow is reduced to the set idle core speed.

Loss of Command Data Link - A test word is among the set of digital commands that are transmitted repeatedly in series from the control room to the engine-mounted digital control computer. An error in this word at any time causes the control to revert to the last set of commands received and to continue operating at this condition until the fault is corrected.

Computer Fault - The program memory in the digital control computer includes test elements which, if found to be incorrect for two successive iterations through the program, will interrupt the control outputs and cause fuel flow to drift downward and VSV's to close.

Fan Overspeed Emergency Shutdown - If the LP turbine (fan) speed signal exceeds an absolute maximum limit, or if it increases at a rate indicating loss in turbine load (as would occur with fan or fan gearbox failure), an electrical signal from the digital control to the hydromechanical control causes fuel flow to be shut off immediately. All elements of this feature are electrically isolated from the remainder of the system so that it also protects against control system faults that might cause overspeed. If a power loss should make this function unavailable, a fault light will alert the operator.

Core Stator Position Transducer Failure - The signals from the two core stator position transducers are normally averaged by the digital control. However, if the signals differ by 10 percent of full stroke or more the control uses the signal with the largest voltage level, discarding the other on the premise that the transducer producing the lower voltage may well have failed because the predominant failure mode for such transducers is loss of signal.

Lube Supply Temperature - If this temperature exceeds 180° F, the engineering panel fault light illuminates, but there is no automatic corrective action.

Gearbox Bearing Temperature - If this temperature exceeds 264° F, the engineering panel fault light illuminates, but there is no automatic corrective action.

Computer Timing Failure - The digital control includes redundant oscillators for timing in both the engine-mounted computer and the control room portion of the digital control. An oscillator failure in the former will illuminate the fault light on the engineering panel, and a fault in the latter will illuminate a light on the interconnect unit in the control room.

The digital control system also includes provisions for monitoring control and engine variables. Some variables are displayed continuously on the operator panel, some are provided for continuous recording in transient data recorders, and some are available for display (one at a time) on a selectable digital display on the engineering panel. A detailed list of monitored information is given along with the digital control description in Section 6.0 of this report.

3.3.4 Remote Mode

The OTW Control System has the capability of being switched into a remote operating mode, simulating operation in response to an aircraft power management computer. In this mode the digital control power setting input and switching inputs for the various optional features (i.e., FICA, core stator reset, and fuel servovalve type) come from a remote digital computer rather than from the operator panel. Also, all condition monitoring data from the digital control will be transmitted to the remote computer.

4.0 CONTROL SYSTEM ANALYSIS

4.1 ANALYSIS BACKGROUND

One fundamental task to be performed in designing an automatic control system is to define the control mode or modes; that is, to define which engine variables (speeds, pressures, temperatures, etc.) should be controlled by the available manipulated variables to achieve the desired operating conditions. This involves analyses comparing potential modes on the basis of accuracy, stability, response, and other performance considerations.

The QCSEE OTW analysis was done initially for a flight engine design having three manipulated variables: fuel flow, core compressor stator position, and exhaust area. The analytical results were somewhat modified after that to accommodate the experimental engine, which will have an exhaust area that is manually adjustable but not operationally variable.

For steady-state operation it was decided at the outset of the analytical effort that one of the three manipulated variables, namely core compressor stator position, would be best controlled by scheduling position as a function of core corrected speed as had been done in the past on engines of this type. Thus, for steady-state operation, there remained two manipulated variables which could be used to control a variety of sensed engine variables or sets of variables, and the initial control mode analysis proceeded on this basis.

Key operational objectives at various conditions were established prior to beginning the automatic control mode analytical process. These were:

- Takeoff - Set guaranteed maximum static thrust or percent thereof. Set inlet throat Mach number (XM11) for optimum noise and performance trade-off.
- Climb - Set guaranteed maximum installed thrust or percent thereof. Control inlet Mach number for optimum installed performance.
- Cruise - Attain minimum installed sfc at required thrust level.
- Descent - Maintain sufficient core speed for air conditioning and power extraction.
- Approach - Attain past thrust response at readily controlled level up to guaranteed maximum.

Control inlet Mach number and airflow for low noise.

- Ground Idle - Low thrust.

Low exhaust pollution.

Low noise.

The sections which follow describe the analytical studies performed to translate these requirements in the choice of control modes.

4.2 CONTROL MODE ANALYSIS

One of the first steps in control mode definition was to perform a control mode analysis. This is a computer-aided process in which the effect of typical engine and control component tolerances on important engine characteristics (thrust, sfc, turbine temperature, stall margin, etc.) are determined for all potential control modes.

The starting point for the mode analysis was a computer deck representing the OTW engine cycle under steady-state, installed conditions. A special computer program was used with this deck to generate matrices of partial differentials of certain dependent variables with respect to certain other independent variables. Among the independent variables were potential control variables, air bleeds, power extraction, and any engine component performance variables that contribute significantly to the propulsion system's overall performance. The dependent variables included such key cycle variables as thrust, sfc, temperatures, stall margins, rotor speeds, and inlet throat Mach number.

The mode analysis consisted of a series of computer runs using the matrices of partial differentials just described. For each run, a different set of potential control variables, equal in number to the manipulated variables (two for the OTW engine), was designated; the matrix used was the one that had these as independent variables. Predicted tolerances for sensors, controls, and engine components were multiplied by the partial differentials. The computer tallied the accumulation of these effects on key dependent variables in several ways, including (1) the arithmetic sum, (2) the square root of the sum of the squares (RSS), and (3) RSS with zero control tolerances. Deterioration factors based on actual field experience were applied to the partials, and the RSS accumulation of these factors was also calculated.

Runs were made at SLS takeoff conditions and at Mach 0.7, 7.62 km (25,000 ft) climb conditions.

Details regarding the potential modes subjected to this type of analysis, the tolerances used, and typical results, are given in the sections that follow.

4.2.1 Definition of Potential Thrust Parameter

One important task in defining potential control modes for analysis was to establish potential thrust parameters which would indicate net thrust at any flight condition as a percentage of the maximum rated thrust at that condition. Ideally, the thrust parameter should be such that it could be used for cockpit indication and correlate with percent-net-available thrust independent of customer air bleed, control errors, engine component variations,

and flight conditions. The ideal thrust parameter would moreover have negligible thrust-correlation errors during engine stalls or control failures.

The potential thrust parameters used in the mode analysis are listed below and discussed in succeeding paragraphs (symbols defined in Appendix A). (Note: This list was originally defined for the QCSEE UTW, but proved to be applicable also for the OTW - except for parameter TP7, which reflects the UTW variable pitch fan, a feature not included in the OTW).

$$\begin{aligned} \text{TP1} &= P49/\text{PTO} \\ \text{TP2} &= \text{PS3}/\text{PTO} \\ \text{TP3} &= f(P8/\text{PTO}) \times (A8) \\ \text{TP4} &= f(P15/\text{PTO}) \times (A8) \\ \text{TP5} &= f(M11)/(A8) \\ \text{TP6} &= f(P15/\text{PTO}) \times f_2(M11) \\ \text{TP8} &= T41C/T1 \\ \text{TP9} &= \text{PCNHR} \\ \text{TP10} &= \text{PS3}/\text{PS8} \\ \text{TP11} &= T8/T1 \\ \text{TP12} &= (T15-T1)/T15 \times f(M11) \\ \text{TP13} &= \text{WFM}/\text{PTO} \end{aligned}$$

TP1 is a good traditional parameter, it is a good indicator of core extracted power and correlates well with net thrust, but the mechanical design for QCSEE does not permit the insertion of total pressure rakes between the turbines. Static pressure measurement was considered as a substitute for P49, but the close-coupled turbine configuration prevents acquisition of a consistently representative static pressure. TP2 provides much better accuracy than could be obtained using PS49 (but not as good as by using PT49); therefore, the mode studies include P49/PTO to provide a standard of comparison and include PS3/PTO as a practical alternative for the experimental program. Core engine temperatures were bypassed in the initial listing of alternatives because the best choice, T49, had the same installation problem as P49, and all of the core temperatures are particularly sensitive to component deterioration.

The expression for TP3 was developed from the equation that states that gross thrust is equal to the product of mass airflow times velocity. With the full exhaust expansion present in the OTW cycle over the range of practical consideration, and with the engine's high-bypass ratio, it is only a minor approximation to assume that the total thrust is a constant times the thrust of the bypass stream. Using this consideration and applying fundamental compressible-flow equations resulted in the transformation of the basic gross-thrust equation into an equation for TP3 as a function of fan exhaust pressure ratio and area, as shown above.

Additional mathematical manipulation translated the P8/PTO function into a P15/PTO (fan pressure ratio) function, resulting in the TP4 expression.

TP5 and TP6 were likewise derived from the basic gross-thrust equation, with manipulations performed so that the mass airflow is expressed in terms of an inlet airflow indicator, that is., inlet Mach number, a variable sensed by the control system for noise control.

The remaining thrust parameters, except for TP12, are corrected engine variables indicative of core engine power (core engine power being fundamentally a more comprehensive indicator of net thrust than any simple fan system parameter). TP12 is a corrected fan power parameter.

A total of 17 controlled variables were considered to have potential for the OTW; 11 of the 12 thrust parameters described previously, plus 6 others. These are listed in Table I with tolerances that were estimated in the manner described below.

4.2.2 Definition of Tolerances

A vital factor in setting up the control mode analysis was the definition of tolerances for the independent variables - that is, for the controlled variables in each mode being studied and for basic engine components characteristics.

Controlled variable tolerance estimates were begun by estimating sensing tolerances. Current state-of-the-art sensors were assumed, with full-scale ranges set according to the OTW cycle and flight envelope. Tolerance distributions were optimized, when possible, for certain scale ranges, according to engine needs. The tolerance assignments also included analog-to-digital conversion errors and estimated sampling errors based on the uncontrolled effects of local flow distortions. Scheduling errors were also estimated where secondary or trim parameters were used to define operating values for the control variables. All of these tolerances were combined by the root-sum-square method to define overall sensing tolerances, as shown on Table II.

The sensing errors from Table II were used to calculate control parameter errors based on derivatives of the control parameter equations. As an example, the error synthesis for T41C (computed T41) is described as follows:

1. T41C is defined by the equation:

$$T41C = k_1 + k_2 T3 + k_3 \left(\frac{WF}{PS3} \right)^{1.245}$$

2. Differentiating this equation, dividing by T41C, and evaluating at SLS conditions gives:

$$\frac{\Delta T41C}{T41C} = 0.476 \left(\frac{\Delta T3}{T3} \right) + 0.6585 \left(\frac{\Delta WF}{WF} \right) - 0.6586 \left(\frac{\Delta PS3}{PS3} \right)$$

3. The three terms in this equation were root-sum-squared to obtain the overall error for T41C.

Table I. Mode Analysis Controlled Variable Tolerances.
(percent of point)

Controlled Variables	SLS Takeoff Errors	Maximum Climb Errors (0.7/25K)
PCNLR - Corrected Fan Speed	<u>+0.52%</u>	<u>+0.57%</u>
A8 - Jet Nozzle Area	1.20	1.63
M11 - Inlet Duct Mach Number	1.66	2.38
P49QOT - LP Turbine EPR (P49/PTO)	1.07	2.01
PS3QOT - HP Turbine EPR (PS3/PTO)	0.97	1.89
TP3 - Thrust Parameter from A8 and P8/PTO	5.50	5.03
TP4 - Thrust Parameter from A8 and P15/PTO	3.74	4.32
TP5 - Thrust Parameter from A8 and M11	1.74	2.44
TP6 - Thrust Parameter from M11 and P15/PTO	1.85	2.41
T41CT2 - T41C/T2	1.04	1.22
T49QT2 - T49/T2	1.05	1.08
T8QT2 - T8/T2	1.04	1.07
PCNHR - Corrected Core Speed	0.30	0.48
WFQPTO - WFM/PTO	1.43	1.98
M15 - Fan Duct Mach Number Parameter	2.53	3.03
P15QOT - P15/PTO	1.11	2.09
P15QOT - P15/PTO from P15-PTO and PTO	0.93	1.24

Table II. Mode Analysis Sensing Tolerances.

(Includes profile, sensors, signal conditioning, and A-to-D conversion)

Sensed Variable	Maximum Value	Minimum Value	Sampling at Takeoff	Sampling at Climb	Overall Takeoff Errors	Overall Climb Errors
(All Errors are Percent of Point)						
PTO(PSIA)	19	2.5	+0.25	+0.25	+0.74	+1.5
PTO-PS11	7.3	1.3	2.08	2.08	2.44	3.32
P15	24.6	5.47	0.50	0.50	0.83	1.45
P15-PS15	3.8	0.82	3.94	3.94	4.45	5.81
P15-PTO	5.0	1.5	3.54	3.54	3.76	4.28
PS3	257	54.5	0.25	0.25	0.62	1.14
P49	70	15	0.50	0.50	0.78	1.32
PO(PS8)	17.7	2.72	1.00	1.00	1.22	2.38
T2 (° R)	620	400	0	0	0.36	0.37
T15-T2	56	34	0.75	0.75	1.14	1.22
T3 (° R)	1400	935	0.75	0.75	0.98	0.99
T49 (° R)	2370	1700	0.75	0.75	0.98	1.02
T8 (° R)	1850	1200	0.75	0.75	0.97	1.01
NL (RPM)	4175	3000	---	---	0.20	0.22
NH (RPM)	14500	11000	---	---	0.23	0.26
WFM (PPH)	7210	1000	*0.44	*0.44	1.20	1.11
A8 (In.) ²	2794	2307	---	---	1.20	1.63

*Heating Value Variations

4. For the parameter T41C/T2, the errors for T41C and T2 were root-sum-squared. The error computed for T41C/T2 using this method and the data in Table II is 1.04%. The final result in terms of T41 was evaluated by the computer mode study and the final results include effects of engine component variations.

The other control parameters had errors evaluated using the same techniques described above for T41C; Table I has the tabulated results.

There are noncontrol factors which influence engine performance to a varying degree depending on the mode of control. These include the engine component variation due to manufacturing tolerances and service wear; they also include engine bleed and power extraction as required for anti-icing and aircraft accessories. Table III lists the values used for these variations in the mode analysis.

4.2.3 Mode Analysis Runs and Results

As noted previously, the control mode analysis itself consisted of a series of computer runs with various combinations of 3 of the 17 potential control variables. The theoretical total of such combinations is 136 but some obviously are of no prospective interest. For example, any combination including two thrust parameters is not reasonable.

The parameter groups that were evaluated are listed in Table IV along with the results for thrust control errors and thrust "deterioration" as determined from the Table III deterioration factors. Note that engine deterioration may result in thrust increases, depending on the control mode. In every case where thrust deterioration is positive, the turbine temperature "deterioration" exceeds that required to maintain constant thrust. Thrust results are all in terms of percent-of-point of installed net thrust.

The results for the climb condition include the effects of a +0.01 variation in the flight Mach number. This variation can be viewed either as a real error in MO or as an error in the MO data provided to the engine control.

Review of the results shown in Table IV quickly eliminated some of the modes because of thrust inaccuracy and sensitivity to deterioration. The following additional considerations led to the elimination of other modes.

1. Modes using TP12 were eliminated from experimental engine candidates primarily (1) for uncertainty regarding water ingestion effects on fan temperature rise measurement and (2) because of the slow response inherent in temperature measurement devices. More data are needed on the correlation of TP12 with thrust under unusual atmospheric condition; more data are also needed for temperature profile variation, which affects the choice of location and the number of sensors.

Table III. Mode Analysis Engine Component Variations.

(Values are Percent of Point)

Variable	Variation	Deterioration
Fan Corrected Flow	<u>+1.5%</u>	-0.5%
Fan Efficiency	1.5	-0.5
Core Compressor Corrected Flow	1.0	-0.7
Core Compressor Efficiency	1.0	-0.5
Burner Pressure Loss (P4/P3)	0.5	0
Burner Efficiency	0.3	0
HP Turbine Area Corrected Flow	1.0	0
HP Turbine Efficiency	1.0	-1.5
LP Turbine Area Corrected Flow	1.0	0
LP Turbine Efficiency	1.0	-1.0
Fan Duct Pressure Loss	0.2	0
Post-Turbine Core Pressure Loss	0.1	0
Compressor Interstage Bleed (% of W25)	1.0	0
Compressor Discharge Bleed (% of W25)	1.0	0
Shaft Power Extraction (Horsepower)	25.0	0
Inlet Duct Area Variation	0.1	0
Core Engine Jet Nozzle Area	0.5	0
Turbine Cooling Flow (WC/W25)	0.55	0

Table IV. Mode Analysis Thrust Accuracy Results.

(Shown as Percent of Point)

Mode No.	Mode Parameters		SLS Takeoff		Climb 0.7/25K	
			RSS FN	FN Det.	RSS FN	FN Det.
1	PCNL	A8	1.52	-0.30	4.95	+0.16
2*	FNIN	PCNL	0	0	0	0
3*	SM12	PCNL	0.86	+0.22	1.46	+0.34
4	P49QOT	PCNL	1.73	-1.32	3.46	+0.68
5	PS3QOT	PCNL	2.54	+0.76	4.11	+1.39
6	TP3	PCNL	3.29	-0.19	9.29	+0.19
7	TP4	PCNL	2.21	-0.19	7.87	+0.19
8	TP5	PCNL	8.57	-2.35	8.82	-2.25
9	TP6	PCNL	2.43	+0.13	21.12	+3.57
10	T41CT2	PCNL	3.76	-1.48	4.57	-3.37
11	T49QT2	PCNL	3.89	-2.32	4.68	-5.36
12	M15	PCNL	3.45	-0.47	5.48	-0.34
13	T8QT2	PCNL	3.10	-0.77	3.58	-1.89
14	P15QOT	PCNL	2.52	-0.19	6.61	+0.20
15**	P15QOT	PCNL	2.13	-0.19	3.98	+0.20
16	PCNHR	PCNL	4.15	+2.19	7.17	+6.66
17	WFQPTO	PCNL	1.81	-0.64	2.55	-1.80
18	TP12	PCNL	2.03	+0.09	2.75	+0.54
19	M11	PCNL	6.48	-2.40	6.30	-2.16
20*	FNIN	M11	0	0	0	0
21*	M11	SM12	1.73	+0.95	2.66	+1.70
22	P49QOT	M11	1.64	-1.38	3.36	+0.60
23	PS3QOT	M11	2.40	+0.58	4.00	+1.29
24	TP3	M11	3.67	+0.05	10.41	+0.48
25	TP4	M11	2.47	+0.05	8.82	+0.48
26	TP5	M11	437	-10.57	303	+0.83
27	TP6	M11	2.36	+0.05	9.82	+0.5
28	T41CT2	M11	3.48	-1.55	4.69	-3.40
29	T49QT2	M11	3.60	-2.33	4.85	-5.48
30	M15	M11	5.11	+0.37	9.74	+1.12
31	T8QT2	M11	3.16	-0.74	4.14	-1.85
32	P15QOT	M11	2.81	+0.05	7.38	+0.48
33	P15QOT	M11	2.39	+0.05	4.43	+0.48
34	PCNHR	M11	3.90	+2.70	7.29	+6.78
35	WFQPTO	M11	1.71	-0.74	2.57	-1.79
36	TP12	M11	1.83	-0.16	2.60	+0.41
37*	FNIN	M15	0	0	0	0
38*	SM12	M15	8.57	+1.98	19.64	+2.92
39	P49QOT	M15	1.53	-1.18	3.27	+0.62
40	PS3QOT	M15	2.20	+0.56	3.88	+1.29

Table IV. Mode Analysis Thrust Accuracy Results. (Concluded)

(Shown as Percent of Point).

Mode No.	Mode Parameters		SLS Takeoff		Climb 0.7/25K	
			RSS FN	FN Det.	RSS FN	FN Det.
41	TP3	M15	5.13	-0.06	12.38	+0.36
42	TP4	M15	3.59	-0.06	10.52	+0.36
43	TP5	M15	5.64	+0.34	10.57	+1.11
44	TP6	M15	2.23	+0.07	6.80	+0.75
45	T41CT2	M15	3.02	-1.26	4.87	-3.56
46	T49QT2	M15	3.13	-1.93	5.11	-5.81
47	T8QT2	M15	3.33	-0.80	5.55	-2.57
48	P15QOT	M15	4.01	-0.06	8.79	+0.36
49*	P15QOT	M15	3.48	-0.06	5.39	+0.36
50	PCNHR	M15	3.54	+2.44	7.41	+6.89
51	WFQPTO	M15	1.59	-0.61	2.59	-1.82
52	TP12	M15	1.69	-0.06	2.51	+0.45
53	SM12	A8	16.69	+6.20	8.91	+0.69
54	P49QOT	A8	1.38	-1.12	3.29	+0.66
55	PS3QOT	A8	2.04	+0.55	3.91	+1.33
56	TP3	A8	5.75	-0.12	11.72	+0.20
57	TP4	A8	3.87	-0.12	9.94	+0.20
58	TP5	A8	2.78	+0.33	11.84	+2.70
59	TP6	A8	2.14	+0.07	7.11	+1.23
60	T41CT2	A8	2.76	-1.17	4.83	-3.56
61	T49QT2	A8	2.87	-1.81	5.05	-5.77
62	M15	A8	12.60	+0.32	38.85	-2.96
63	T8QT2	A8	3.40	-0.82	5.04	-2.60
64	P15QOT	A8	4.39	-0.12	8.30	+0.21
65**	P15QOT	A8	3.73	-0.12	5.03	+0.21
66	PCNHR	A8	3.34	+2.35	7.38	+6.84
67	WFQPTO	A8	1.41	-0.57	2.59	-1.82
68	TP12	A8	1.37	-0.03	2.51	+0.51
69	M11	A8	2.19	+0.35	10.30	+2.76
70*	FNIN	SM12	0	0	0	0
71*	FNIN	A8	0	0	0	0

*These cases are not true control modes; they are for derivatives only.

**Modes were repeated using a second estimate for the P15QOT statistical error. (That is, a sensing system was assumed that would use fan ΔP , and PTO - the P15QOT error was reduced from 1.11 to 0.93 using this method).

2. Modes using P49/PTO were eliminated from the experimental program because the applicable F101 engine hardware did not allow adequate instrumentation. Analysis results do not show a decisive superiority of P49/PTO over PS3/PTO considering the added cost, weight, and reliability factors associated with engine design (close-coupled turbine and multiple-probe acquisition system needed to get an accurate P49 signal).
3. The control modes using T41C were not seriously considered in the elimination process leading to the primary control, basically because a turbine temperature parameter had already been chosen to provide a safety override function. Therefore, a redundancy advantage would be lost if the temperature were also used as the thrust parameter. T49 was eliminated for the reasons given above for P49.
4. The control modes that include WF/PTO were eliminated for a combination of factors. The deterioration effects were relatively large (but not so large as to be definitive without other factors); fuel flow measurement is used in the computed temperature parameter T41C; the estimated fuel flow measuring accuracy needs more experimental verification; and perhaps more development may be needed for assurance reasons.

Following the elimination process above there remained only two candidate modes, mode 1 and mode 5, the former using PCNL as the thrust parameter and the latter using PS3/PTO. Both incorporate a scheduled A8. Both were retained for further assessment as to parameter schedulability and stability.

4.3 PARAMETER INTERRELATIONSHIPS

A control mode analysis such as just described normally does not identify the relationship between manipulated and controlled variables. Further analysis is normally required to define which manipulated variable should be used to control each controlled variable. This task was not required for the selected OTW modes because A8 is both a manipulated and a controlled variable in both modes. For each of the two modes, fuel flow controls the thrust parameter (PCNL or PS3/PTO) and A8 is positioned in accordance with a power demand and/or flight condition schedule.

4.4 SCHEDULABILITY

Another study performed in conjunction with the control mode analysis was one involving schedulability. Power control scheduling requirements were considered for alternative modes using PCNL and PS3/PTO as thrust parameters. Flight-type schedules were considered in order that mode selection criteria would be comprehensive. Cycle data were run as required to define ideal schedules for both takeoff and climb conditions. The operating conditions covered by the cycle data were as follows:

Takeoff: $0 < MO < 0.378$, $10.1 < PTO < 16.22$, $0.74 < T2/T \text{ Ref.} < 1.06$

Climb: $0.378 < MO < 0.80$, $7.57 < PTO < 16.22$, $0.82 < T2/T \text{ Ref.} < 1.10$

Matrices of cycle points were run for five levels of the T2 parameter, four levels of MO, and four levels of PTO. A minimum of 80 points for takeoff and 80 points for climb was considered necessary to evaluate characteristic trends; much more data would be run for final design schedules. The rationale for organizing data requirements is as follows:

1. The matrix is defined in terms of the schedule parameters which would be used for scheduling the mode-controlled variables.
2. T12/T Reference was chosen over T12 in order that the control schedules data arrays would use the minimum number of points for accuracy and at the same time accommodate the engine rating plan. This choice leads to a sharp separation between the temperature range on which thrust is flat-rated and the range in which it decreases to prevent turbine overtemperature. This separation is established on the basis of a differential above standard day temperature. Thus, the temperature at which the thrust rating changes from flat to decreasing varies with altitude.
3. T Reference is defined as a function of PTO (Figure 9), which is a measured parameter, rather than as a function of PO, which probably will not be available on the typical aircraft installation. To accommodate this approximation a nominal climb profile appropriate to the aircraft is defined (MO vs. PO; see Figure 10), and MO is treated as a plus and minus trim from the nominal MO profile. The situation is analogous to the T2 reference scheme, but an explicit MO-reference schedule is not as important as for T2 because no sharp discontinuities are required for MO effects on the control parameters.

The schedulability analysis was directed initially at the takeoff condition. At takeoff, the OTW cycle deck was set up to approximate the typical transport engine flat-rating (i.e., takeoff thrust constant at any ambient temperature up to about 90° F, then gradually reduced as a function of increasing ambient temperature to maintain rated turbine temperature). The takeoff condition is plotted in terms of the two candidate thrust parameters in Figures 11 and 12. These plots show that aircraft velocity has a marked effect on the thrust parameter setting required for takeoff. This effect is greater on the QCSEE than on current transport turbofans because of the characteristics of the high Mach number inlet incorporated on the QCSEE for noise reduction.

Takeoff schedules for both PCNLR and PS3/PTO were generated from the cycle data matrix. The basic schedules are shown in Figures 13 and 15, with aircraft Mach number trim for each schedule shown in Figures 14 and 16.

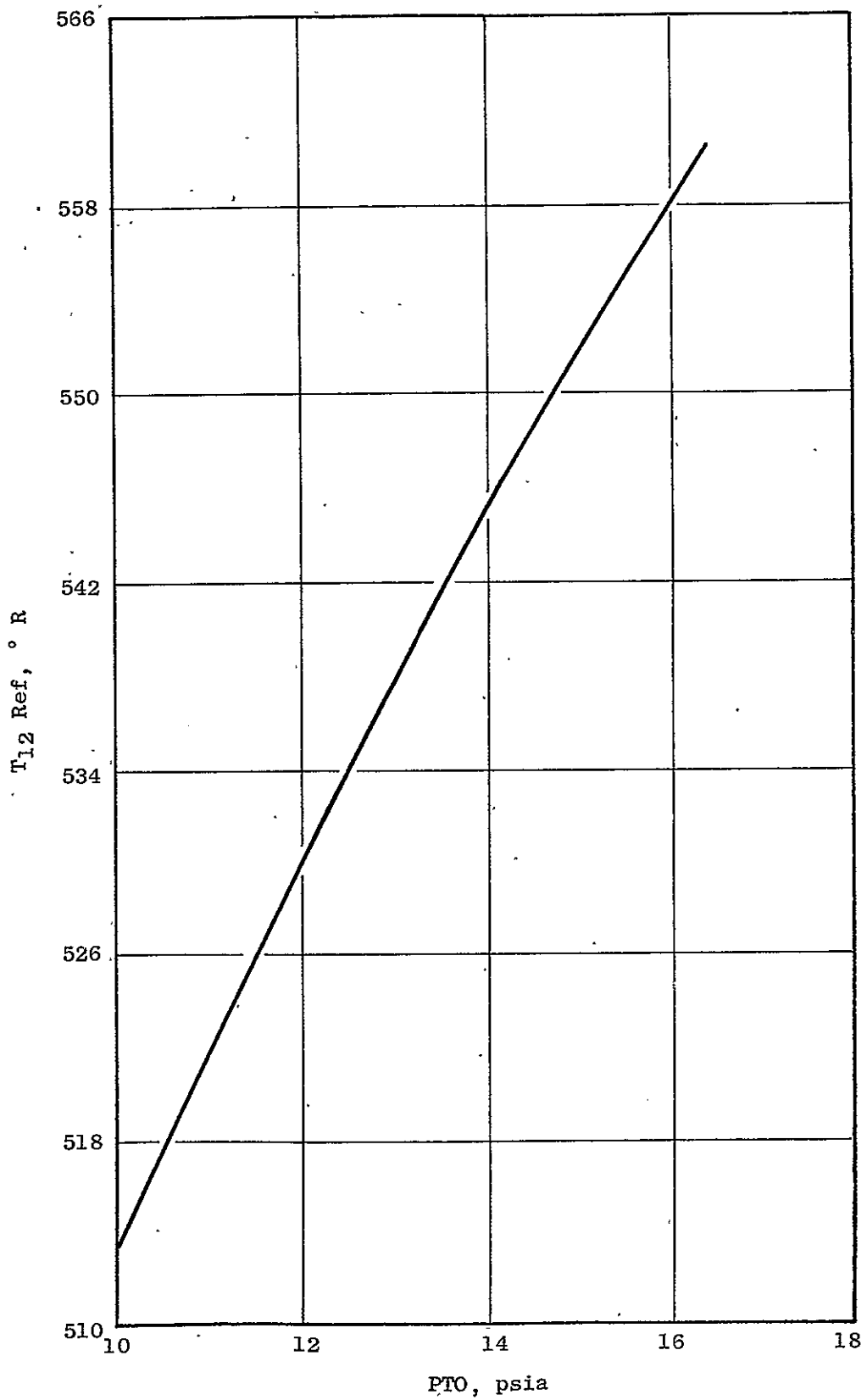


Figure 9. T12 Reference.

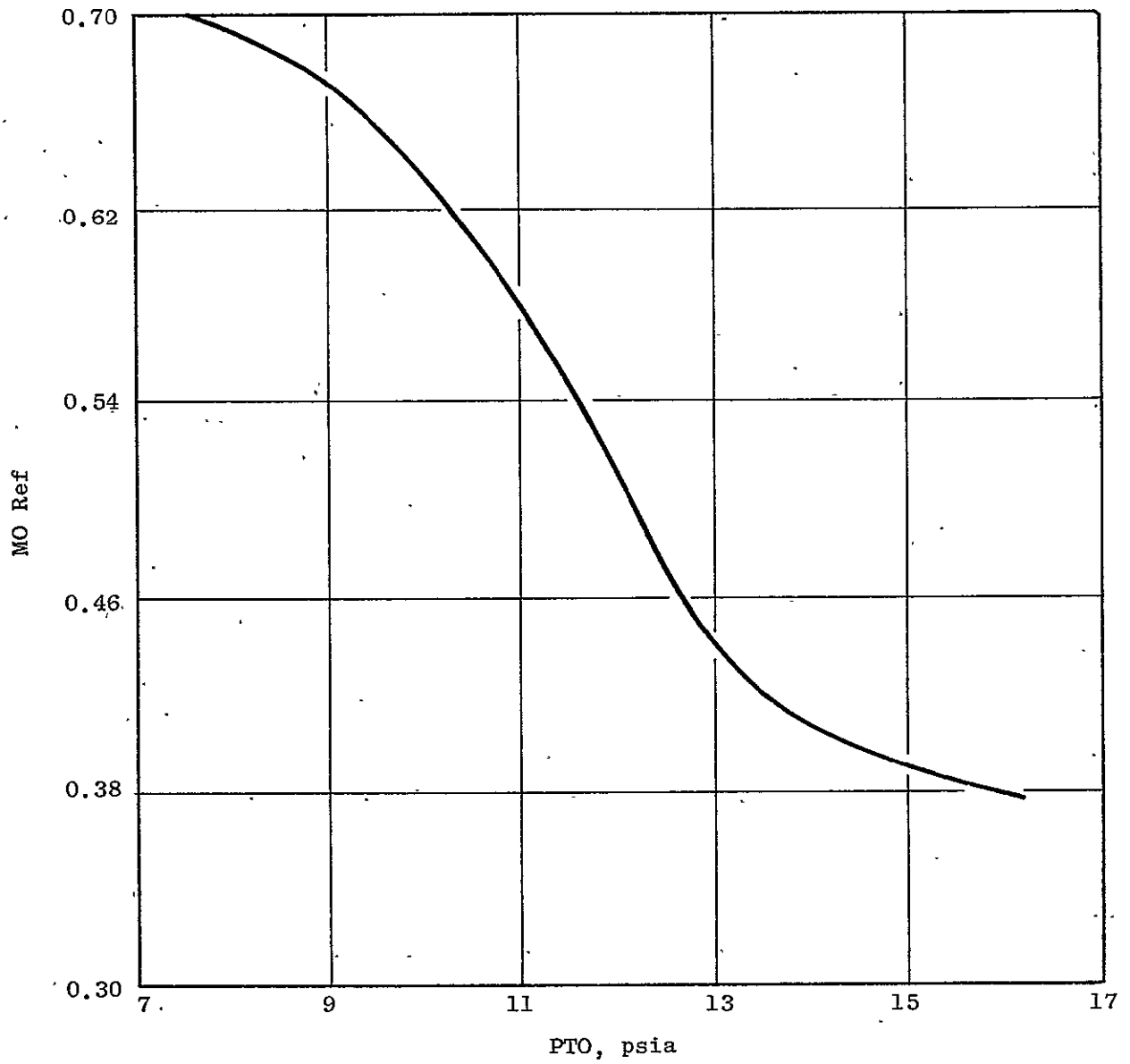


Figure 10. Free-Stream Total Pressure Versus Aircraft Mach Number.

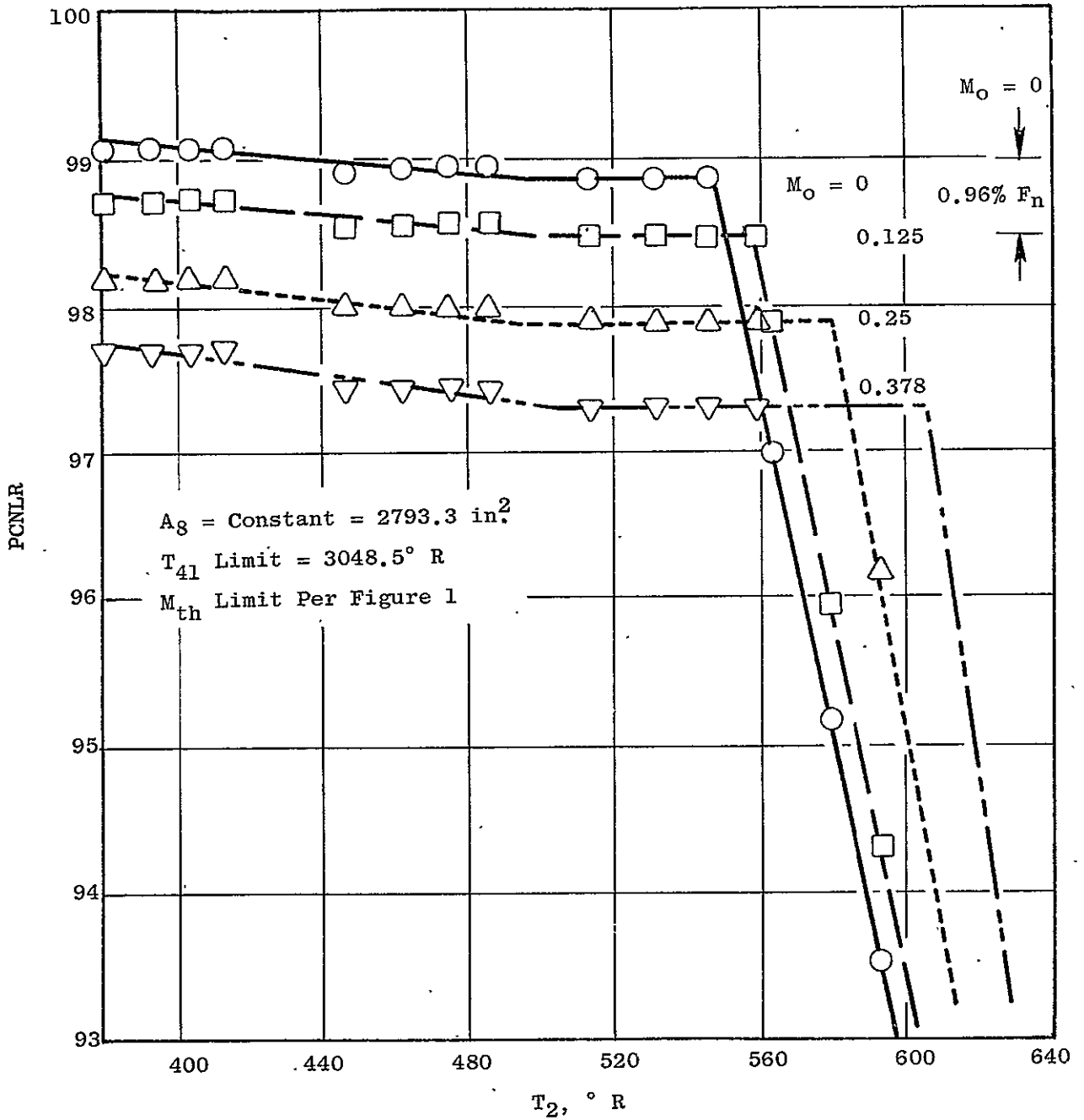


Figure 11. OTW Speed Schedule for Takeoff Rating.

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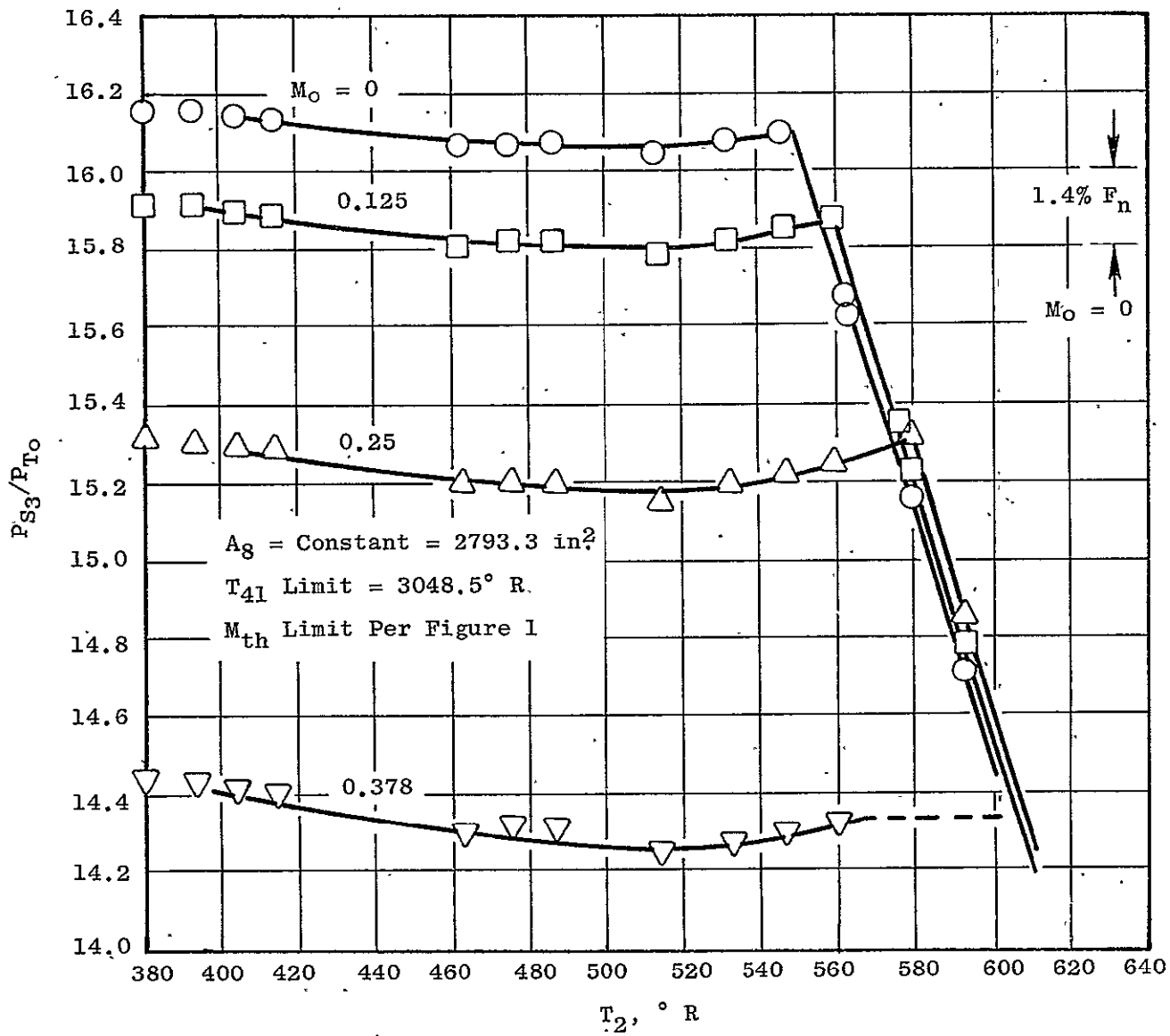


Figure 12. OTW P_{S3}/P_{T0} Schedule for Takeoff Rating.

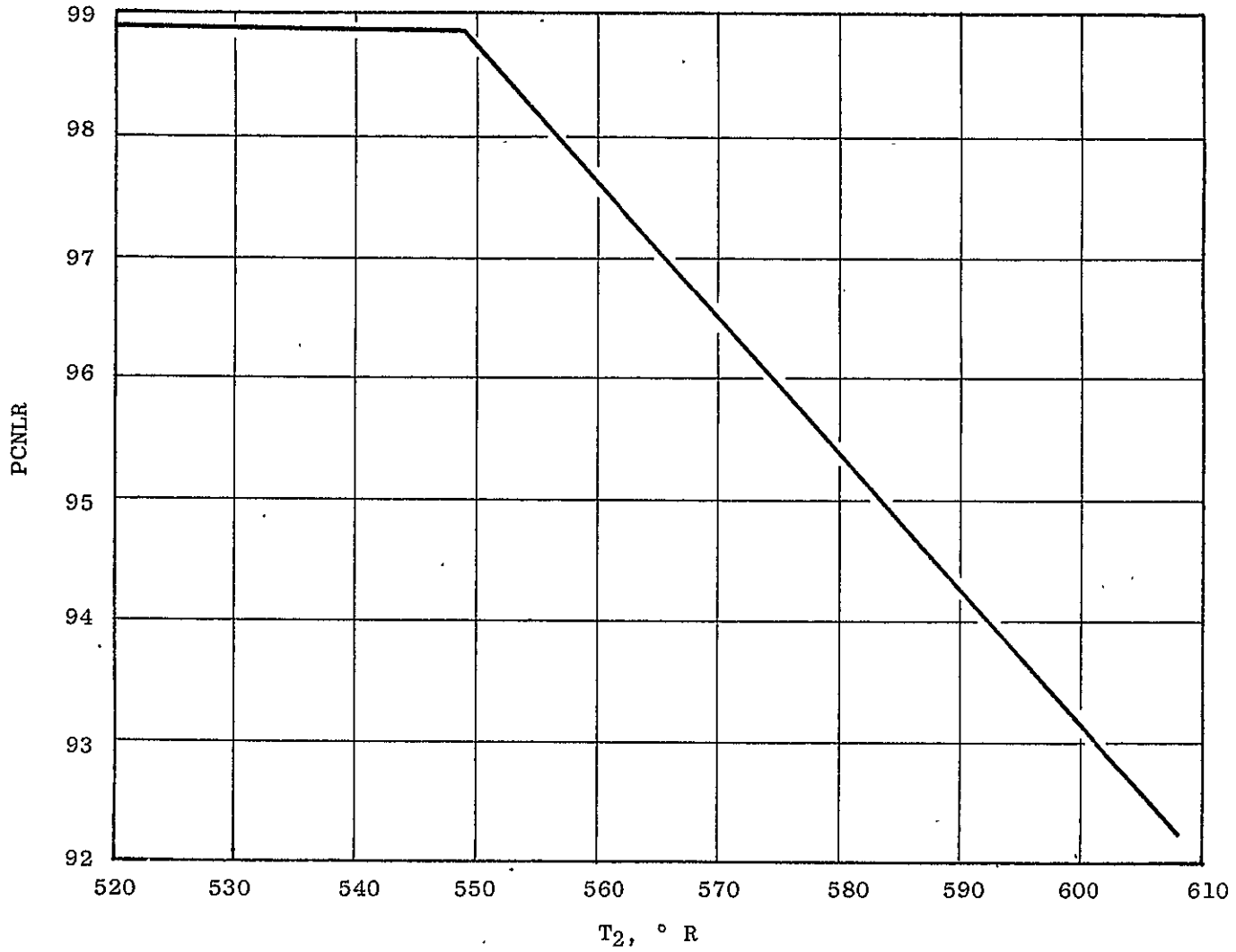


Figure 13. OTW Base Takeoff Schedule for PCNLR.

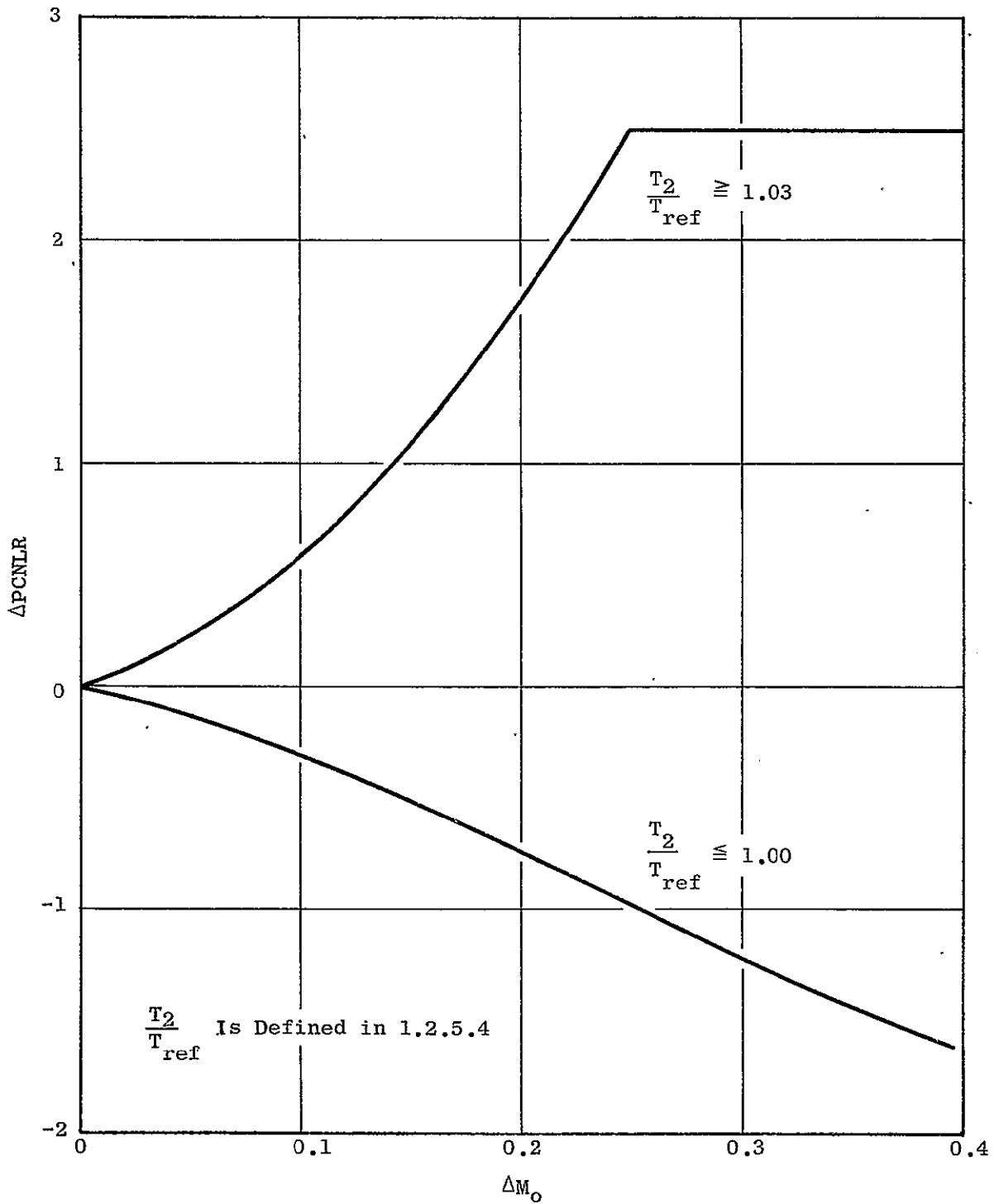


Figure 14. OTW Trim Schedule for PCNLR.

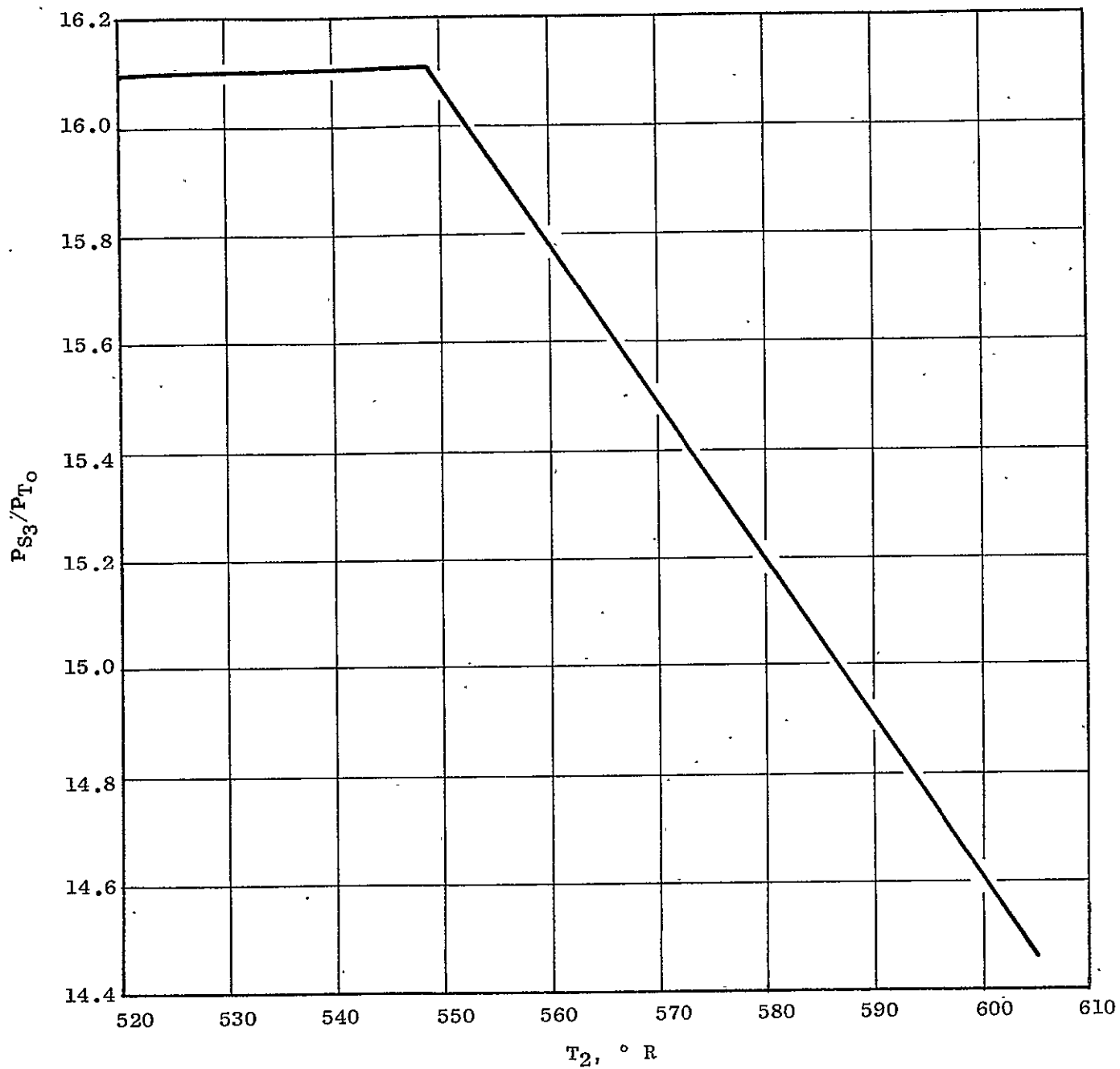


Figure 15. OTW Base Takeoff Schedule for P_{S_3}/P_{T_0} .

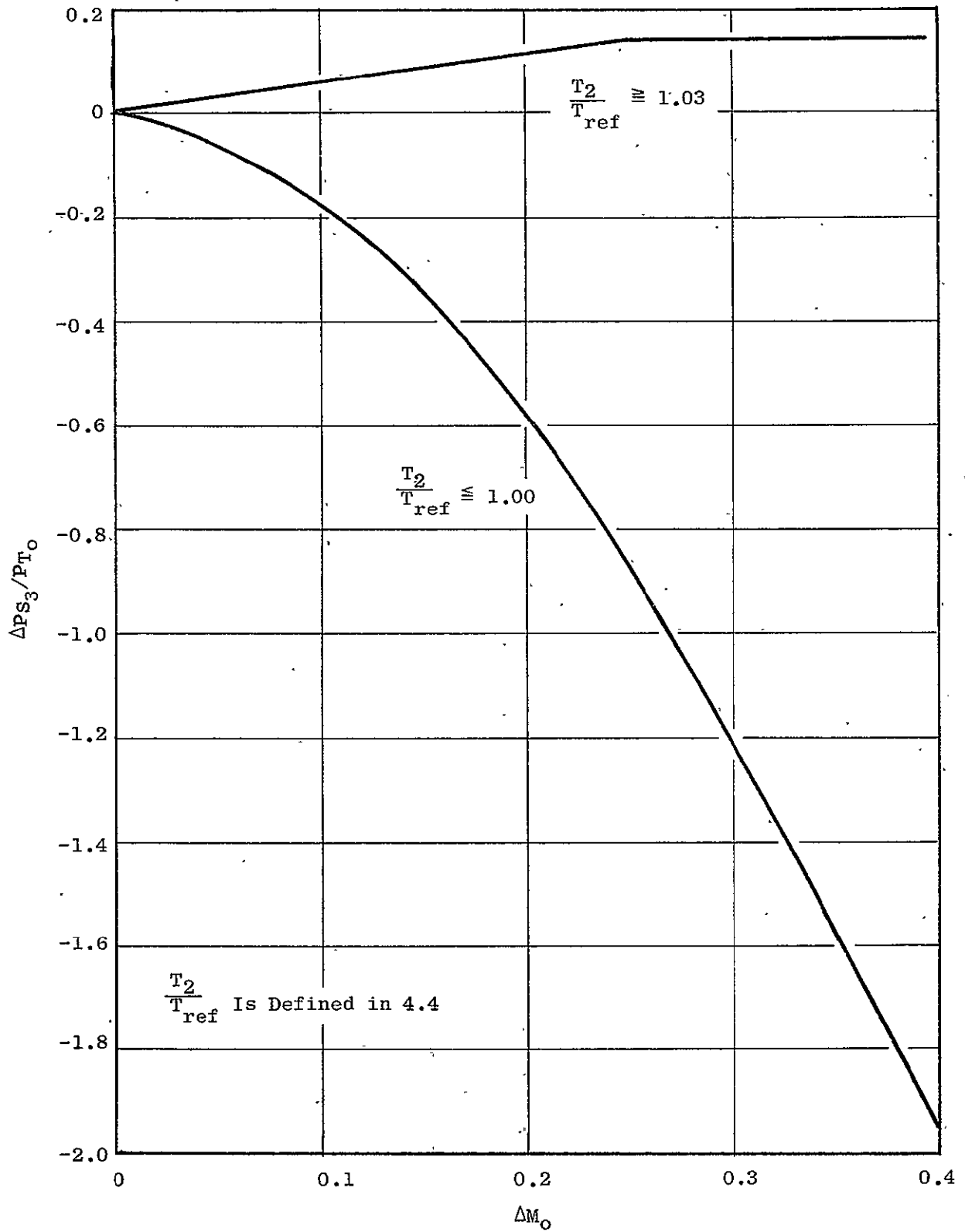


Figure 16. OTW Trim Schedule for PS_3/P_{T_0} .

The cycle data matrix was also used to investigate the climb power rating. On current transport turbofans the thrust parameter level for climb power is allowed to gradually increase to keep turbine temperature nearly constant as altitude increases and inlet temperature decreases. On the QCSEE OTW this thrust parameter increase must be limited to prevent an excessive inlet Mach number. Based on this finding the thrust parameter schedules were not modified to reflect climb power considerations. This matter would require detailed study in designing for an actual aircraft application.

Based on the foregoing analysis it was concluded that the two candidate control modes were equivalent with regard to schedulability.

At this point in the analytical process the emphasis shifted to analyses related primarily to operation of the OTW experimental engine. Control of A8 was no longer a concern, because the exhaust nozzle on the experimental engine, although manually adjustable with engine shutdown, will not be variable while the engine is operating. Also, it was decided at this point that PCNL would be the primary controlled variable on the experimental engine. Factors leading to this decision were: 1) thrust accuracy was slightly better at SLS conditions for the PCNL control mode than for the PS3/PTO mode; 2) PS3/PTO will be evaluated as a control variable on the QCSEE OTW; and 3) PCNL is a more familiar control variable and is less likely to deter the demonstration of the OTW technology innovations, which include full authority digital control, Kalman Filter application, and incorporation of a fail-fixed servovalve.

4.5 TRANSIENT RESPONSE CAPABILITY

Another factor considered during the control system analysis process was transient response. This was done primarily through the use of a hybrid computer simulation of the engine and control system.

The basic QCSEE OTW response time requirement is 1.0 second maximum from 62 to 95 percent net forward thrust (sea level to 6,000 feet elevation) during a throttle burst from 60 to 100 percent of takeoff thrust. This thrust response requirement is aimed primarily at the landing approach condition, where rapid thrust recovery is required.

The manipulated variable inputs to the QCSEE OTW experimental engine are fuel flow and variable core engine compressor stator angle (Note: the plan is to add a variable exhaust nozzle for an OTW flight-type engine as considered in the previous analytical effort.) Prior engine control designs with the above two manipulated variables typically control steady-state fan speed and thus thrust by manipulating fuel flow. Fan speed is scheduled as a function of power setting and fan inlet pressure and temperature. Compressor stator angle is directly positioned with respect to a schedule that is a function of the core compressor corrected speed $(NH/\sqrt{T25})$ -- during both steady-state and transient operation. During an acceleration transient, fuel flow is scheduled as a function of $NH/\sqrt{T25}$ and the compressor discharge pressure (PS3). The time from 62 to 95 percent net thrust for such prior engine control designs generally ranges from 1.4 to 2.0 seconds. To achieve the 1.0-second acceleration time required for the OTW experimental

engine, attention was directed to more effective utilization of the core compressor stators. It was determined that this 1.0-second requirement could be met with the following control action:

- Reset the core stators further closed than the normal stator schedule at the 62 percent net thrust operating conditions.
- Rapidly open the core stators to the normal stator schedule during the acceleration to 100 percent net thrust.

During an aircraft approach, the control system functions in the following manner. Fan speed, and thus engine thrust, is controlled by manipulating fuel flow. If the pilot desires the capability for fast recovery from approach to takeoff thrust, the proposed procedure is to activate the digital control core stator reset mode button. The control logic causes the core stators to slew in a closed direction. The final stator position is determined by summing the core stator reset schedule and the normal core stator schedule (the reset schedule being a function of power setting; the normal schedule, a function of core engine corrected speed). Closing the core stators reduces the compressor airflow. If fuel flow is held constant, the engine cycle will balance at a lower fan speed. The fan speed control senses the deceleration tendency and increases fuel flow to maintain the scheduled fan speed. As a consequence, the core engine rotor settles out at a higher speed when steady-state operation is achieved. The basic objective of the core stator reset at the approach power setting is for the core engine rotor speed to settle close to the speed at the takeoff power setting. Thus, when the pilot demands a fast recovery from approach to takeoff thrust, the core engine rotor is essentially at its final speed, and only the fan rotor need be accelerated to its takeoff speed condition. Such operation removes the core rotor inertia's dynamic effect on engine acceleration and achieves fast response from approach to takeoff thrust.

Subsequent paragraphs discuss the effect of core stator reset on engine steady-state operation, the simulated transient response for a go-around maneuver, factors which affect acceleration time, and deceleration transients.

4.5.1 Effect of Core Stator Reset on Steady-State Operation

Figure 17 shows the effect of core stator reset on pertinent engine variables at 62 percent of takeoff thrust for the sea level static, standard day, zero bleed condition. When the stator schedule is reset 30 degrees closed, core speed increases to about 13,800 rpm, which is some 150 rpm above the speed at the takeoff power setting. As the stator schedule is reset from 0 to 30 degrees closed, fuel flow increases from 3,940 to 4,440 pph (i.e., an increase of 500 pph); specific fuel consumption (sfc) increases from 0.313 to 0.354. In effect, a tradeoff is being made between the specific fuel consumption and the capability to meet the 1.0-second acceleration requirement when stator reset is used. For example, if 30 degrees of stator reset is used to achieve the required acceleration response, the cost is only 8.33 pounds more fuel for each minute of operation at the 62 percent thrust approach condition.

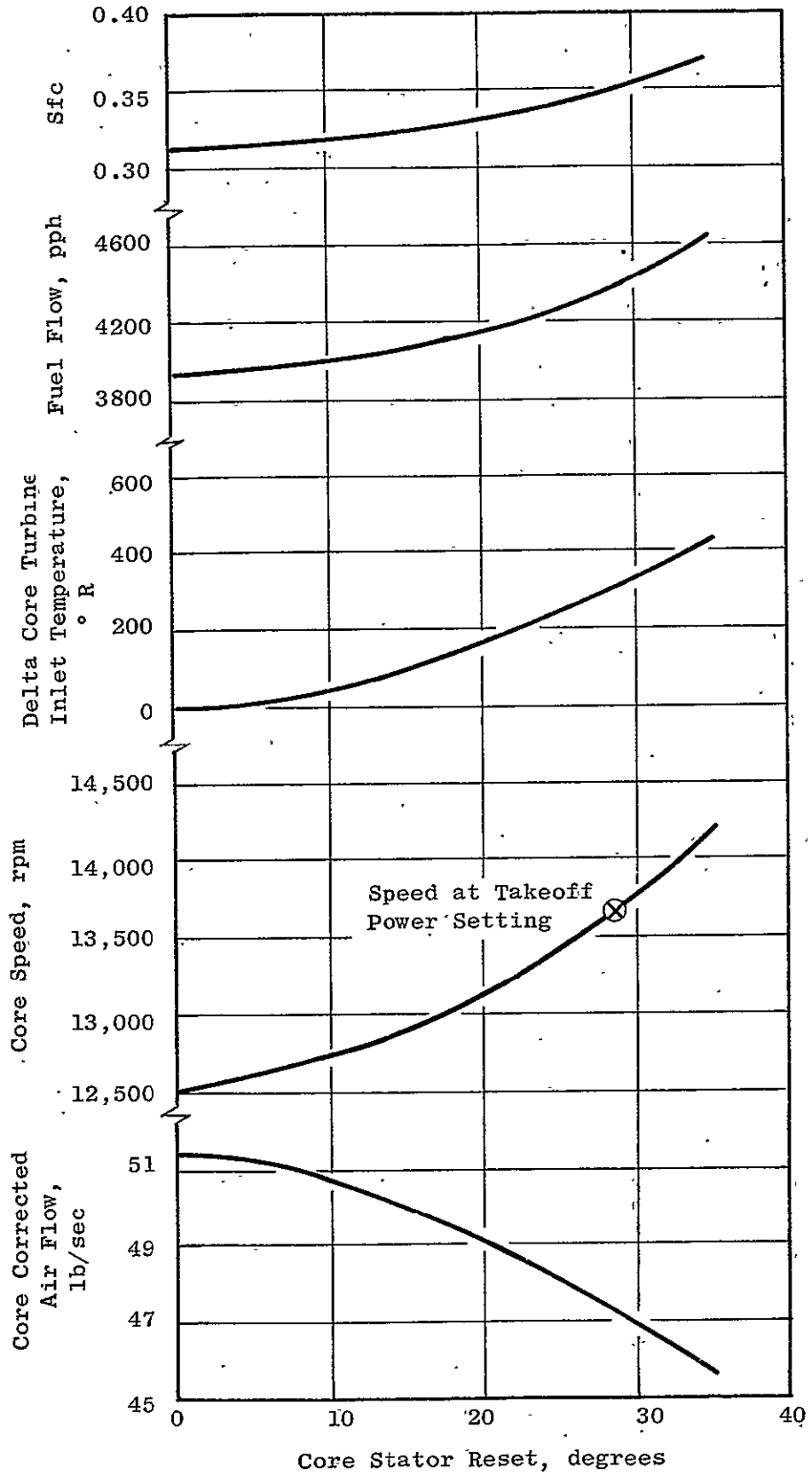


Figure 17. QCSEE OTW Engine Variables at 62% Net Thrust Vs. Core Stator Reset.

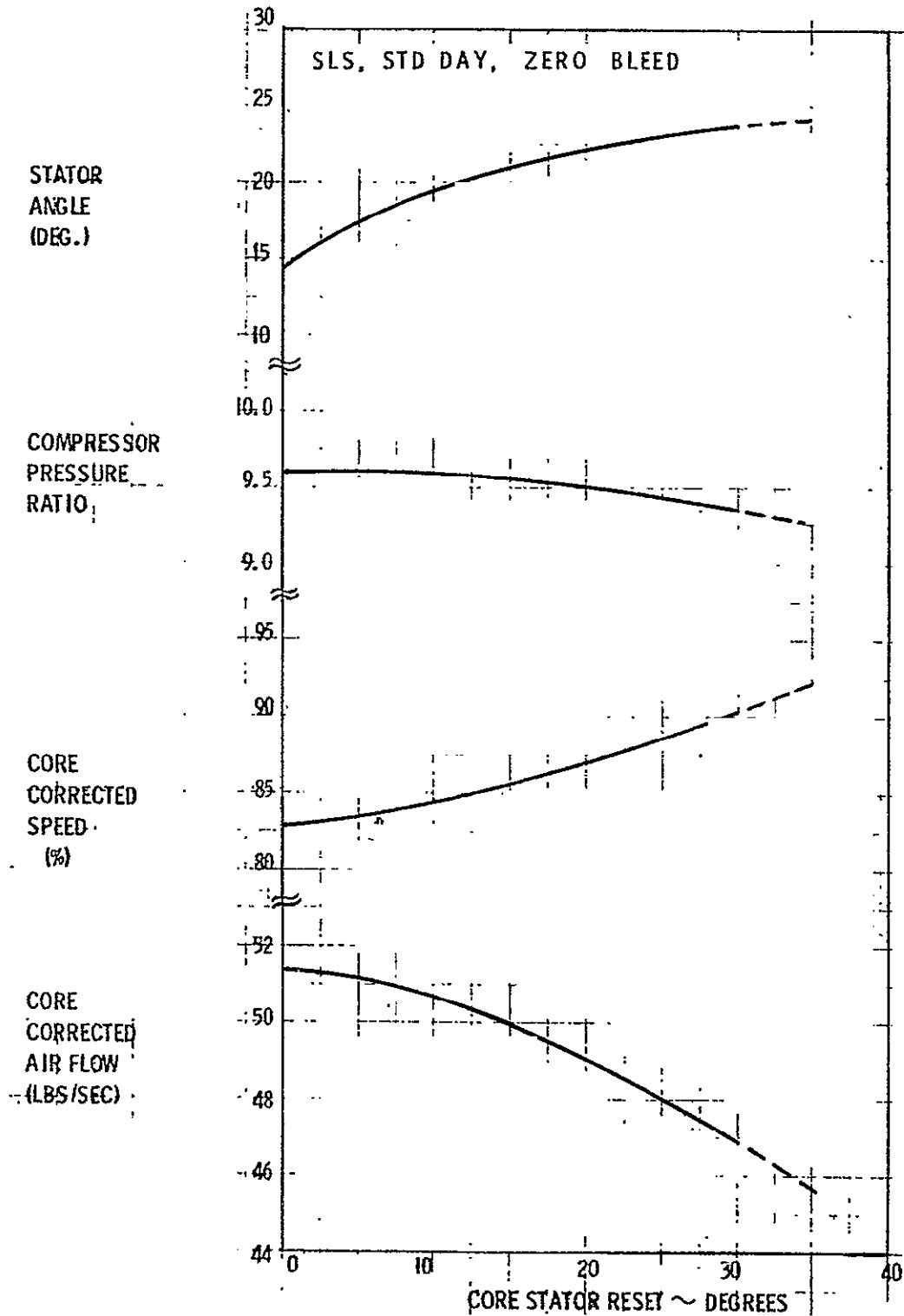


Figure 17. QCSEE OTW Engine Variables at 62% Net Thrust Versus Core Stator Reset (Concluded).

4.5.2 Simulated Go-Around Maneuver

Simulation transient recordings for an acceleration from 62 to 100 percent net thrust are shown in Figure 18. The left end of Figure 18 shows the conditions at the 62 percent net thrust condition. The stator reset at 62 percent net thrust is +30 degrees (closed), as shown by the recorder channel for core compressor stator error. A core corrected speed of 90.4 percent is indicated in the adjacent channel. At this speed, the nominal stator schedule as a function of core corrected speed calls for the stators to operate on the full open stop, that is -6 degrees. Thus -6 degrees plus the 30 degrees reset result in an actual stator position of +24 degrees, which is shown by the recorder channel labeled core stator position.

After the step increase in power setting, Figure 18 shows that:

- The response time from 62 to 95 percent of takeoff thrust is 0.73 seconds, which is well within the 1.0 second requirement.
- The core stators start opening within the first 0.05-seconds and slew to the full open stop (-6 degrees) at a rate of 60 degrees per second, producing a rapid increase in compressor air flow. The open stop is reached in approximately 0.55 seconds.
- Fuel flow increases due to the step in corrected fan speed demand (scheduled as a function of power setting). During the first 0.45 seconds, fuel flow is limited by the WF/PS3 acceleration fuel schedule.
- During the interval from 0.45 to 0.85 seconds, the rate of fuel flow increase is limited by the calculated core turbine temperature control. It has anticipated that turbine inlet temperature is approaching but that it is still below the control reference; this reference is set to limit temperature to 250° R above the steady-state temperature at takeoff power, sea level static, standard day. At 0.85 seconds, turbine temperature is 220° R greater than the final steady-state temperature at takeoff.
- Minimum compressor stall margin during the transient is 14.9 percent.
- After 0.85 seconds, the fan speed has accelerated to the point where it again controls fuel flow. Core speed peaks at 14,200 rpm. Both rotor speeds, the core stators, and fuel flow settle out at the final takeoff operating levels within the next 1.75 seconds.

4.5.3 Acceleration Studies

Several factors were evaluated to establish the transient control design for the OTW engine. The design process started with the development of the WF/PS3 acceleration fuel schedule. This schedule was designed to use 5 percent of the available core compressor stall margin during accelerations

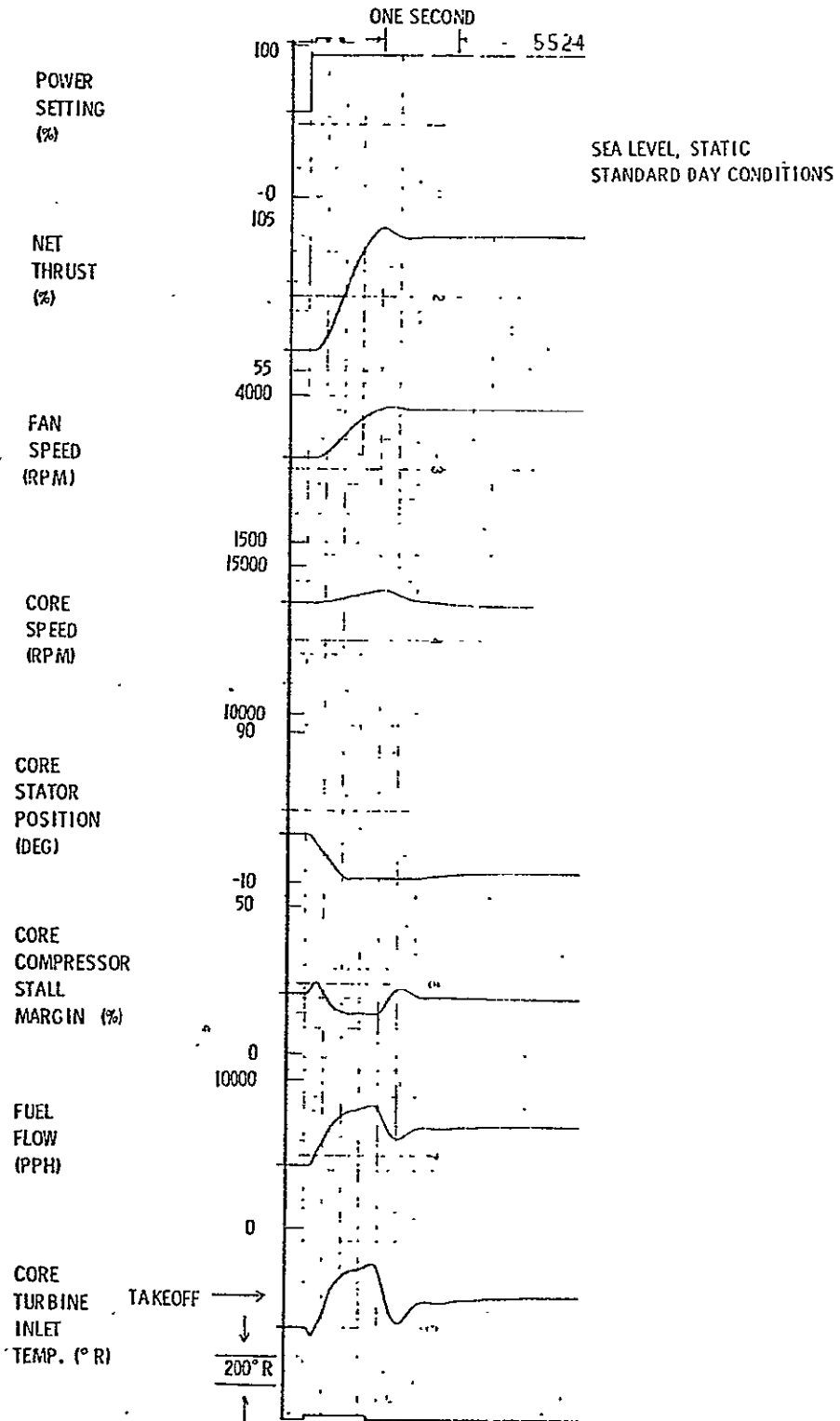
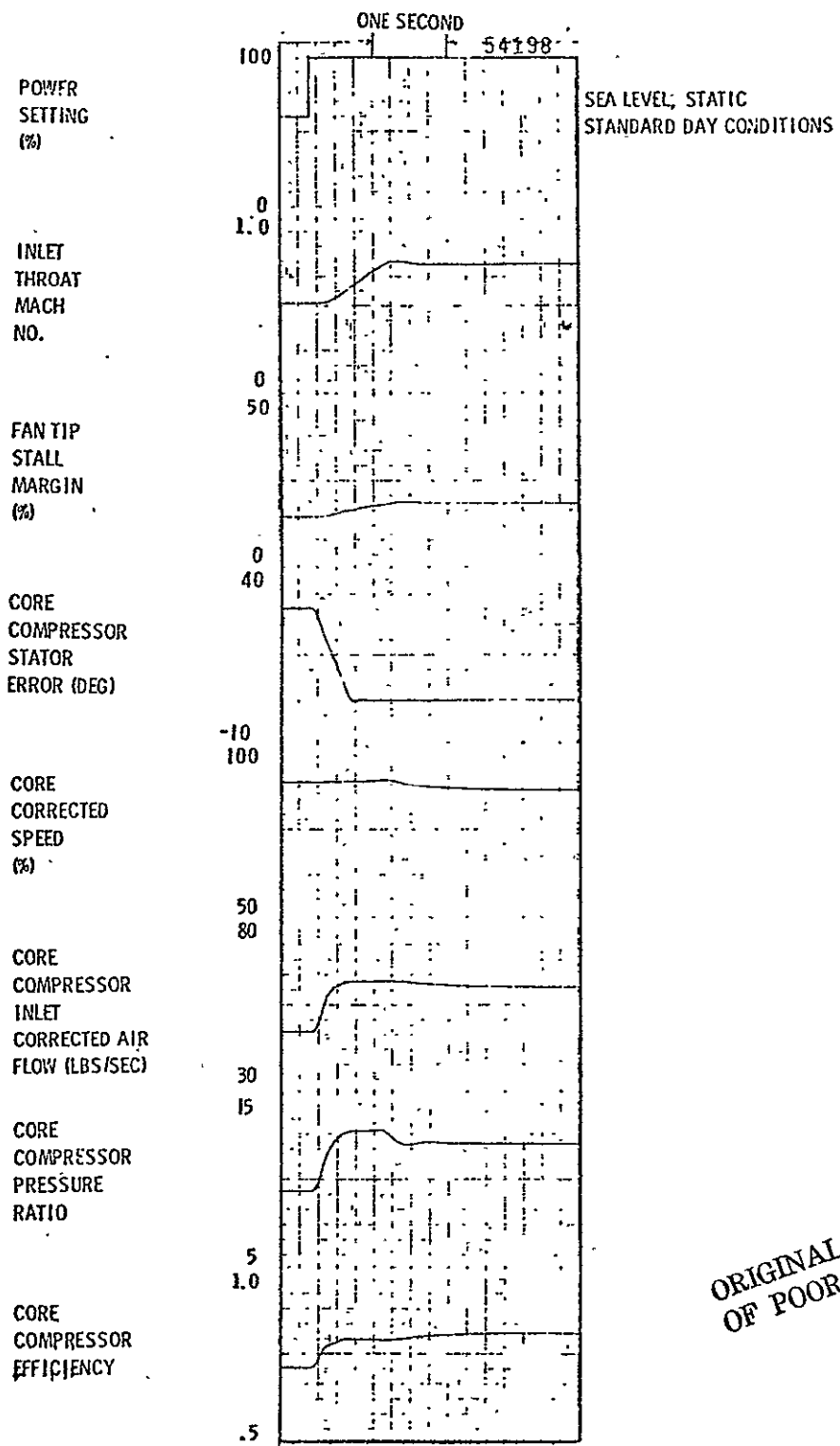


Figure.18. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Linear Servovalve and Core Stator Reset.



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Figure 18. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Linear Servo valve and Core Stator Reset (Concluded).

with no core stator reset. Results from initial simulation studies on transient core stall margin are plotted versus corrected core speed in Figure 19. This figure contains typical stall margin transients for a control with no stator reset and for a control with stator reset, and indicates satisfactory performance in both cases.

The rate of removing core stator reset (i.e., the opening rate of the compressor stators) was also investigated in the initial design studies. As shown in Figure 20, rates greater than 60 degrees per second do not provide a significant reduction in acceleration time. The adequacy of the fuel pump to supply stator actuator flow for the 60 degrees per second rate was checked and it was determined that it could be achieved with the current pump design. This 60 degrees per second opening rate was chosen for the control design and maintained throughout the remainder of the simulation studies.

The OTW experimental engine has a titanium fan; however, a lower-inertia, composite fan is planned for a flight type engine. The initial study predictions in Figure 21 indicate an 0.2 second reduction in acceleration time when the composite fan is used and the control design includes 30 degrees core stator reset at 62 percent thrust.

In the final acceleration design studies, the core turbine inlet temperature control loop was refined so that the fuel control would remain in the acceleration fuel schedule mode for a longer period of time during the transient. Rate feedback limits were "tuned" to provide the desired anticipation for the different control loops. The final simulation predictions for the experimental engine acceleration times as a function of initial thrust level are shown in Figure 22. The predicted time from 62 to 95 percent net thrust is 0.73 seconds for the nominal control design.

4.5.4 Deceleration Study

The hybrid computer simulation was also used to investigate decelerations to approach power. The WF/PS3 deceleration schedule was checked out to ensure that combustor blowout conditions will not occur.

A transient for a deceleration from 100 to 62 percent of takeoff power at sea level static, standard day conditions is shown in Figure 23. For this transient, the core stator control logic is set in the "reset on" mode. The response time from 100 to 62 percent thrust is 0.8 seconds. Both thrust and fan speed settle close to their final values within 2.5 seconds after the step decrease in power setting. The core stator control limits the rate at which reset is added to the normal core stator schedule in order to prevent a transient mismatch between fan and core airflow and pressure fan hub stall margin. This rate limit is approximately four degrees per second; thus, it takes approximately 7.5 seconds to reset the stators 30 degrees closed, as shown by the core compressor stator error recording in Figure 23. This closing rate limit is significantly lower than the 60 degree per second opening rate limit used during accelerations.

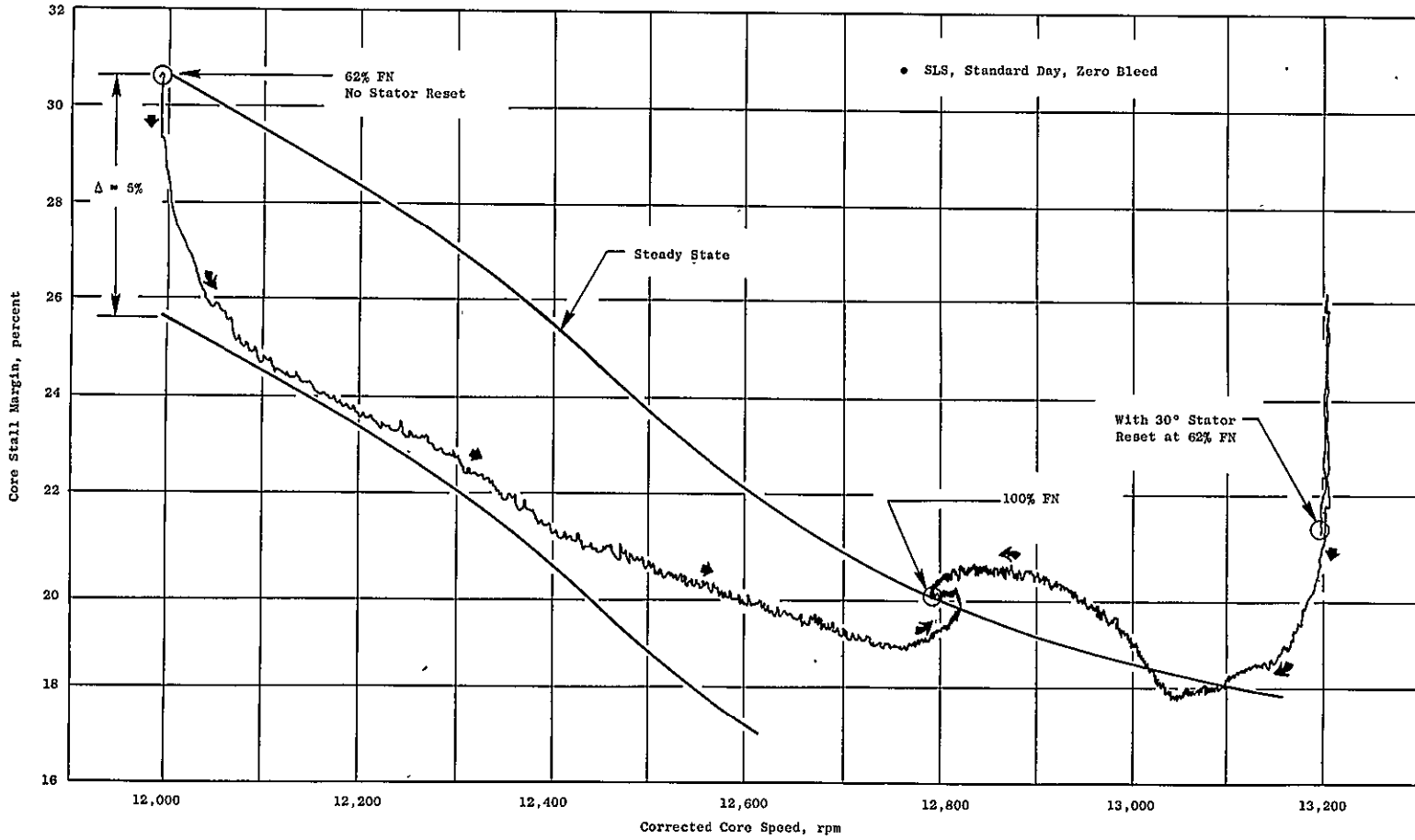


Figure 19. Initial Predictions of Core Stall Margin for Throttle Burst from 62 to 100% FN.

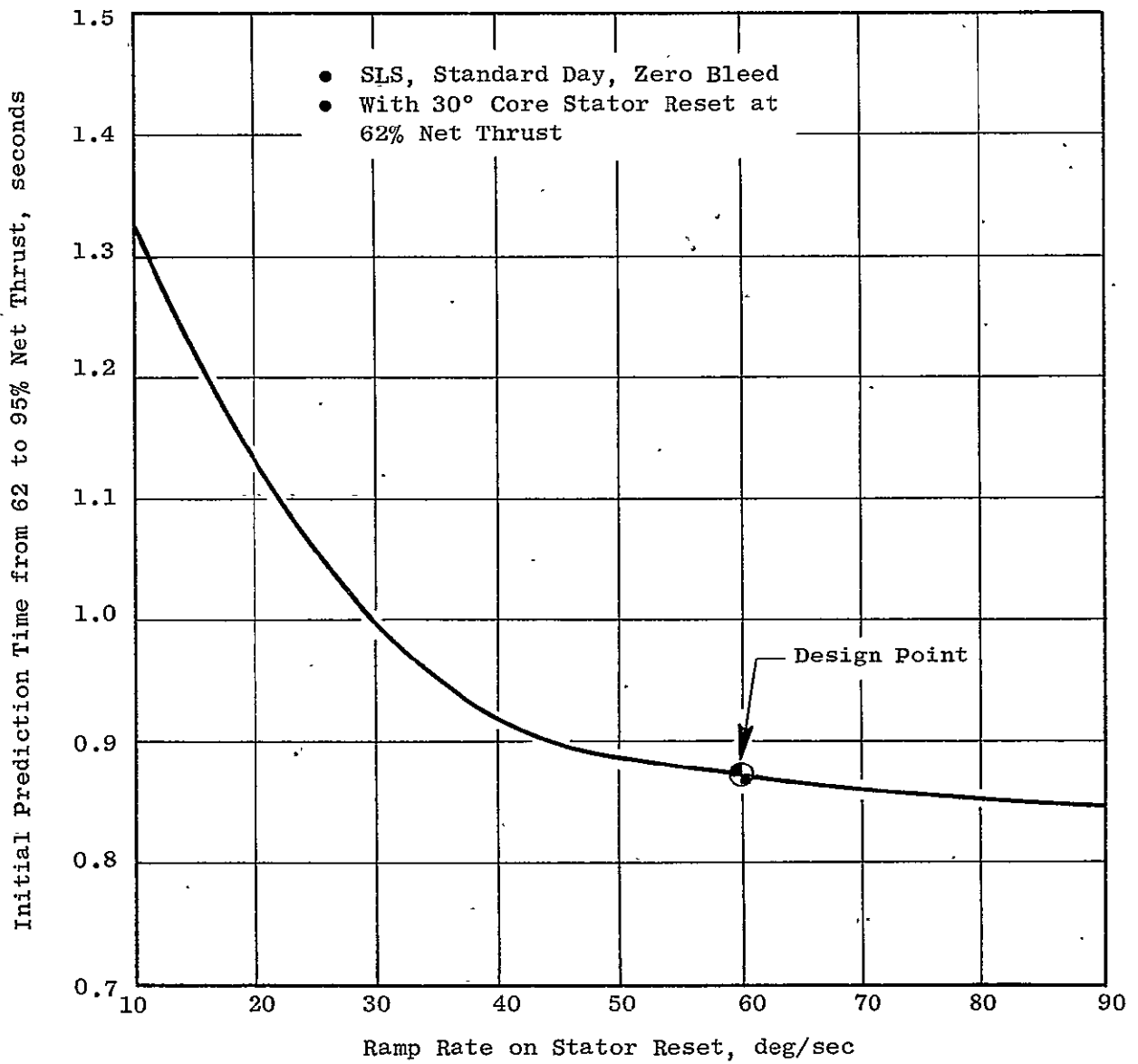


Figure 20. OTW Transient Response Accel Time Vs. Rate of Removing Core Stator Reset.

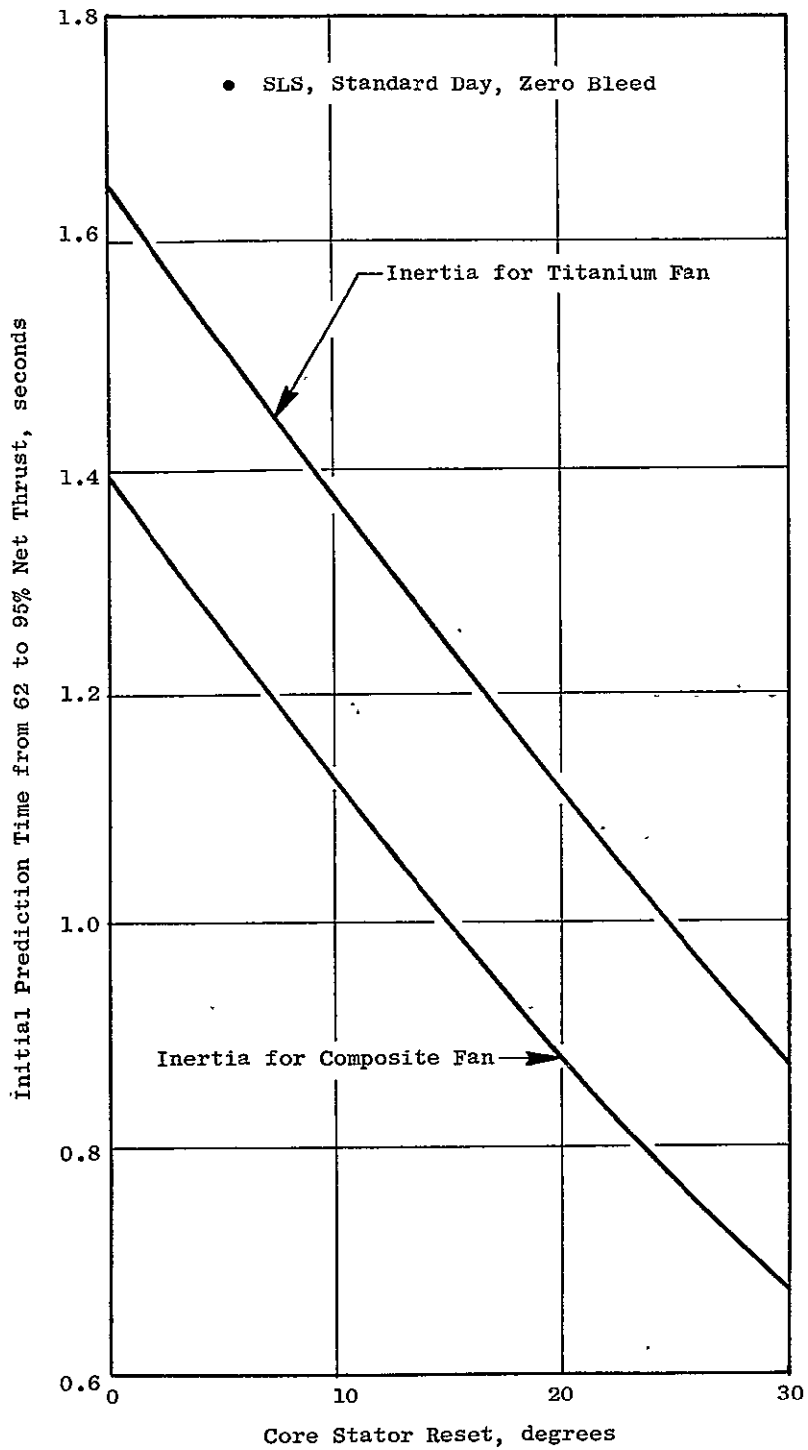


Figure 21. Initial Predictions - OTW Transient Response Accel Time Versus Core Stator Reset and Fan Rotor Inertia.

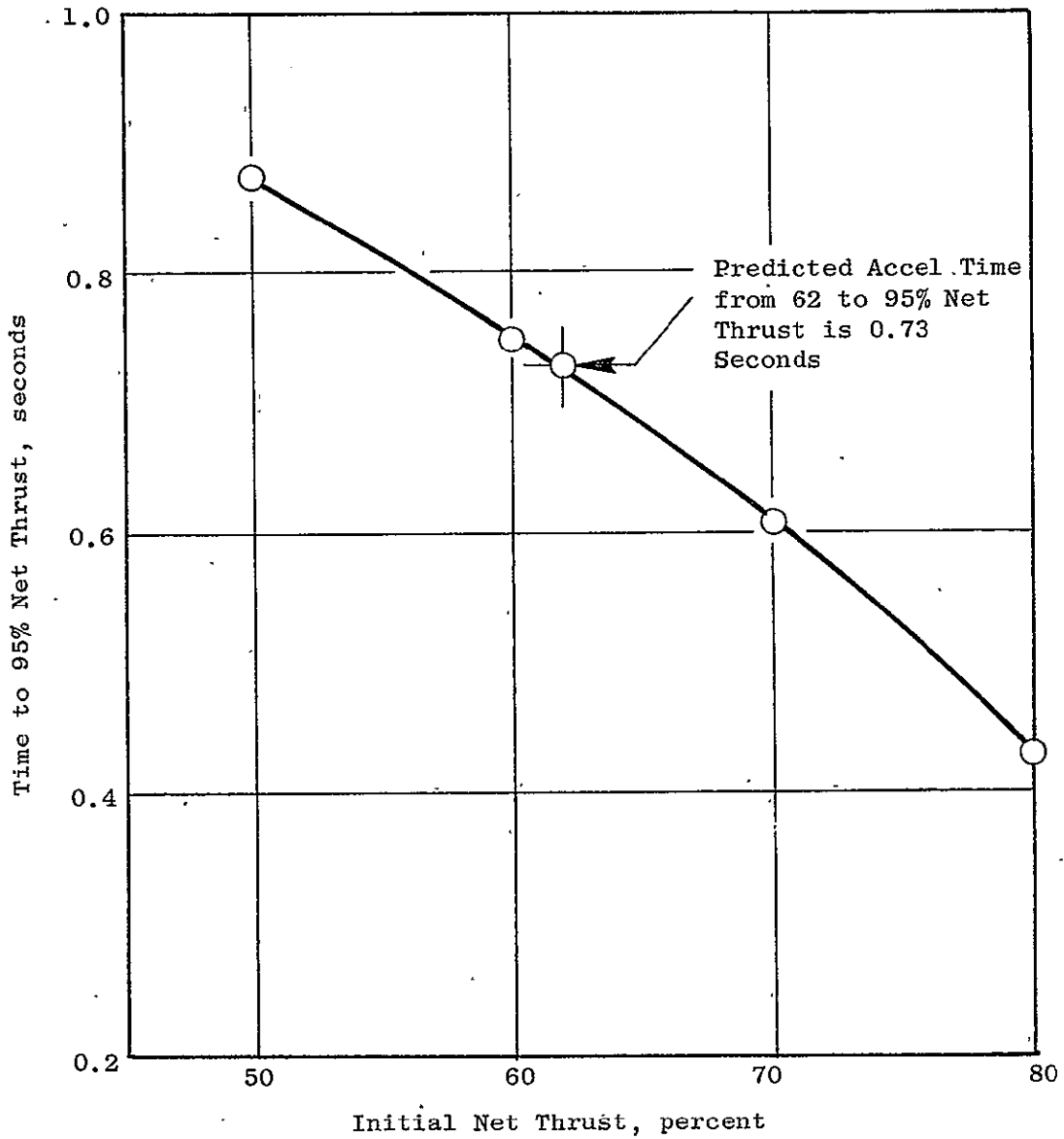


Figure 22. Final Prediction of OTW Transient Response for Throttle Bursts to 100% Net Thrust at Sea Level, Static, Standard Day, Zero Bleed Conditions.

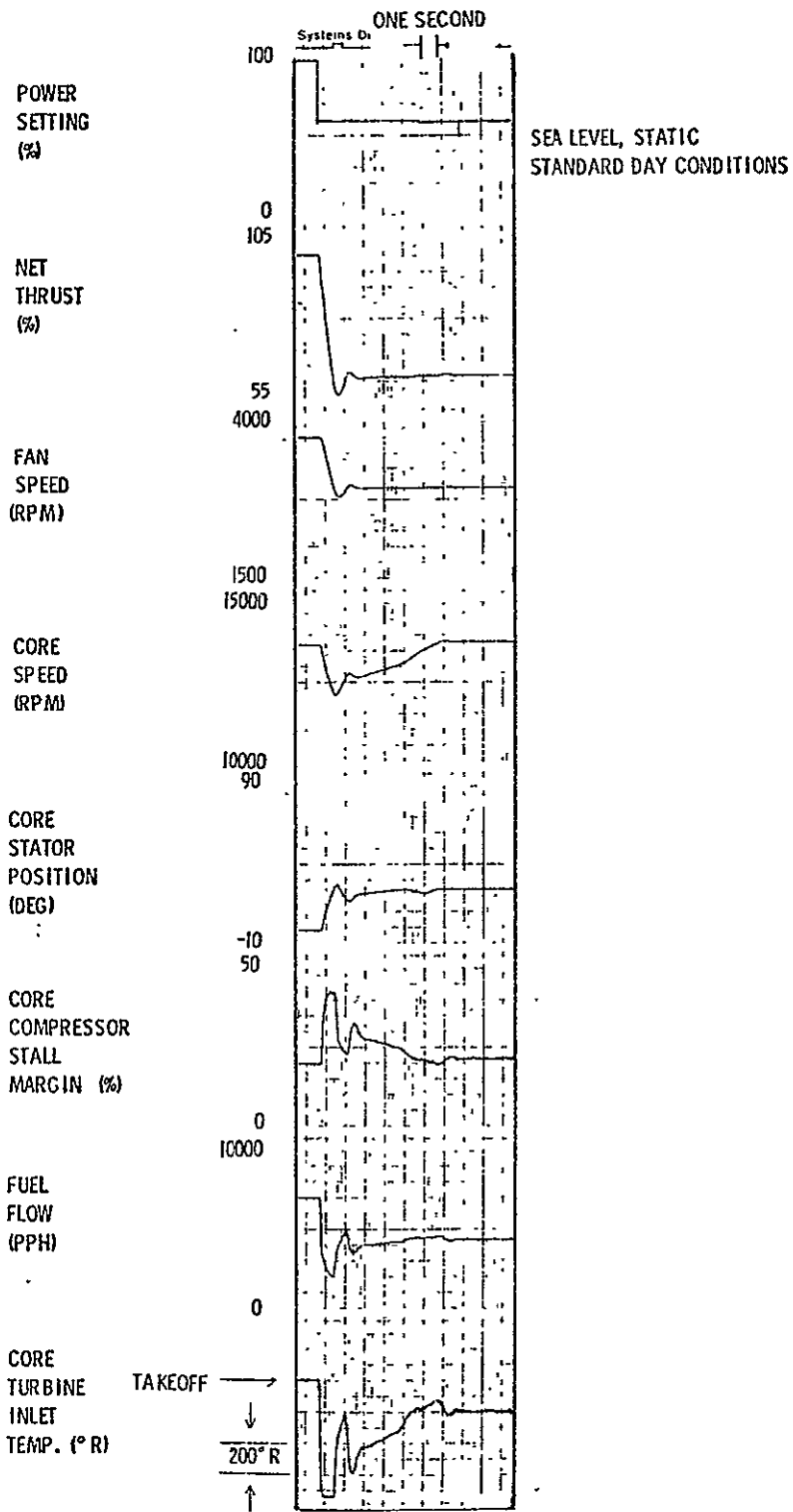


Figure 23. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Linear Servovalve and Core Stator Reset.

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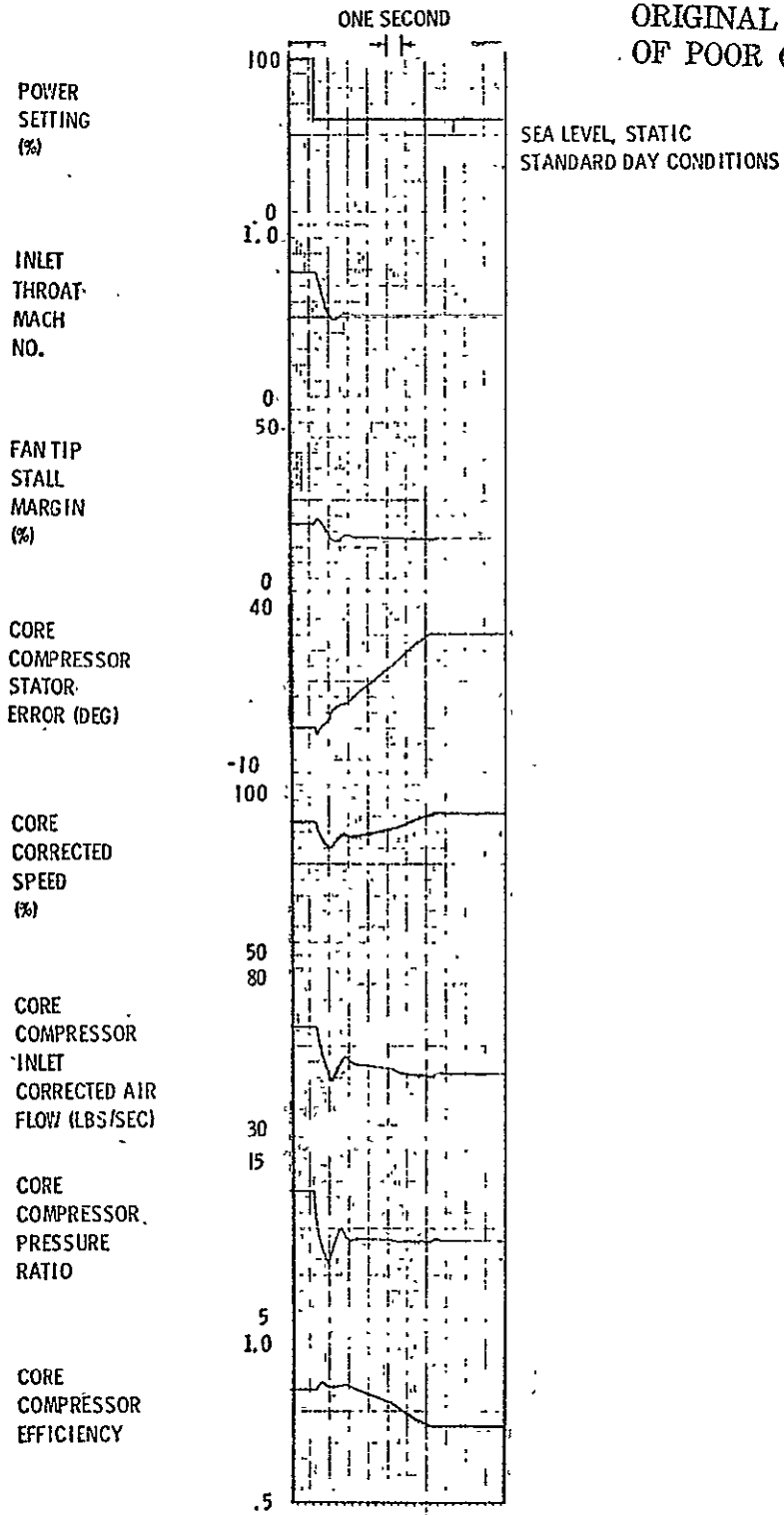


Figure 23. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Linear Servovalve and Core Stator Reset (Concluded).

4.6 STABILITY ANALYSIS

A stability analysis was performed to define system dynamic characteristics that will provide accurate, stable, fast-response, closed loop control of the OTW experimental engine. This engine has two manipulated variables, fuel flow and core compressor stator angle. Results from the control mode analysis studies (reported in Section 4.2) indicated that these two manipulated variables should be used to control the engine in the conventional manner of:

- Manipulating fuel flow to control the corrected fan speed.
- Scheduling the core compressor stator angle as a function of the core compressor corrected speed.

Linear stability studies for both the fan speed control and the core stator position control were performed at the takeoff, sea level static, standard day conditions. Conventional stability analysis methods were applied. Adequate stability margin for these controls was based on the following criteria:

- Magnitude of the closed loop frequency response less than or equal to 1.5.
- At least 2 to 1 (i.e., 6 decibels) gain margin when the phase margin of the open-loop transfer function is zero.

To perform the linear stability studies, the QCSEE OTW cycle deck was used to generate engine partial derivatives at the takeoff power setting. Next, transfer functions for the sensor and the hydromechanical control components were developed from information provided by the component engineers. The above stability criteria were used to size the dynamics for the fan speed and core stator controllers. These dynamics have been implemented in the digital electronic control, and the combined operation of these two controllers with the sensors, hydromechanical components, and engine has produced stable and fast response.

Fan speed controller dynamics were selected to produce an integration-type control with lead compensation. The lead time constant compensates for the lag dynamics in the engine transfer function. This lead over an integration was mechanized by using lagged-rate feedback in the inner servo loop of the fan speed control rather than using proportional-plus-integral dynamics in the forward path of the outer loop.

Open-loop frequency response results for the fan speed control at takeoff sea level static, standard day are contained in the Nichols chart in Figure 24. This figure shows that the maximum magnitude of the closed-loop response for the fan speed control should be slightly less than 1.5 (as indicated by the open loop response plot being almost tangent with the $M=1.5$ circle at $\omega=9$ radians per second). Next, this figure shows that the gain margin is $1/0.545 = 1.835$ to 1 at the open-loop phase margin of zero

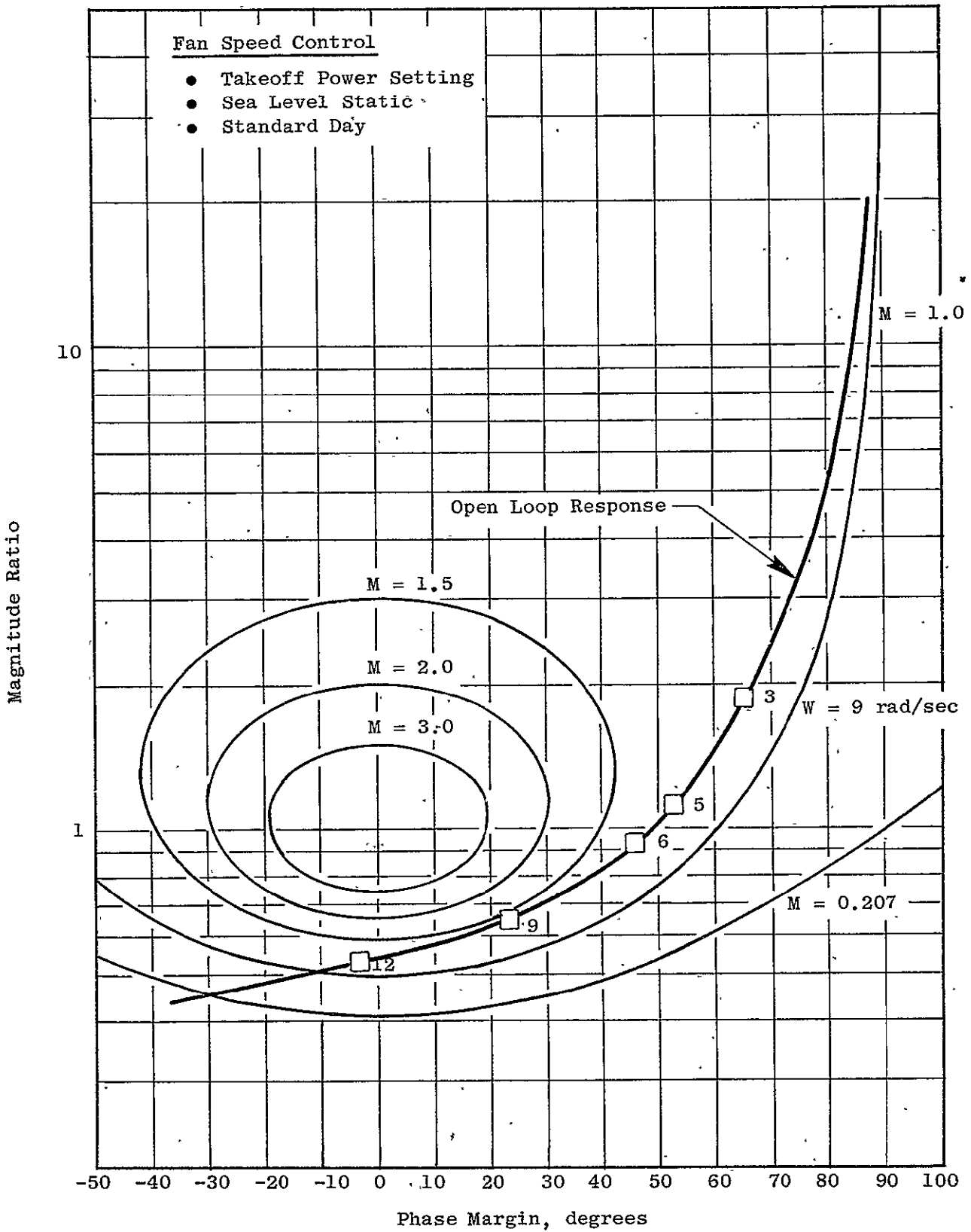


Figure 24. Phase Magnitude Ratio Diagram, Fan Speed Control.

degrees. These results indicate that the fan speed control meets the above standard that the closed loop magnitude be less than or equal to 1.5. Although the gain margin of 1.835 to 1 is a bit smaller than the desired margin of 2 to 1, we judged that a gain margin of 1.835 to 1 would be adequate for the fan speed control of the OTW experimental engine.

The core stator control is a single-loop, position control. The demand reference for this control is the sum of the stator reset command and the scheduled stator angle - the latter being a function of core compressor corrected speed. The core stator controller computes the error between the demand reference and the sensed position of the core stator actuators; the electrical current output from the controller is proportional to a gain times this error. The electrical current sets the position of a torque motor-operated servovalve and, subsequently, the hydraulic flow rate to the two stator actuators. The position of these actuators is proportional to the integral of the hydraulic flow and thus to the current output from the core stator controller.

Open-loop frequency response results for the core stator control at takeoff, sea level static, standard day are contained in the Nichols chart in Figure 25. This figure shows that the maximum magnitude of the closed-loop response is slightly less than 1.5 (as indicated by the open loop response plot being almost tangent with the $M=1.5$ circle at $W=16$ radians per second). Secondly, this figure shows that the gain margin is $1/0.38 = 2.63$ to 1 at the open loop phase margin of zero degrees. These results indicate that the core stator control meets the above stability standard that closed loop magnitude be less than or equal to 1.5 and the gain margin at least 2 to 1.

After making the linear stability studies on the fan speed and core stator controls at the takeoff power setting, the hybrid computer simulation of the OTW engine and control system was used to check and ensure that the stability margin was adequate over the range of part power settings. For example, the simulation recordings for fan speed and core stator position in Figure 23 indicate stable operation for each of these controls at 62% thrust. Figure 23 shows stable and fast response of core stator position both during and at the completion of the deceleration from 100% to 62% thrust. Figure 23 also shows a stable and desirable settling time of fan speed at 62% thrust.

The dynamics of the idle core speed, the maximum core speed, and the maximum turbine temperature (T41C) controls for the OTW engine were set equal to the dynamics used in these controls for the UTW engine. The same dynamics could be used because the OTW and the UTW have the same core engine design. Stable operation of the above controls with the OTW engine was checked by using the hybrid simulation.

During the UTW control design program, considerable work was devoted to the effect of digital control sampling rate on control system stability. In researching this we used the engine exploring control simulations. This work is reported in Reference 3. The results of this work were applied

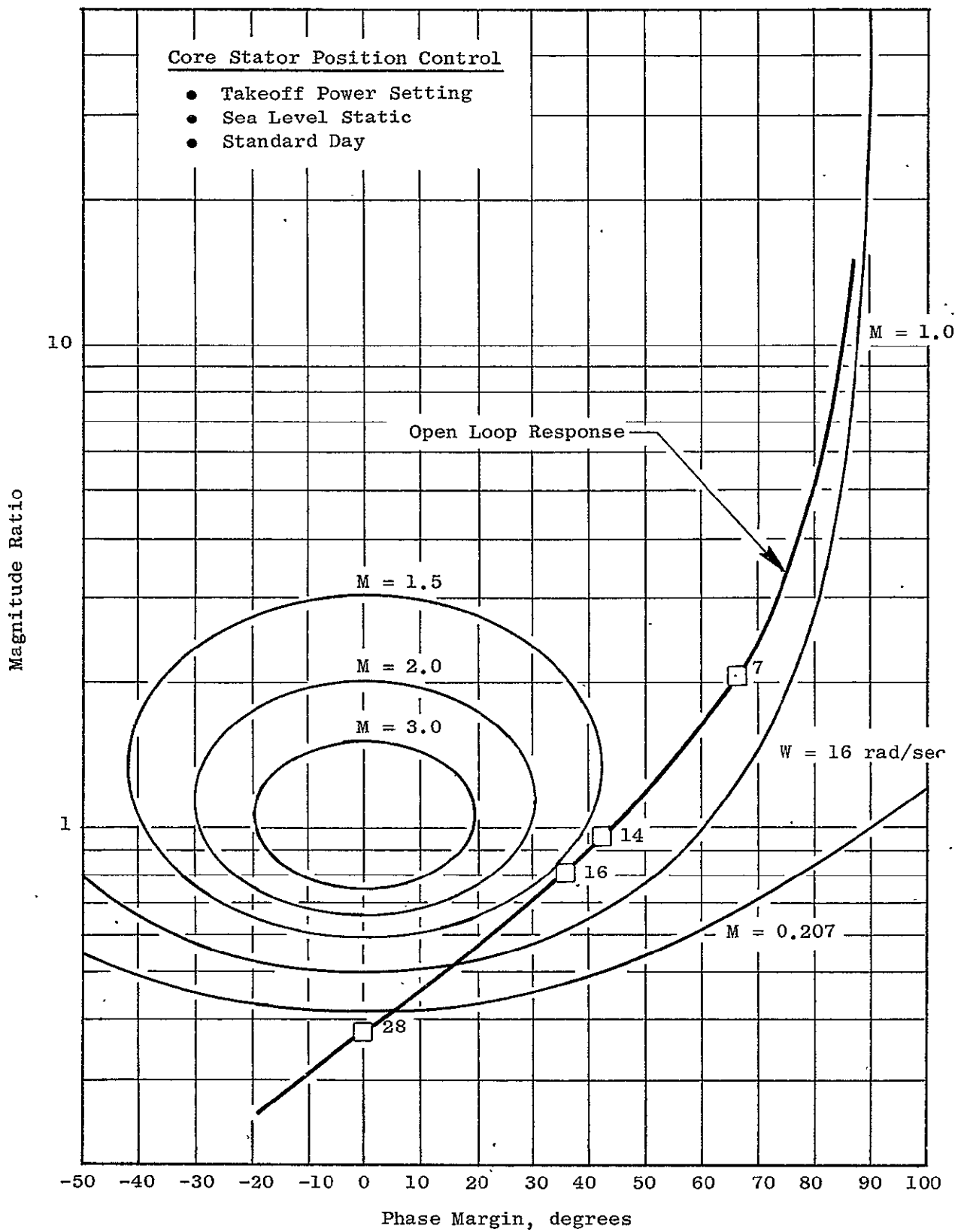


Figure 25. Phase Magnitude Ratio Diagram, Core Stator Position Control.

to the design studies on OTW control dynamics. In summary, the sampling rate effect was considered to be equivalent to a time delay of 1.5 times the digital control sampling rate. Thus, the time delay used in the OTW design studies was $1.5 \times 0.0135 = 0.0203$ seconds and, in the frequency analysis, was inserted at the point of each control's digital-to-analog converter. Using an 0.0203 second time delay in each control loop was felt to be reasonable, since the bandwidth of the controls was much lower than the sampling frequency.

4.7 FAIL-FIXED SERVO VALVE DESIGN ANALYSIS

One of the new technology elements to be demonstrated in the OTW control system is the fail-fixed servovalve. This servovalve and its driver circuit are described respectively in 7.3 and 6.2.3. An analysis was performed to investigate the characteristics of this new device and to define the best method of controlling it. The analysis was accomplished primarily by incorporating servovalve design characteristics into the hybrid simulation of the engine and control system and then evaluating their effects on steady-state and transient operation. Two types of pulse width-modulated torque motor driver amplifiers for this servovalve were considered in the analysis. Simulation results indicated that the digital control must include logic to compensate for the servovalve's null shift and dead-zone characteristics. The logic for the null shift and dead-zone compensation was developed and then included in the digital control specification. The next several paragraphs describe the models for the two types of driver amplifiers, the simulation results, and the compensation logic.

4.7.1 Fail-Fixed Servovalve Simulation

The input to the fail-fixed servovalve is a pulse width-modulated current from the digital control, as shown schematically in Figure 26. The simulation representations for two types of pulse width-modulated torque motor driver amplifiers. The unipolar pulse driver amplifier uses current pulses of only one polarity, the polarity being chosen by the sign of the digital word. The bipolar pulse driver amplifier uses a train of positive and negative pulses whose width is determined by the sign and magnitude of the digital word. Both operate at a frequency of 500 Hz. Operation of the servovalve with the unipolar amplifier was felt to have better resolution from percent digital word to flow, but poorer null shift and dead-zone characteristics than operation with the bipolar amplifier. Figure 27 illustrates the difference between servovalve operation with the unipolar and bipolar amplifiers.

Since the primary concern was the effect of the dead zone and null shift, the digital word-to-servovalve flow characteristics were linearized and limited, as shown in Figure 28. Tolerances for both dead zone size and amount of null shift were estimated based on past experience with similar valves. The pulse driver amplifiers and the servovalve were assumed to respond like first-order lags, with respective time constants of 0.01 and

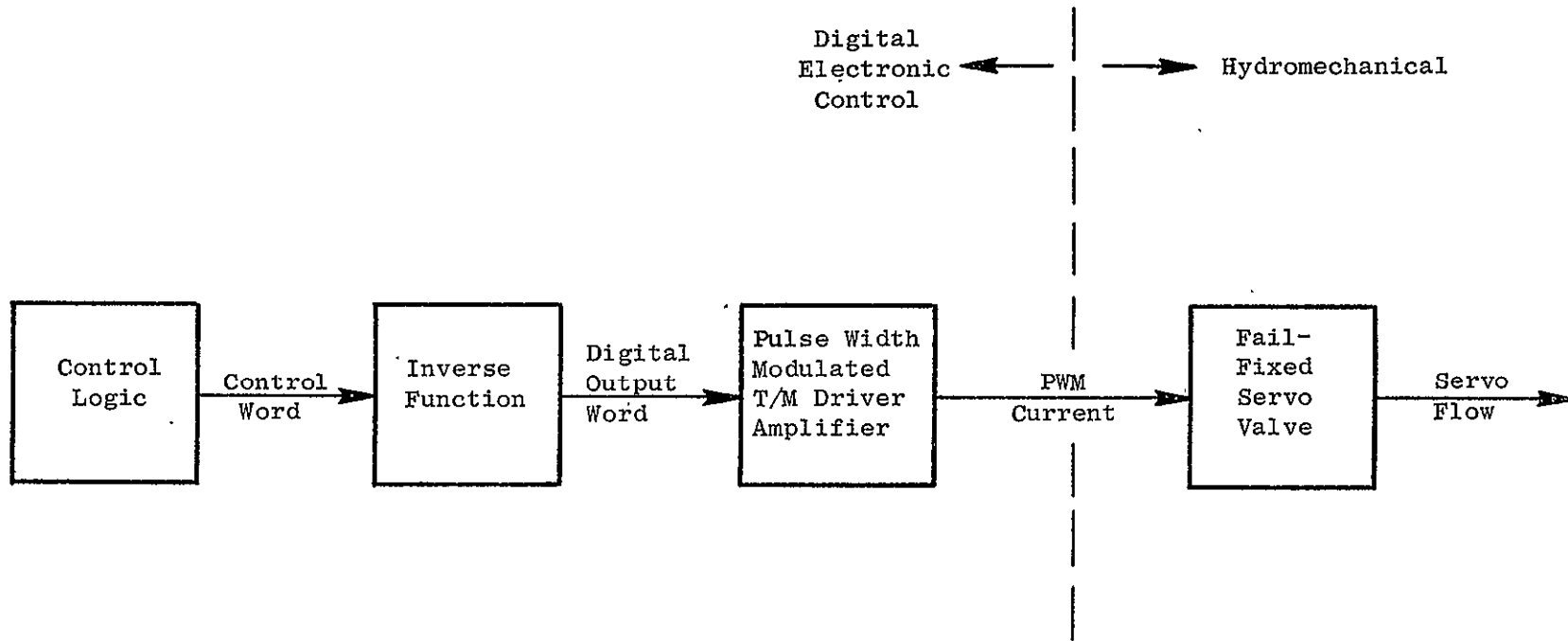


Figure 26. Functional Schematic for Digital Control and Fail-Fixed Servo Valve.

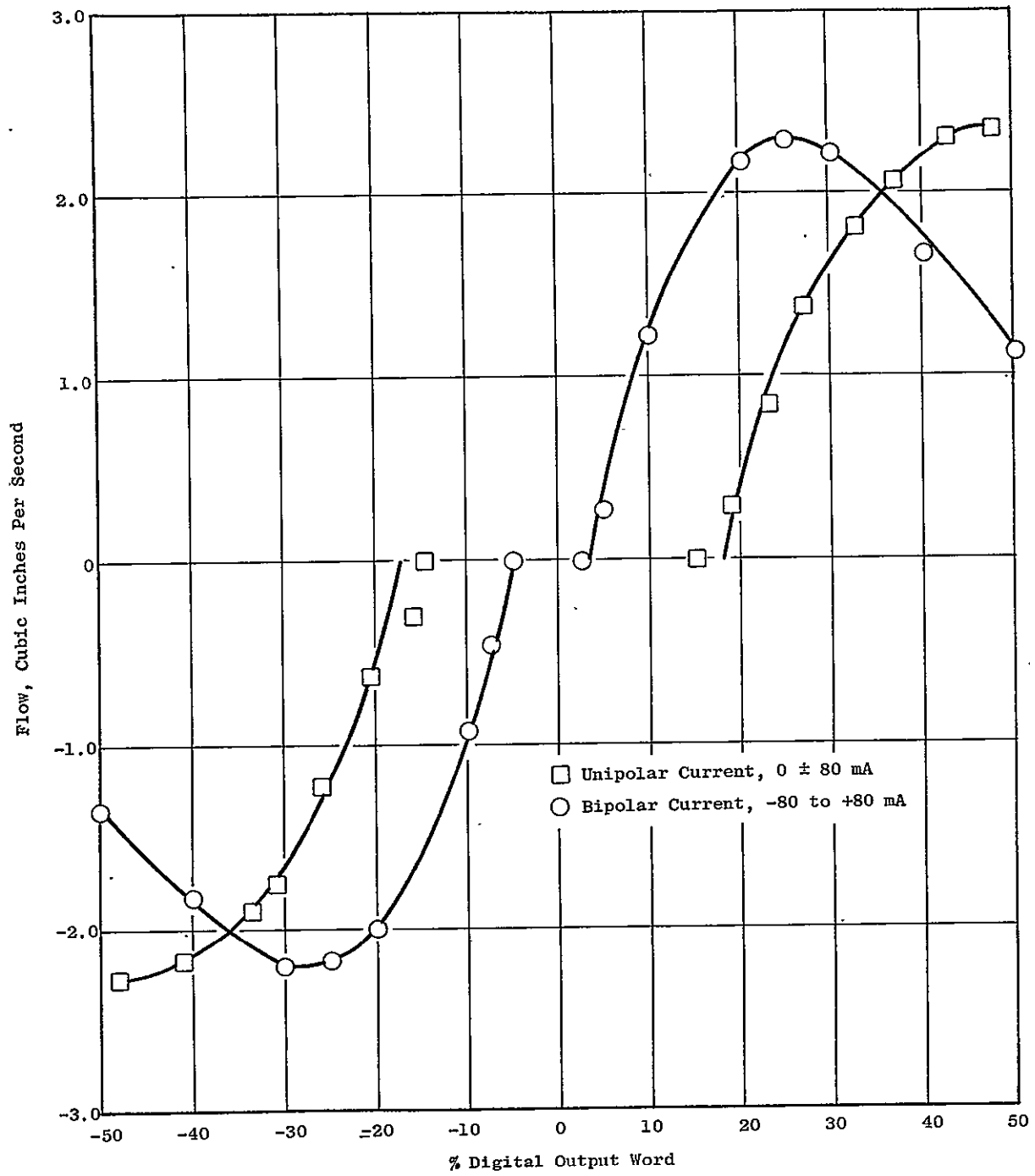


Figure 27. Fail-Fixed Servo Valve Characteristics, Digital Amplifier and Servo Valve, 500 Hz, Pulse Width Modulation.

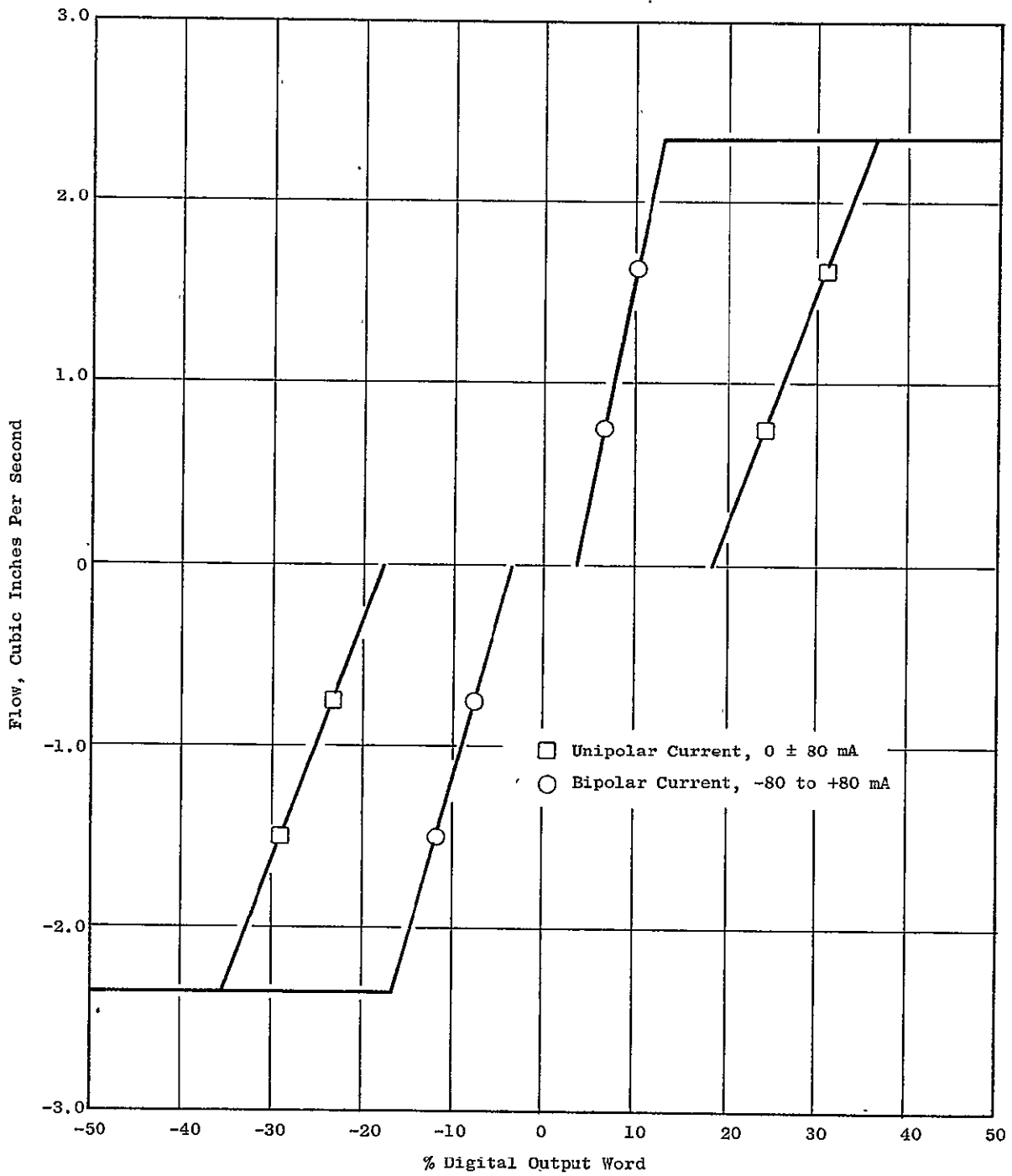


Figure 28. Simulation of Fail-Fixed Servovalve Characteristics.

0.03 seconds. (These time constants are the same as those normally assumed for an analog-type torque motor driver amplifier and linear servovalve design.)

4.7.2 FFSV Simulation Results

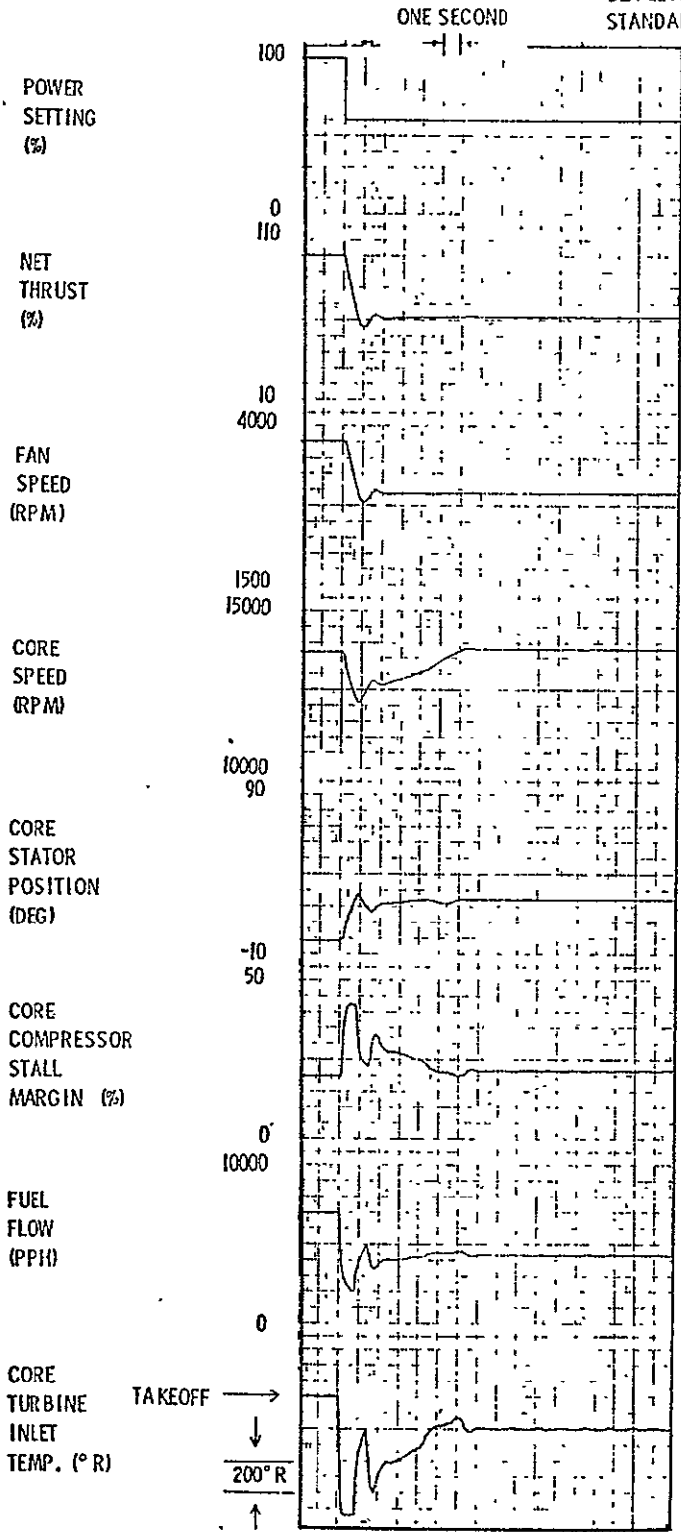
The fail-fixed servovalve study started using characteristics from the unipolar pulse driver amplifier because of its better resolution from percent digital word to servo flow. Without additional compensation, this control will not perform transients because of the large dead band and the use of rate feedback to provide the control loop integration. With the system at steady-state, the rate feedback is zero and the fan speed error is not large enough to overcome the dead zone.

An "inverse function" (referred to in Figure 26) was developed to compensate for the fail-fixed servovalve dead zone and to provide characteristics equivalent to a linear servovalve. The effect of perfect dead zone compensation on a throttle chop to approach power and a burst back to takeoff power is shown in Figures 29 and 30. The effect of an inverse function overcompensating the dead zone is shown in Figure 31, in which the compensation is 10 percent greater than the dead zone. This produces a step in the digital control word - servo flow relationship resulting in a very high gain at null and sustained fuel flow oscillations at takeoff. Thus, any dead zone compensation must be sized for the minimum expected dead zone.

When the maximum null shift (± 5 percent of digital output word) for a unipolar pulse was used with the dead zone compensation, the control would not perform approach-power transients. Depending on the polarity of the null shift, the control could either decelerate to 62 percent takeoff thrust or accelerate back to takeoff thrust, but not both. This was due to the effect of the dead-zone compensation, which created a dead zone on one side of null and a vertical step on the other side of null. This is illustrated in Figure 32 for a maximum positive null shift. Because of the dead zone, the vertical step does not produce an oscillatory system. However, the dead zone prevents transients that require the same polarity of the servo flow as the dead zone.

To improve the performance with null shift, the unipolar pulse driver amplifier was replaced with the bipolar pulse driver amplifier, which has a maximum null shift of ± 1 percent of the digital output word. The effect of having no dead-zone compensation during a chop to approach power and a burst back to takeoff power is shown in Figures 33 and 34. Note the large inaccuracy in thrust at approach - 41 percent instead of 62 percent of takeoff thrust. This is due to the large dead zone and the use of rate feedback to provide the integration of the control. Since the system has reached steady state, the rate feedback is zero and the error in fan speed is not large enough to overcome the dead zone. A similar phenomenon is seen when an attempt is made to accelerate back to takeoff power, with the engine stopping at 62 percent of takeoff thrust.

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Figure 29. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Fail-Fixed Servovalve with Perfect Dead-Zone Compensation.

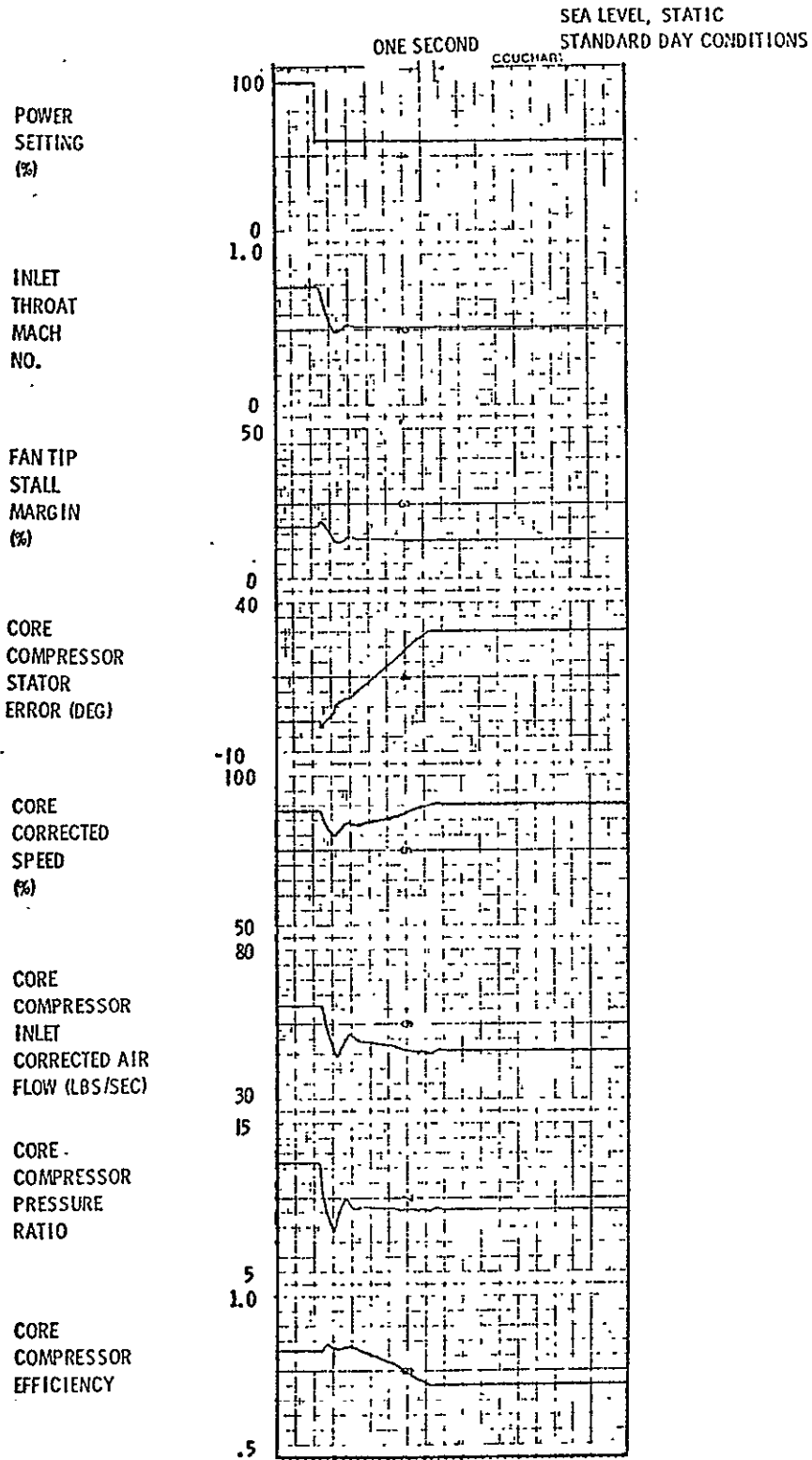


Figure 29. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Fail-Fixed Servovalve with Perfect Dead-Zone Compensation (Concluded).

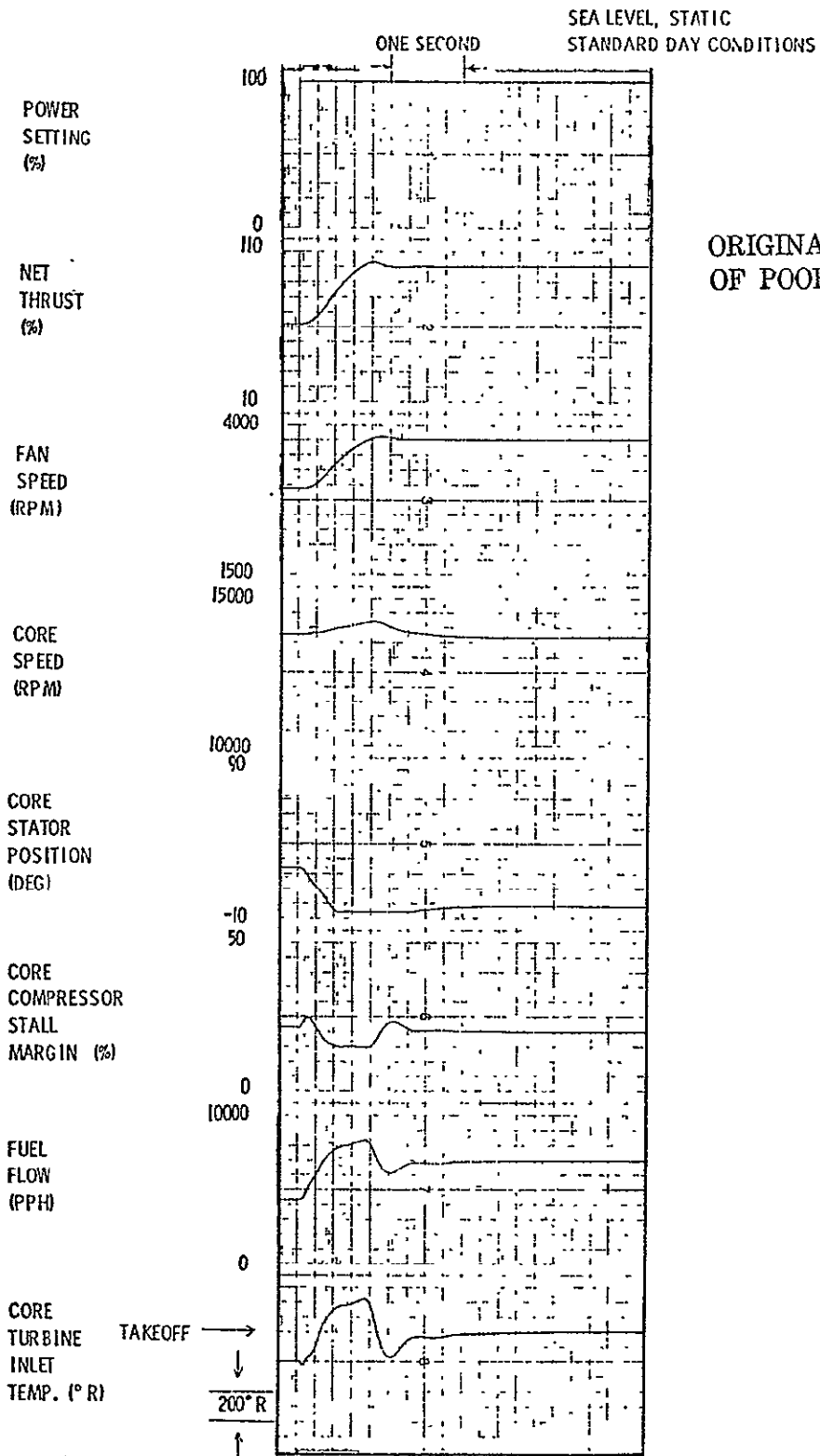


Figure 30. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Fail-Fixed Servovalve with Perfect Dead-zone Compensation.

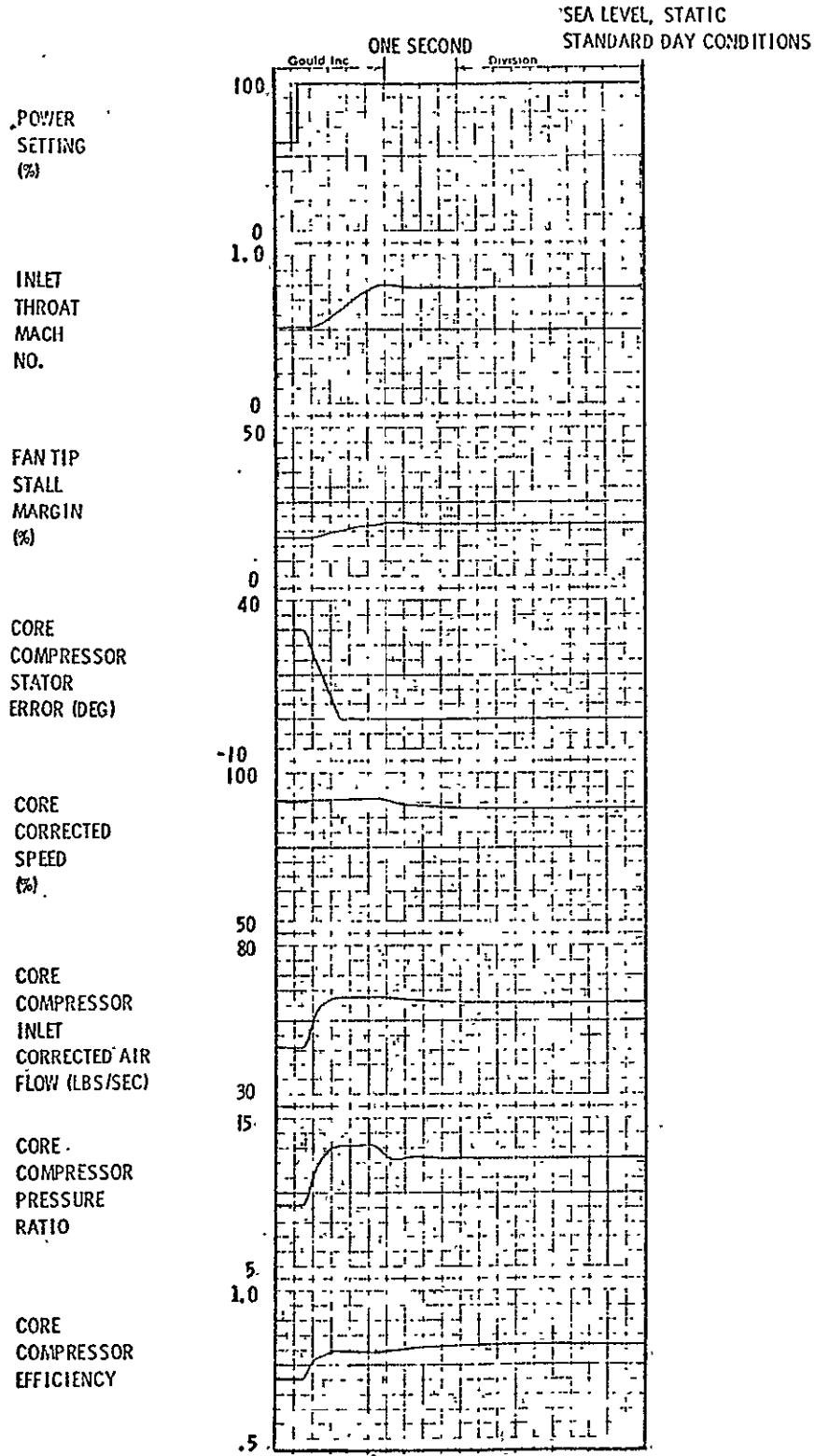


Figure 30. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Fail-Fixed Servovalve with Perfect Dead-zone Compensation (Concluded).

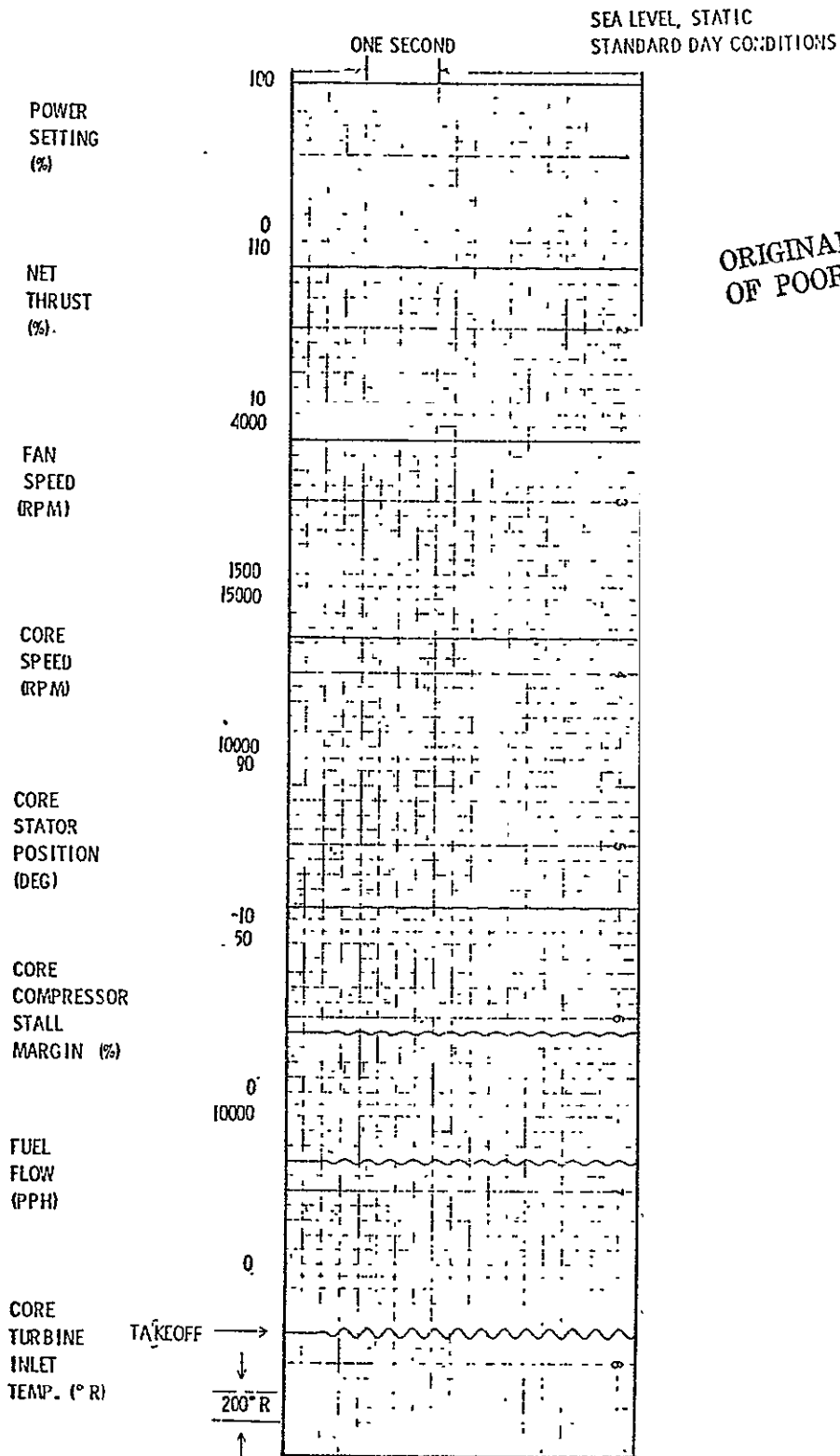


Figure 31. QCSEE OTW at Takeoff Thrust Using Fail-Fixed Servovalve with Deadzone Compensation 10% High.

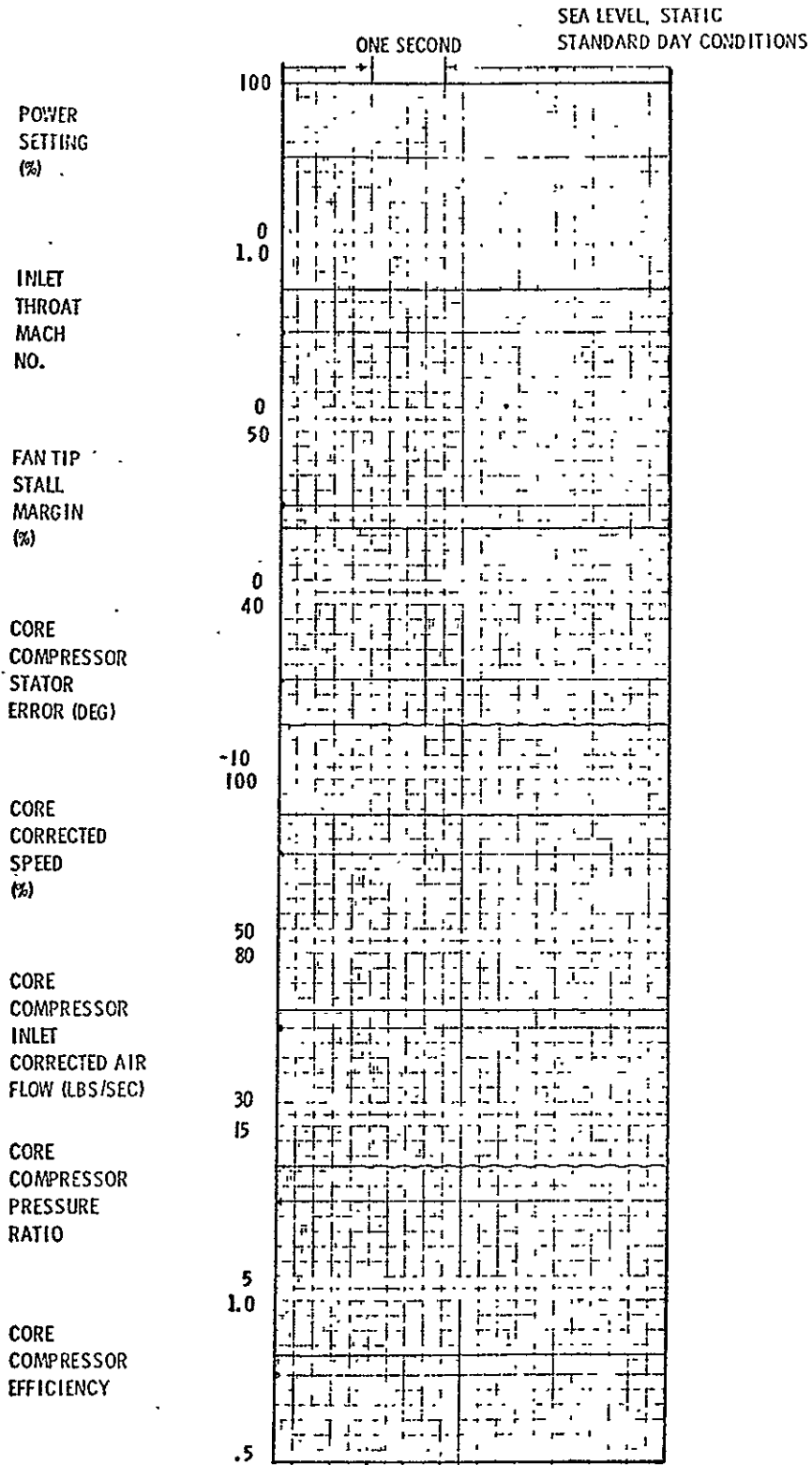


Figure 31. QCSEE OTW at Takeoff Thrust Using Fail-Fixed Servo valve with Deadzone Compensation 10% High (Concluded).

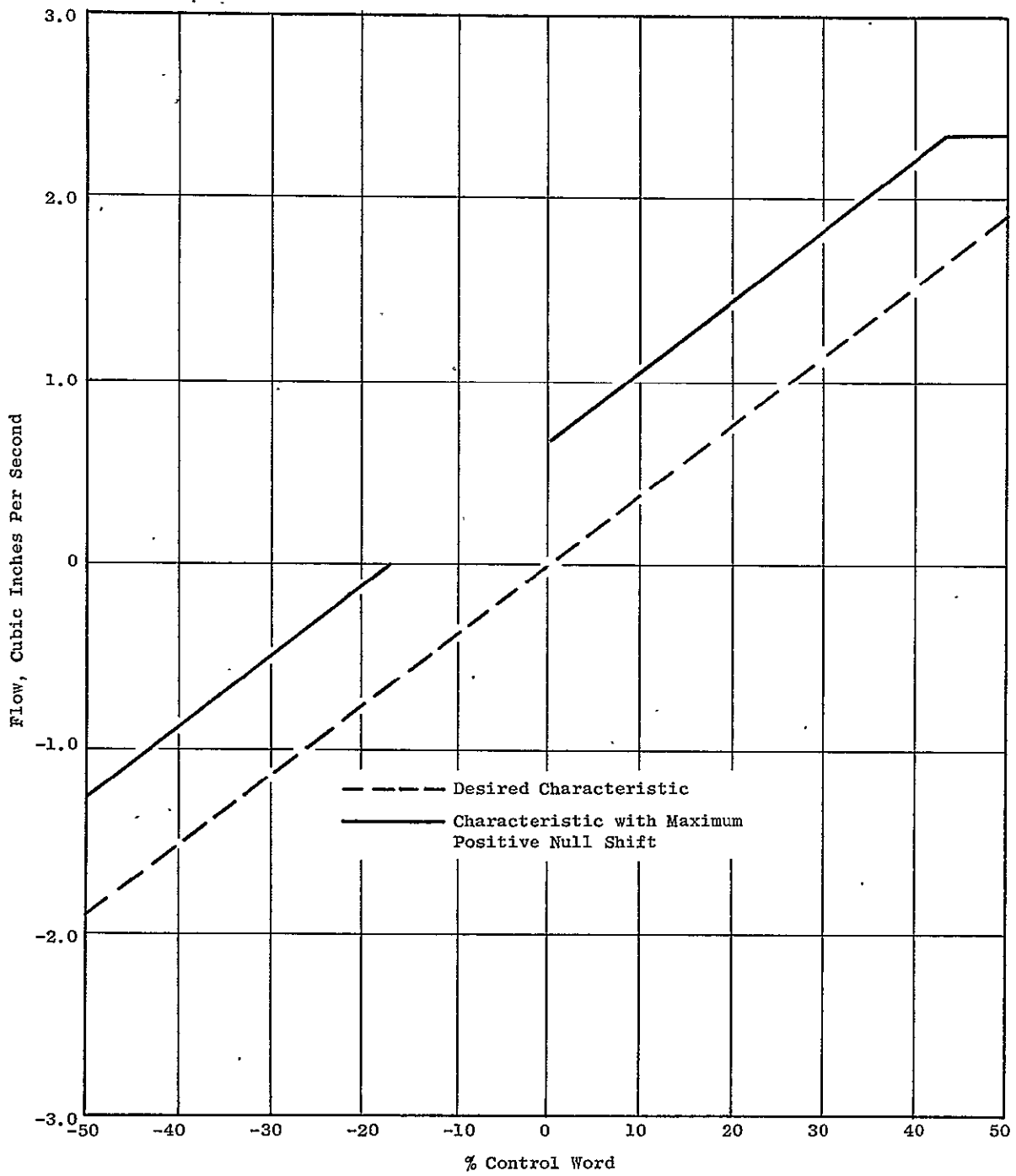


Figure 32. Effect of Null Shift on Simulation of Overall Fail-Fixed Servo Characteristic.

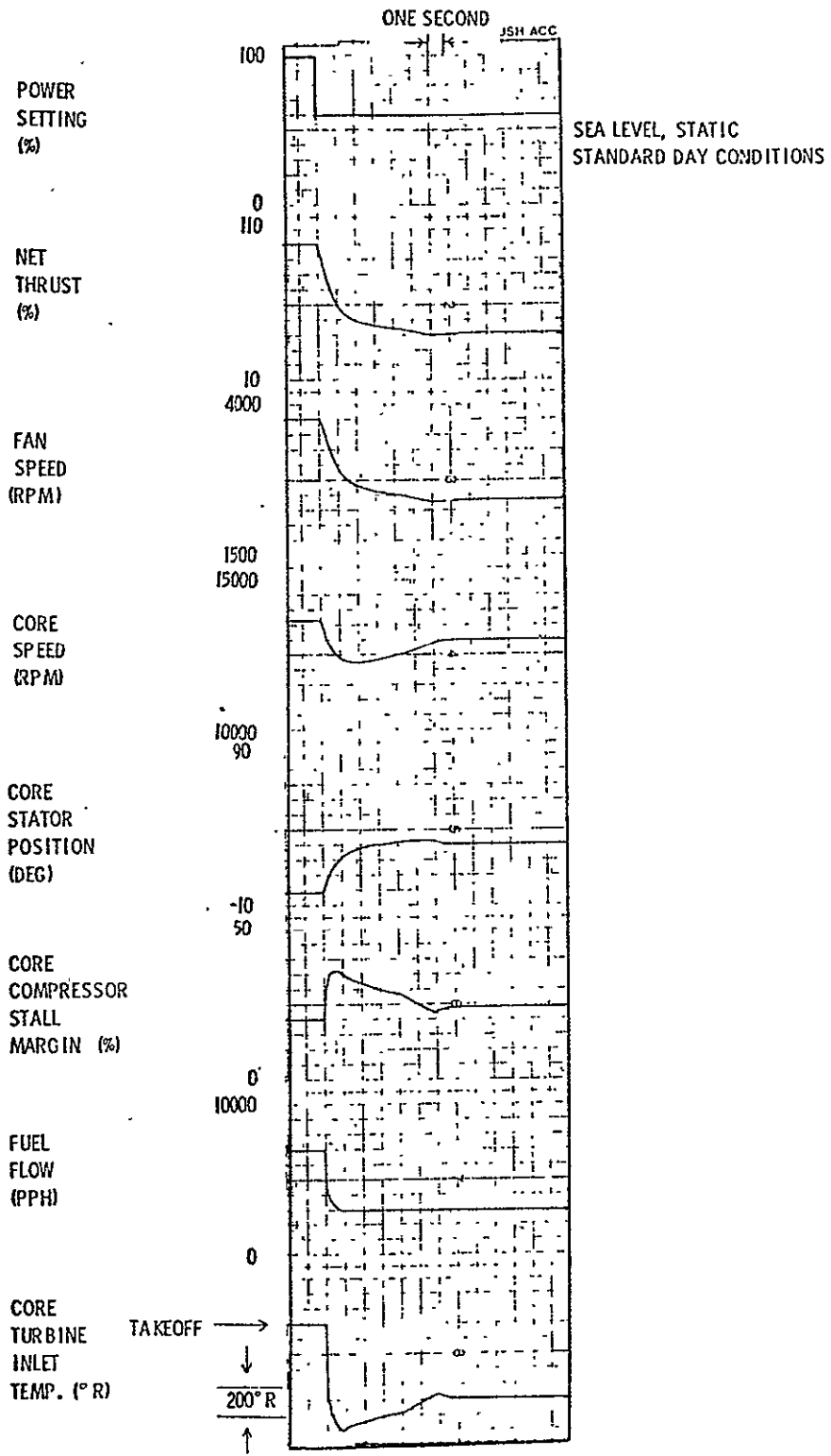


Figure 33. QCSEE OTW Throttle Chop to 62% Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation.

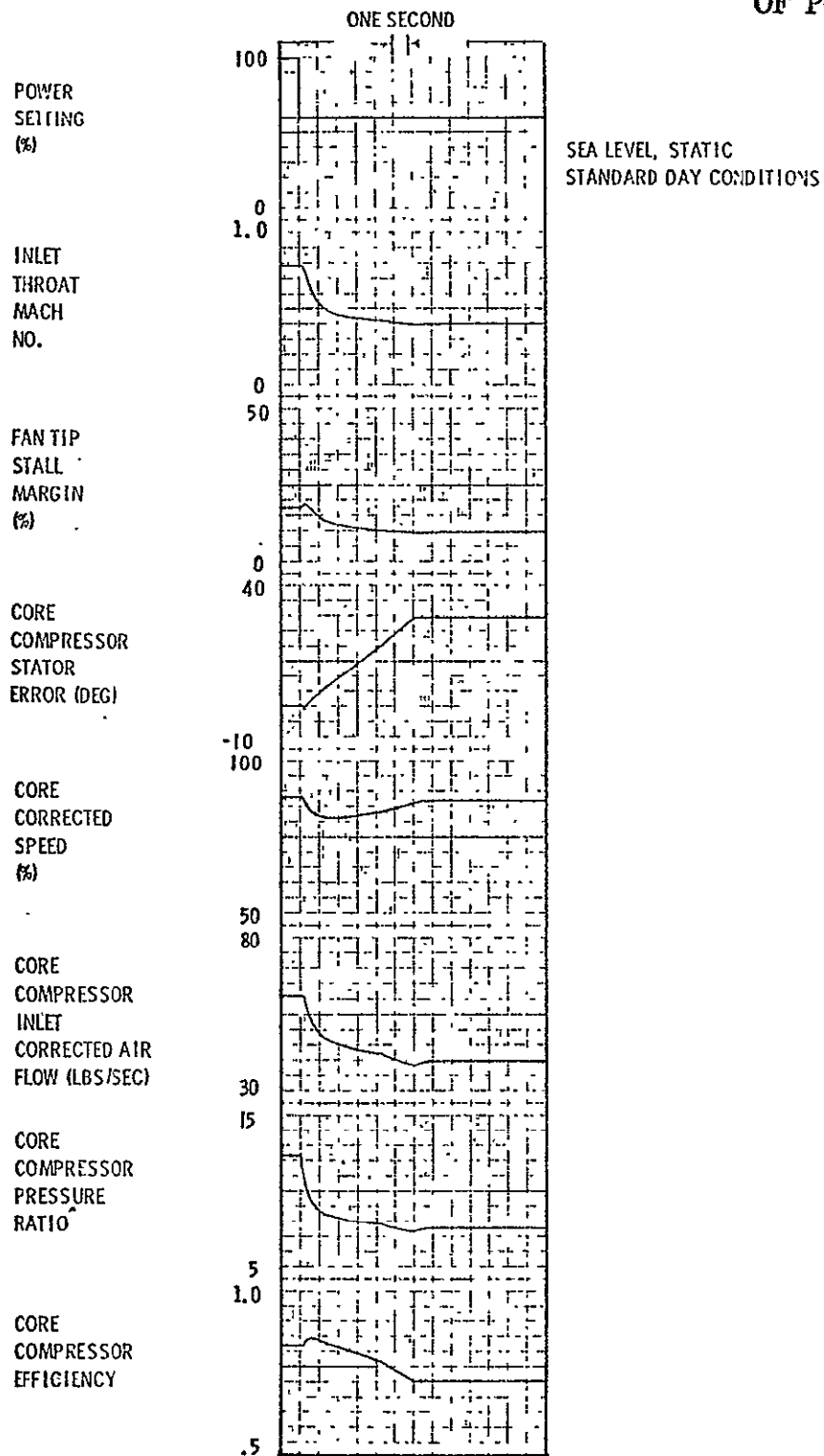


Figure 33. QCSEE OTW Throttle Chop to 62% Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation (Concluded).

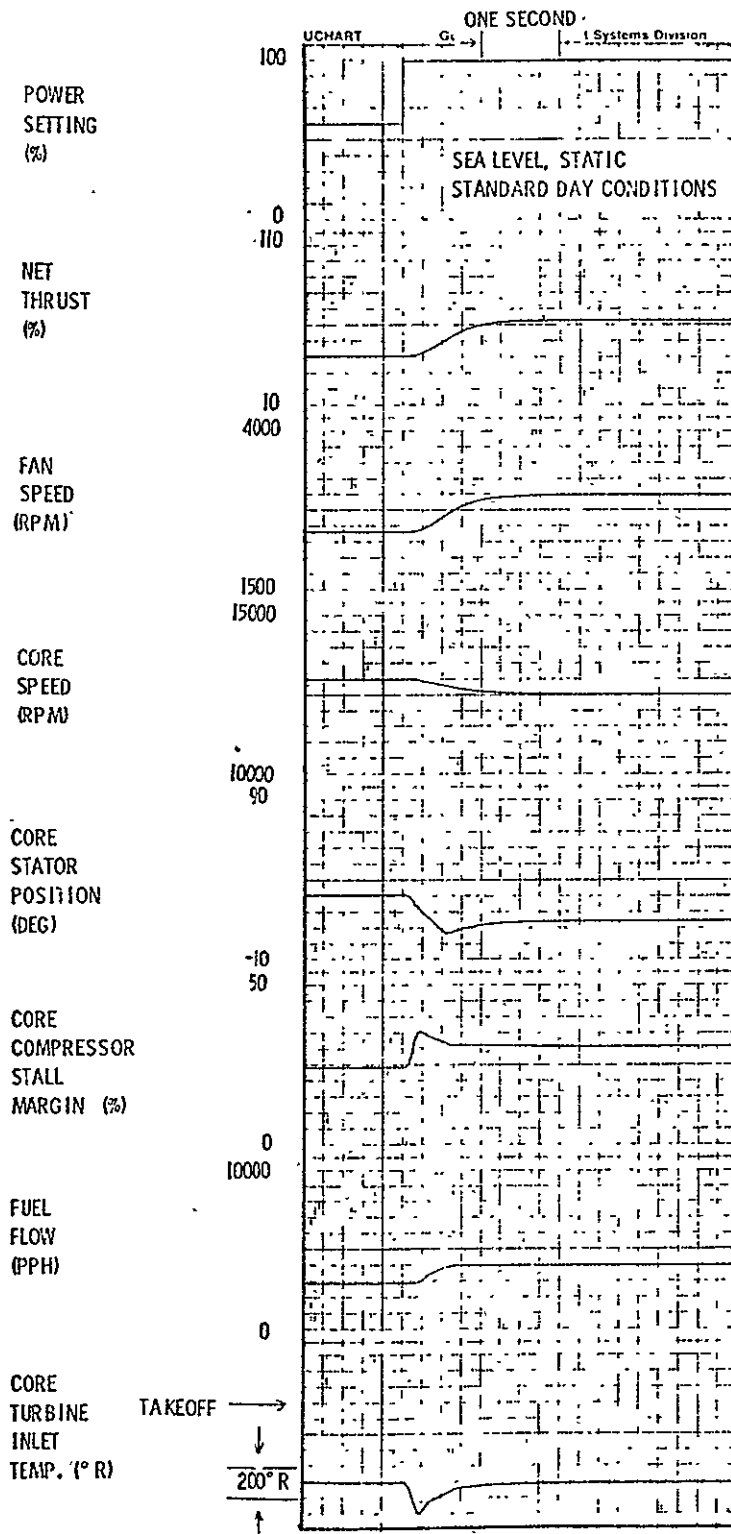


Figure 34. QCSEE OTW Throttle Burst to Takeoff Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation.

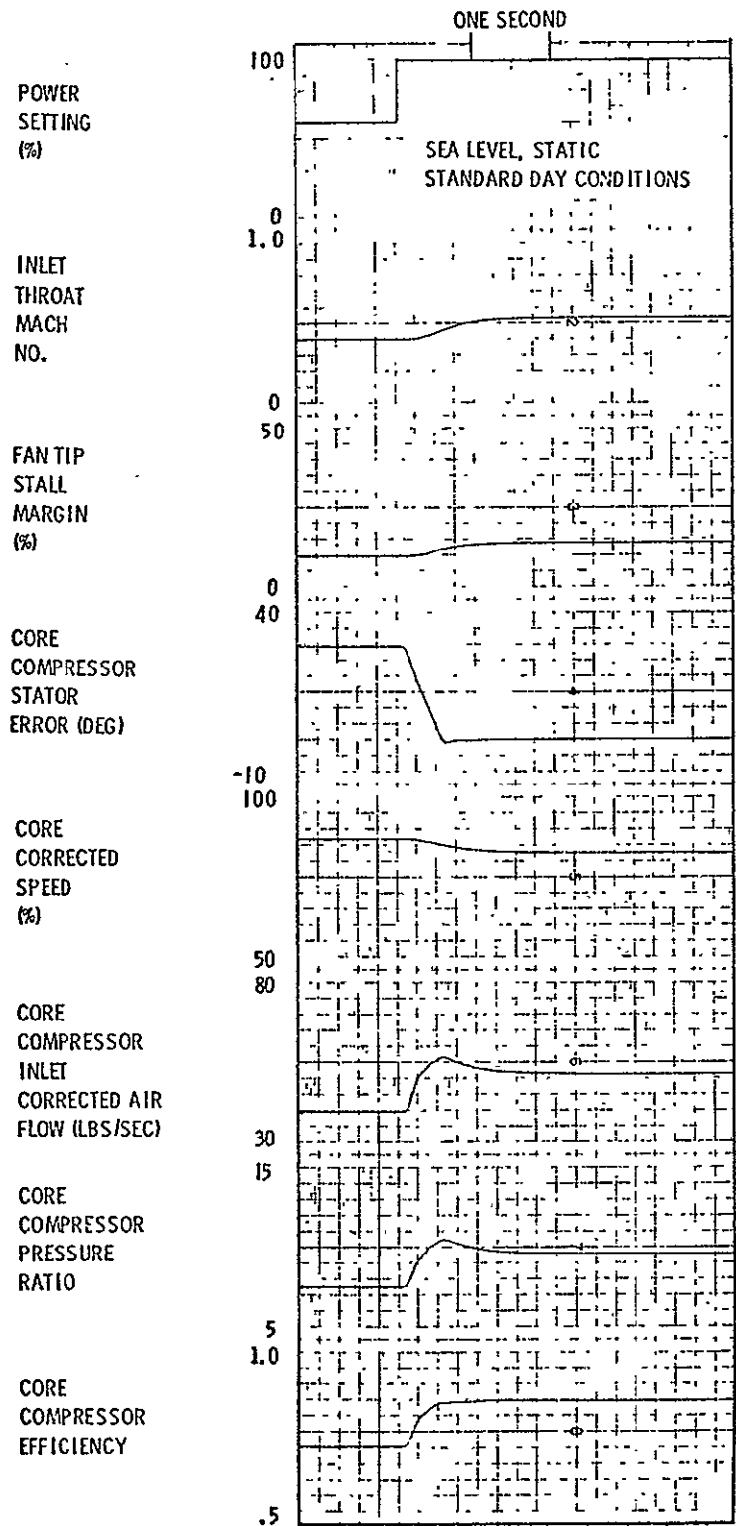


Figure 34. QCSEE OTW Throttle Burst to Takeoff Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation (Concluded).

4.7.3 Control Logic for Null Shift and Dead-Zone Compensation

Based on the above simulation predictions of control inaccuracies due to fail-fixed servovalve null shift and dead zone, compensation logic was added to the digital control specification. Figure 35 describes this logic.

The inputs to the null shift compensation logic are the digital control words proportional to demanded metering valve rate (DXMVR) and to sensed metering valve position (DXMV). The difference

$$\left[\frac{K_{ER}}{T_{ER}S + 1} \right] * DXMVR - [S] * DXMV$$

feeds a low gain integrator, whose output is added with the digital control word to counteract the null shift. If the expected rate gain (K_{ER}) and expected rate lag (T_{ER}) exactly match the hardware, there will be no transient effect once the null shift compensation has settled out. The low integrator gain (K_{DC}) reduces the transient effect of the compensation if transients are initiated before the compensation has settled or if the hardware is not perfectly matched. If the dynamics used to generate the expected rate are well tuned to the hardware, the compensation will respond to a null shift as a lag, with a time constant approximately equal to $K_{FF}/(K_{ER} K_{DC})$.

Figure 35 also describes the logic specification on dead-zone compensation for the fail-fixed servovalve. An engineering control panel potentiometer (called FFSV Deadband Compensation Adjust) provides the capability to "tune out" dead zone during the control system bench tests, prior to control delivery to the engine. The potentiometer is adjusted to be equivalent of one-half the servovalve dead zone; the potentiometer output is either added to or subtracted from $K_{FF} * DXMVR$, depending on the polarity of DXMVR. The one-half dead zone adjustment range of the potentiometer is 0 to 14.25 milliamperes; this range has been sized based on 1.5 times the average from test data on servo valves S/N 2 and S/N 3.

Since the servovalve characteristics are symmetric and linear with respect to effective current in the operating range, the inverse function (referred to as f (DIFFS) in Figure 35) will be used to linearize effective current with respect to the digital control word. This should make the servovalve characteristic linear with respect to the digital control work in the operating range.

As indicated by Figure 35, the control includes logic for driving a linear servovalve - which is the backup for the fail-fixed servovalve. The null shift compensation logic is also designed to feed and thus counteract the null shift characteristics of the linear servovalve.

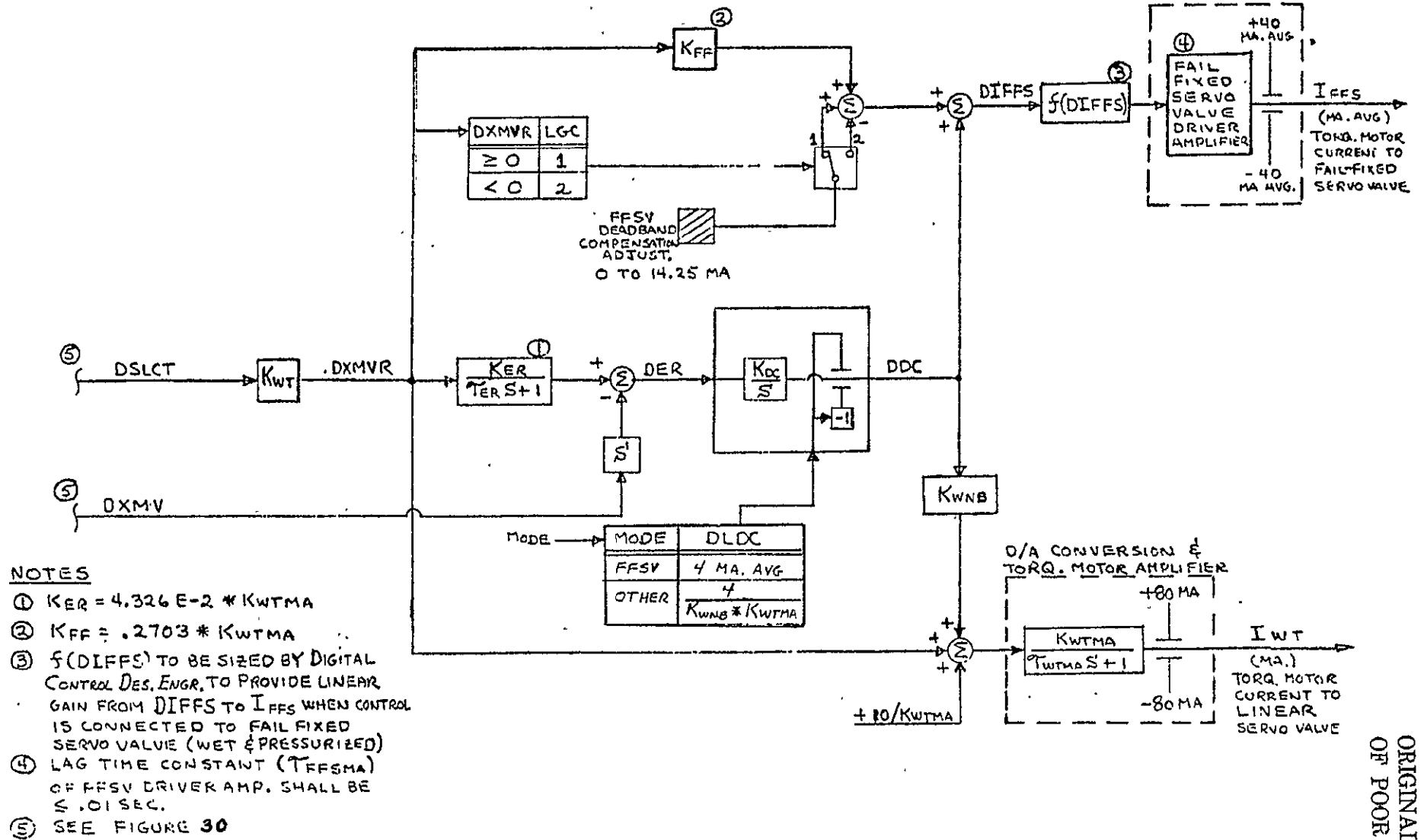


Figure 35. QCSEE OTW Servovalve Fuel Control Block Diagram.

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4.8 FAILURE ANALYSIS

A QCSEE OTW control system failure analysis was undertaken when the system and component designs were essentially complete. Its purpose was to check on how well the system meets the design goal of having no failure modes that can cause serious engine damage or, in a flight design, cause flight safety problems. This failure analysis is included as Appendix B and is discussed below.

The analysis was conducted using the failure mode and effects technique, in which first a list is made of the various system element failures that might occur, and then the effects of each potential failure on the system and engine are defined. The analysis verifies that most control system failures either (1) have little or no effect because of redundancy or backup limits, or (2) induce safety-enhancing operational changes for an experimental engine or an engine on a multiengine aircraft. Failures that do not fall into one of these categories are discussed below.

Loss of LPT RPM Signal (Failure B3) - This results in acceleration to the N2 or T41C limits (if not already at one of them) and a large open error in core stator vanes (VSV) because of a low calculated T25. The open VSV error, if large enough, can cause compressor stall. A VSV closed reset with LPT signal loss was considered for incorporation into the system but was ultimately left out to conserve digital control memory. This omission is considered a low risk because of the good reliability record of the speed sensor on the F101, the limited scope of the experimental engine program, and the ability of the F101 core to tolerate stalls.

T12 Sensor Short Circuit (Failure C3) - This results in a false low T12 which reduces rpm (because of false corrected rpm sensing) and creates an open VSV error because of a false low calculated T25. A backup T12 signal, adjustable control room was considered but not incorporated into the sensor, for the same reasons given in the previous paragraph.

T3 Thermocouple Short Circuit (Failure C5) - This can cause turbine overtemperature but only when the engine is operating at the T41C limit. Under normal conditions this limit will not be encountered frequently, so a method of protecting against this failure mode is not being pursued.

4.9 SENSOR LOCATION STUDIES

Analytical studies were conducted regarding the sensing of several variables used in the OTW system. One of these covered the sensing of a total-to-static pressure differential indicative of inlet throat Mach number, an important variable on QCSEE engines because of their roll-in inlet noise attenuation and inlet pressure recovery. This study was done initially for the UTW engine but is applicable to the OTW.

For sensing total pressure, several possibilities were considered: P12, the average fan inlet pressure; PS12, wall static pressure near the fan inlet; and PTO, a free-stream total obtainable either inside or outside of the inlet

duct. P12 would be difficult to obtain and would offer no advantage over PTO. Extensive testing of scale model inlets have provided data showing that an immersion of no more than 14.0 cm (5.5 in.) (full-scale inlet) is sufficient to get PTO at all conditions when the probe is as close as 0.61 m (2.0 ft) to the fan inlet. For reasons of noise generation (probe wake and fan blade interaction), ice shedding, and damage possibilities, the choice of an inside PTO measurement was rejected in favor of an outside PTO measurement. The outside location was chosen on the bottom at the nacelle maximum OD. This location was based on consultation with McDonnell Douglas. The final alternative, PS12, was rejected because with PS12-PS11 sensing, inlet duct losses at maximum flow and with high angles of attack would have an undesirable effect. The indicated throat Mach number would fall with increased losses (more than 1% for each 1% increase in pressure loss between sensing points). This is in the wrong direction with respect to our preference and is a regenerative process in an inlet Mach number control loop. In conclusion, the choice for the engine inlet pressure is a free-stream total pressure (PTO) measured outside the nacelle at the bottom of its maximum outer diameter.

Data from NASA-Lewis acoustic suppression inlet testing with a 12-inch model inlet were used to establish the location for sensing the inlet static pressure (PS11) needed for controlling the inlet throat Mach number. Typical data from this testing are shown in Figures 36 and 37. These and similar data led to a decision to sense PS11 by using two manifolded static taps in the inlet inner wall, axially located at $XL = 0.4$ (X = the distance from the inlet's front face to the sensing tap, L = the distance from the inlet's front face to the fan blade's leading edge), each tap on the inlet horizontal centerline 180° apart circumferentially. The $XL = 0.4$ location was chosen because it is affected little by aircraft angle-of-attack and crosswinds and it provides satisfactory accuracy.

A study was also conducted regarding sensing of core compressor inlet temperature (T25). On the OTW a T25 electrical input is required for the digital control. Two alternatives were considered; 1) an electrical sensor in the passage between the fan and the core inlet, and 2) computation of T25 from fan inlet temperature (T12) and fan rpm. The major disadvantage of measured T25 is that the lag inherent in a mechanically practical temperature sensor creates significant transient T25 errors. This has been a problem requiring complex compensation on some current turbofan engines. Because T12 doesn't change significantly during normal thrust transients and because digital control computation is extremely fast, lag is not a problem with the computed T25 concept.

To evaluate the accuracy of computing T25, a large amount of OTW cycle data was analyzed and a T25/T12 versus fan corrected speed relationship derived which shows an accuracy of ± 0.3 degrees F. It is estimated that digital control curve fitting would add a like amount of error and an additional error up to 1.8° F might be expected due to engine-to-engine variations and fan efficiency deterioration. It was concluded that this T25 computation accuracy is acceptable. The computed T25 approach was selected for the OTW because of its superior transient capability and satisfactory steady-state accuracy.

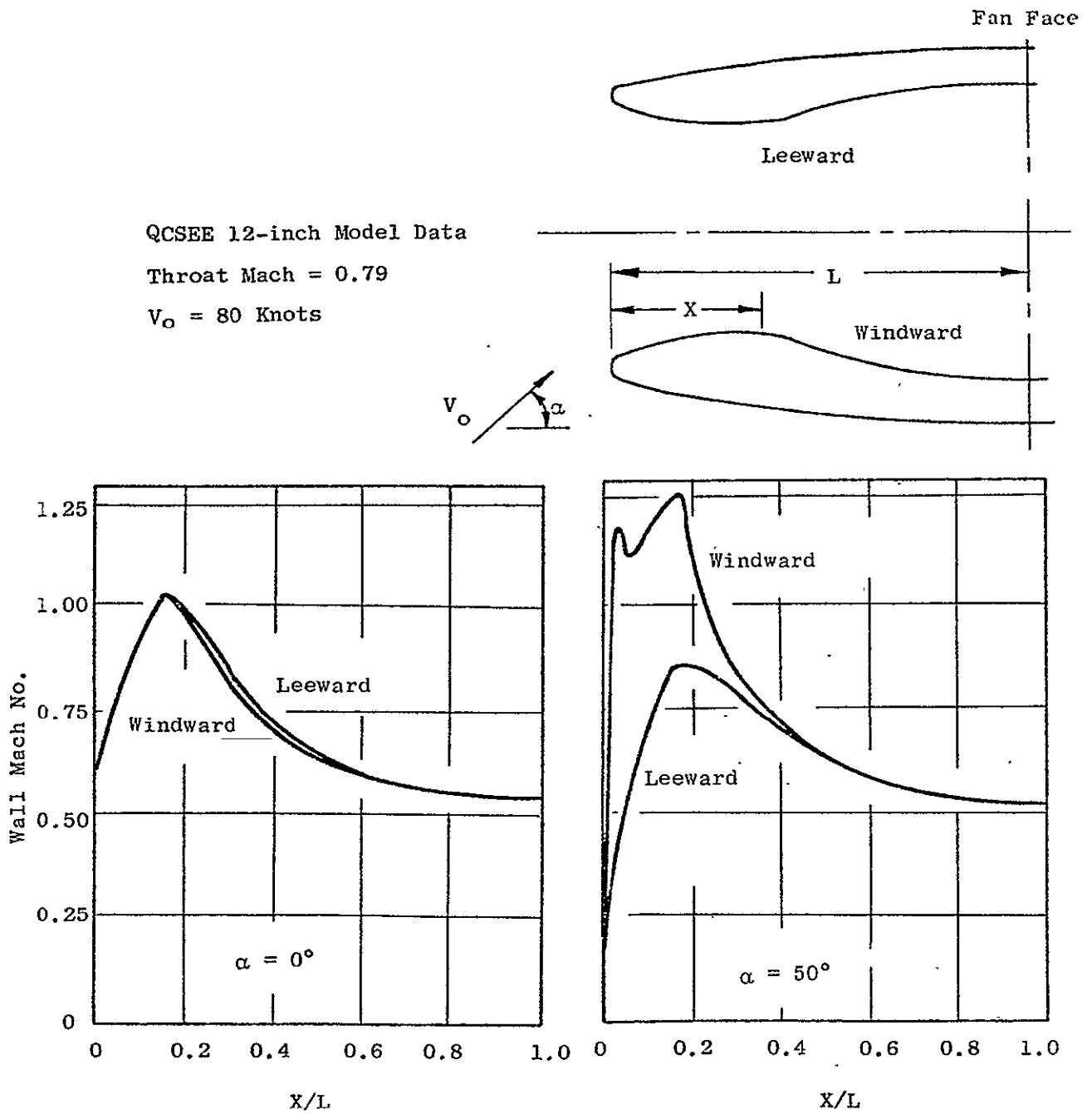


Figure 36. Inlet Pressure Sensing Data.

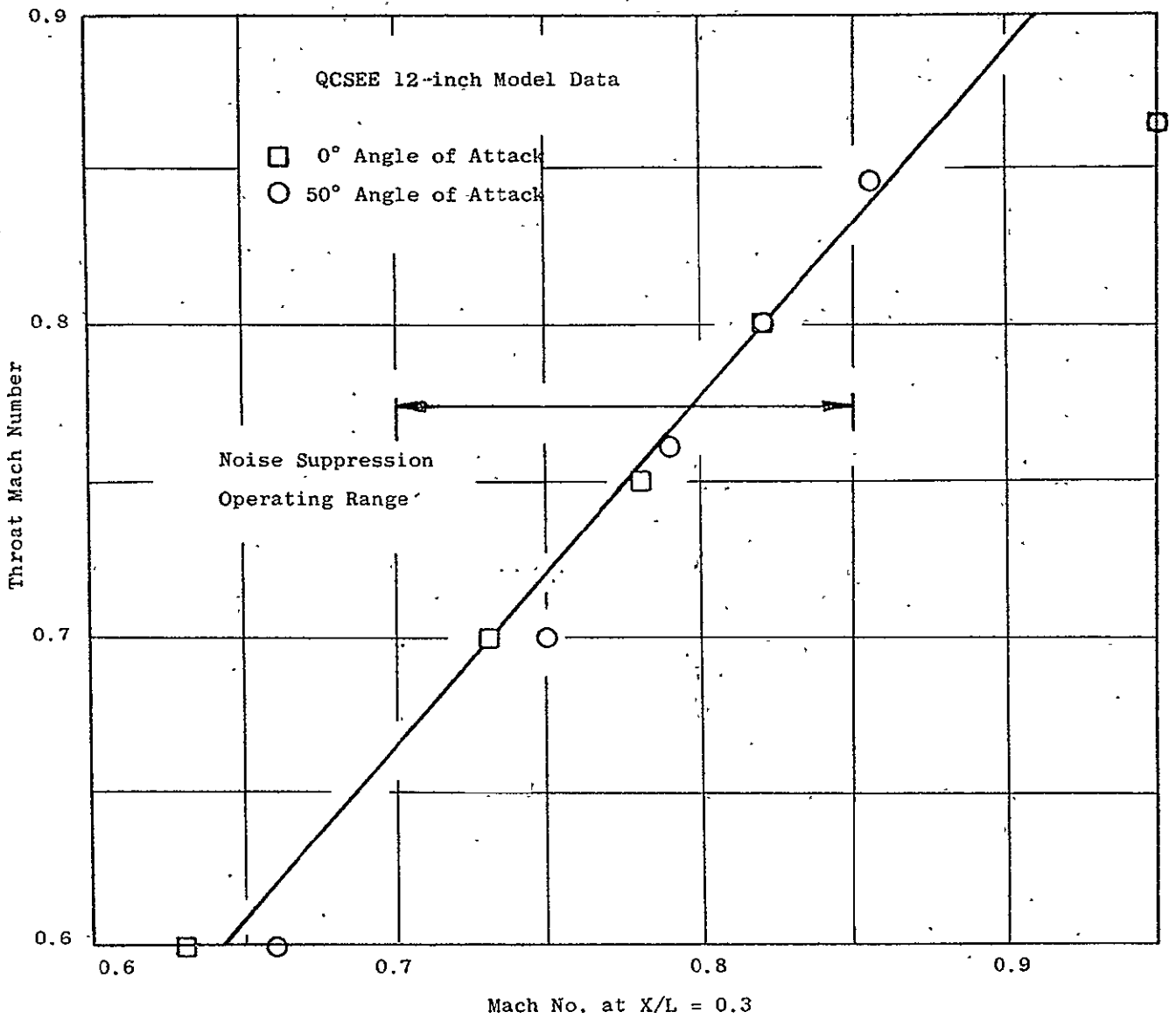


Figure 37. Inlet Mach Number Correlation Data.

4.10 STARTING STUDIES

An analysis of the QCSEE high-pressure rotor starting performance was conducted to support the selection of a starter for development engine testing. Since the QCSEE core is basically an F101 PFRT (preliminary flight rating test design) core, there is a great deal of factory-and-field-starting experience on which to base this analysis.

During the successful completion of the F101 PFRT ground-starting torque test, a level of engine unfired and fired torque was demonstrated. It can be assumed that the QCSEE core engine will exhibit approximately the same level of unfired torque and be capable of the same level of fired torque as was demonstrated by the F101 PFRT engine. Consequently, the engine torques used for the QCSEE starter selection study reflect the F101 experience and are shown in Figure 38.

In addition to these torque requirements, other criteria considered in choice of a starter were cost, timing, installation envelope, 11,100 rpm idle requirement, a 4000-rpm maximum motoring speed goal, and the fact that there was no firm start-time requirement for this development engine. The base case for this study was the sea level static, standard day condition.

A start-time calculation program was constructed that combined the engine torques with typical air turbine starter characteristics. After examining a number of possible starters, a satisfactory characteristic was defined. This proposed starter was submitted to various starter vendors and their replies evaluated. This led to the selection of AiResearch Division's AT5100-277A starter (Figure 39) for the QCSEE Program.

Estimates were made of the engine torques over a range of ambient temperatures and the corresponding start times calculated. These times are shown in Figure 40.

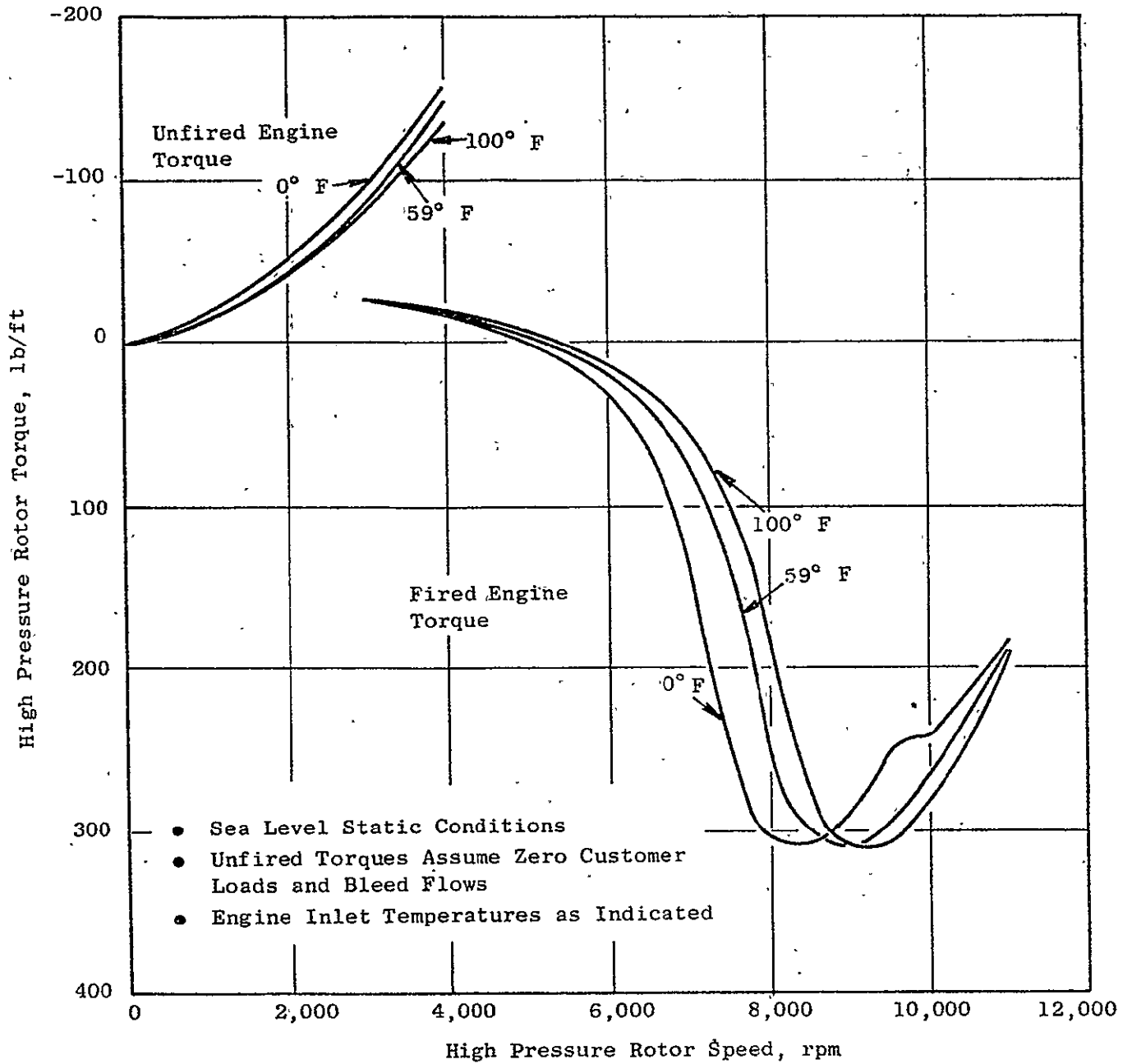


Figure 38. Estimated QCSEE Engine Torques.

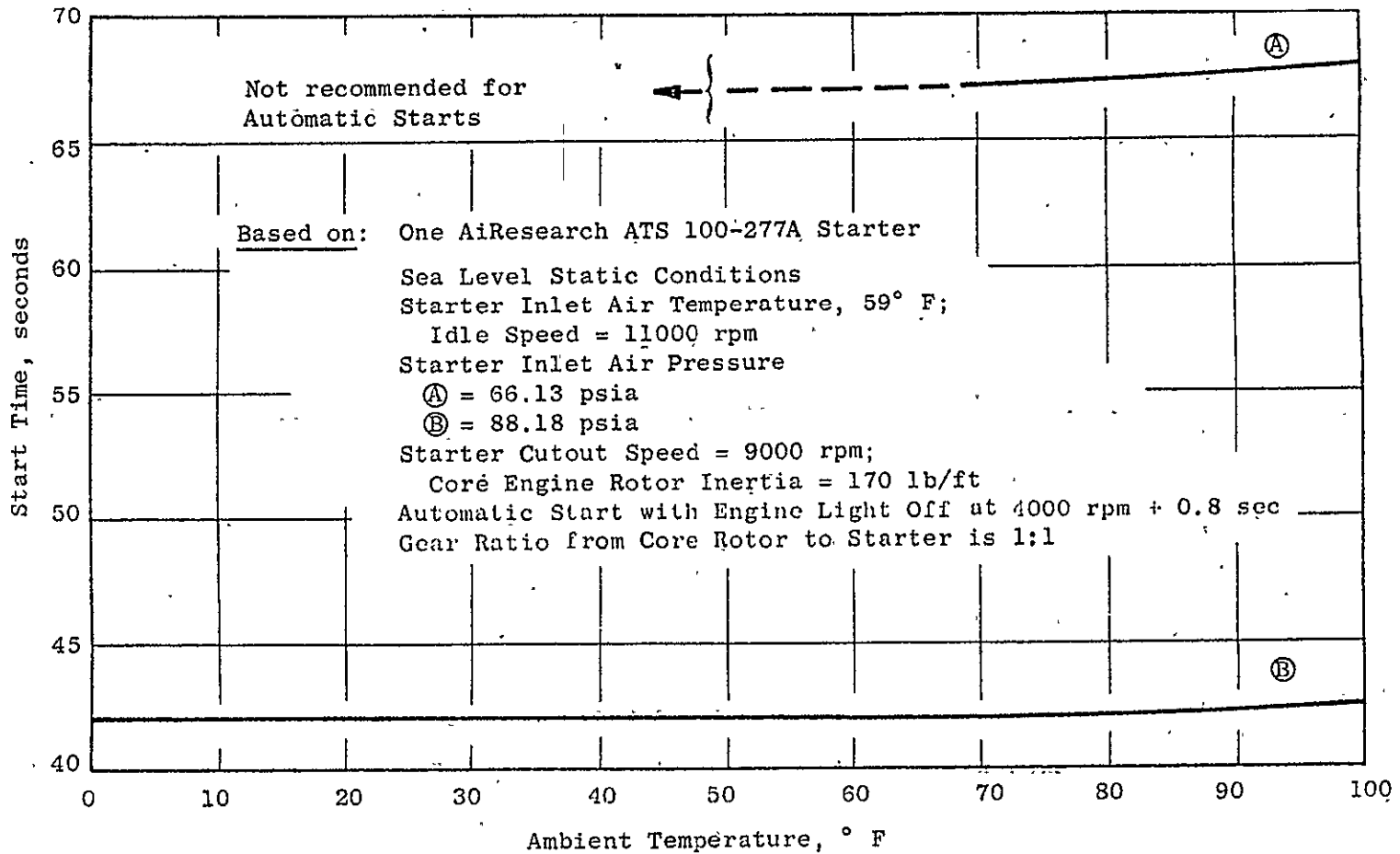


Figure 39. QCSEE Start Time Study.

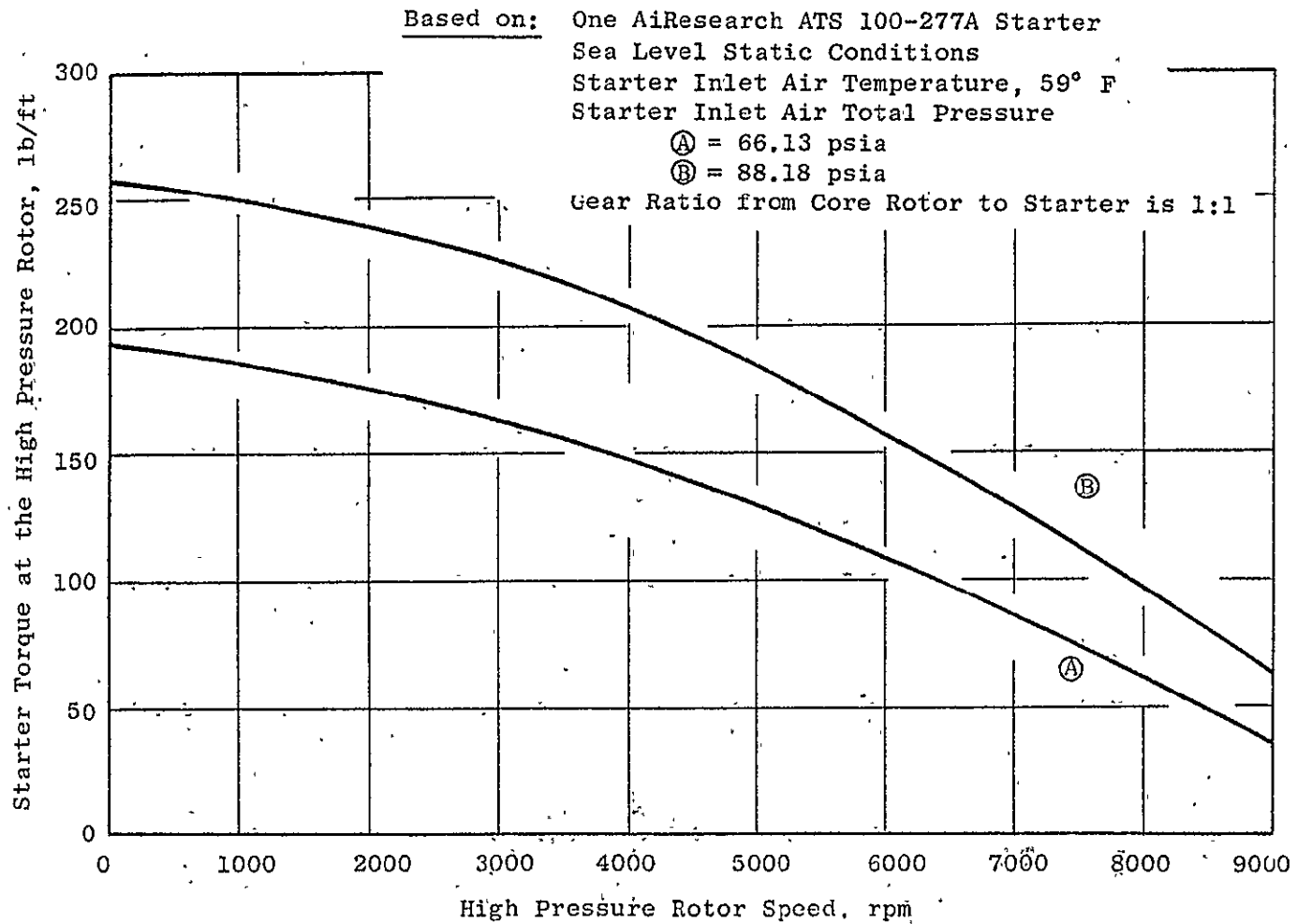


Figure 40: Expected Starter Torque for QCSEE Development Engine.

5.0 FAILURE INDICATION AND CORRECTIVE ACTION

5.1 GENERAL DESCRIPTION

In this section a Failure Indication and Corrective Action strategy for the QCSEE OTW engine is discussed. This strategy allows continuing control of the engine in the event of a sensor failure. An extended Kalman filter is used to provide the best estimate of the state of the engine based on currently available sensor outputs. Should a sensor failure occur the control is based on the best estimate rather than the sensor output.

The extended Kalman filter consists of essentially two parts: 1) a nonlinear model of the engine, and 2) up-date logic that causes the model to track the actual engine. Details on the model and up-date logic are presented. To allow implementation, approximations are made to the feedback gain matrix that result in a single feedback matrix suitable for use over the entire flight envelope. The effect of these approximations on stability and response is discussed. Results from a detailed nonlinear simulation indicate that good control can be maintained even under multiple failures.

As the complexity of turbofan engine controls increase, it will become more difficult to meet the reliability of the current production engines. However, availability of the on-engine digital engine controller reduces the problem in two ways. First, it allows these controls to be implemented without a corresponding increase in hardware complexity. Second, it allows the implementation of strategies that take advantage of the natural redundancy of information from the currently available sensors to provide continuing control in the event of a sensor failure.

5.2 FICA CONCEPT

The Failure Identification and Corrective Action (FICA) is an integral part of the digital control on the engine. The FICA will replace the output of a sensor in the event of its failure. The FICA has no effect on a non-failed sensor output, so the FICA can be separate from the rest of the control system. The inputs to the FICA are the sensors and the control outputs. The outputs from the FICA are the estimated values of the failed sensors and of the unfailed sensors.

The FICA strategy has been developed and has its first application in the QCSEE OTW engine full authority digital control. It is based on an extended Kalman filter incorporating a nonlinear model of the engine to provide a best estimate of the state of the engine controls, as well as of their expected sensor outputs.



Since the FICA acts only in the event of a sensor failure, it has no effect on the normal control action. The logic, schedules, and dynamics of the control were designed independently of the FICA, and the FICA was designed with the control in place. The simulation of the FICA was run on one computer while the engine and control of the QCSEE engine was simulated on a second computer. The connections between the two computers were analog trunk lines. In adding the FICA, the simulated sensor outputs were reconnected to the FICA and the FICA supplied the sensor outputs to the controls simulation. For non-failed sensor operation the FICA does not alter the sensor output signals.

The control inputs and sensed output variables for the QCSEE engine are shown in Figure 41. The inputs are 1) current to the fuel flow valve, I_{WF} , and 2) current to the compressor stator blade torque motor, I_B . The actual fuel flow and actual compressor stator angle are sensed output variables. Also sensed are the high and low rotor speeds, compressor discharge pressure and temperature, and turbine discharge temperatures, making a total of seven sensed output variables. In addition, the three environmental variables P_2 , T_2 , and P_{AMB} are sensed and used for model inputs.

An overall block diagram of the failure detection and correction strategy is shown in Figure 42. The strategy consists of three parts: 1) a nonlinear model of the engine, 2) decision logic to determine when a failure has occurred and to take corrective action when a failure is detected, and 3) a feedback gain matrix to update the model and keep it in close agreement with the actual engine. The engine control logic is unaffected by the failure detection and correction logic. The same control signals are applied to the model as well as to the engine. These outputs of the model which are the expected outputs of the engine are compared with the actual outputs of the engine. If the difference between the actual and expected outputs is too large, it is assumed that the sensor has failed. In that case, the sensor output is replaced by the expected output from the model for control purposes. The difference between the actual and expected output for an unfailed sensor is fed back through a gain matrix to correct the model.

Obviously, this strategy relies heavily on the nonlinear model. This will be discussed in more detail below. The theory behind the feedback gain and decision logic is also given below. Since the strategy is to be implemented with an on-engine digital computer, certain simplifying assumptions had to be made. The simplifying assumptions and their effect are discussed below. The strategy has been extensively tested using an accurate hybrid simulation of the engine. Some results of these tests are shown in Reference 4.

5.3 MODEL

The model is designed to have good dynamic and static accuracy and yet be simple enough to be solved by an on-engine digital computer. The high accuracy is necessary to allow tight control even when a sensor has failed.

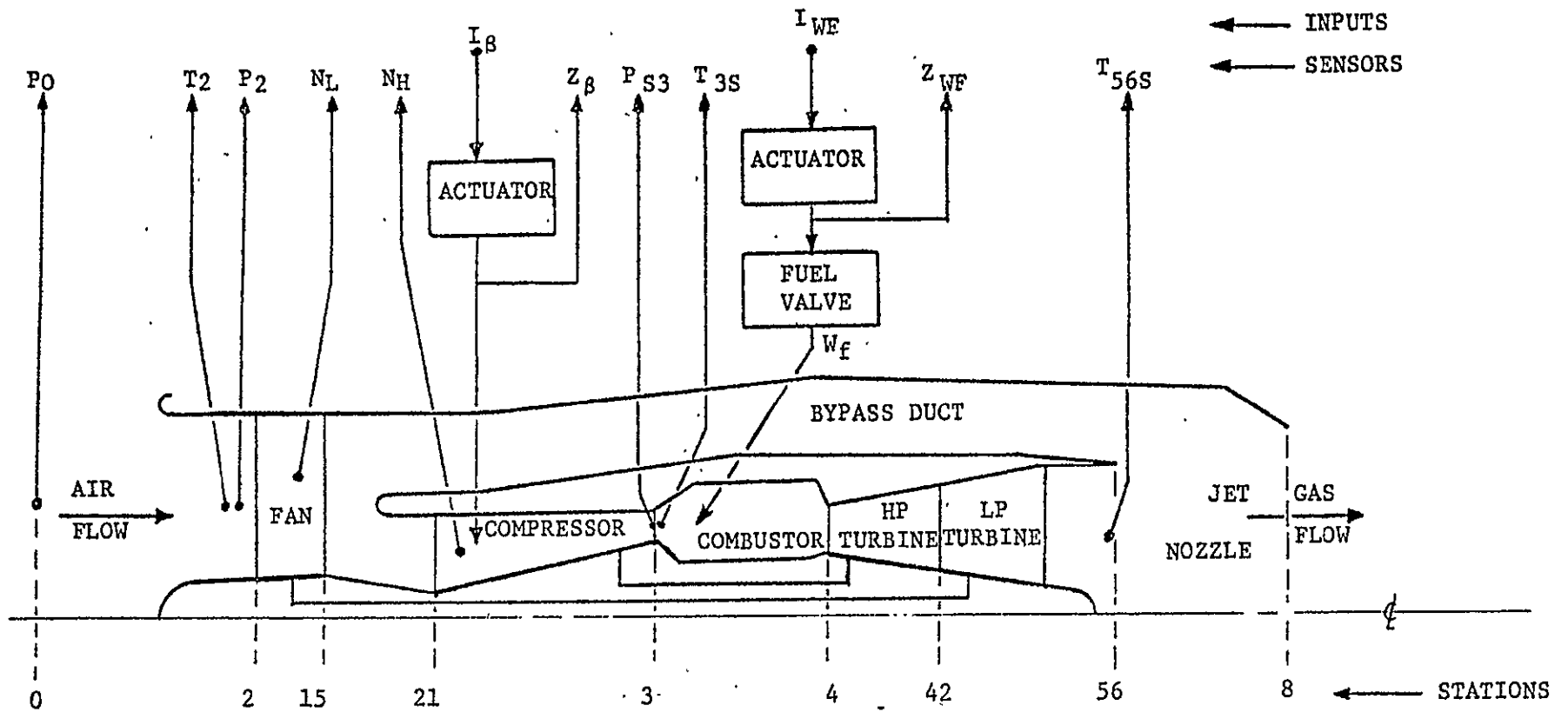


Figure 41. QCSEE Engine Schematic - Stations, Inputs, and Sensors.

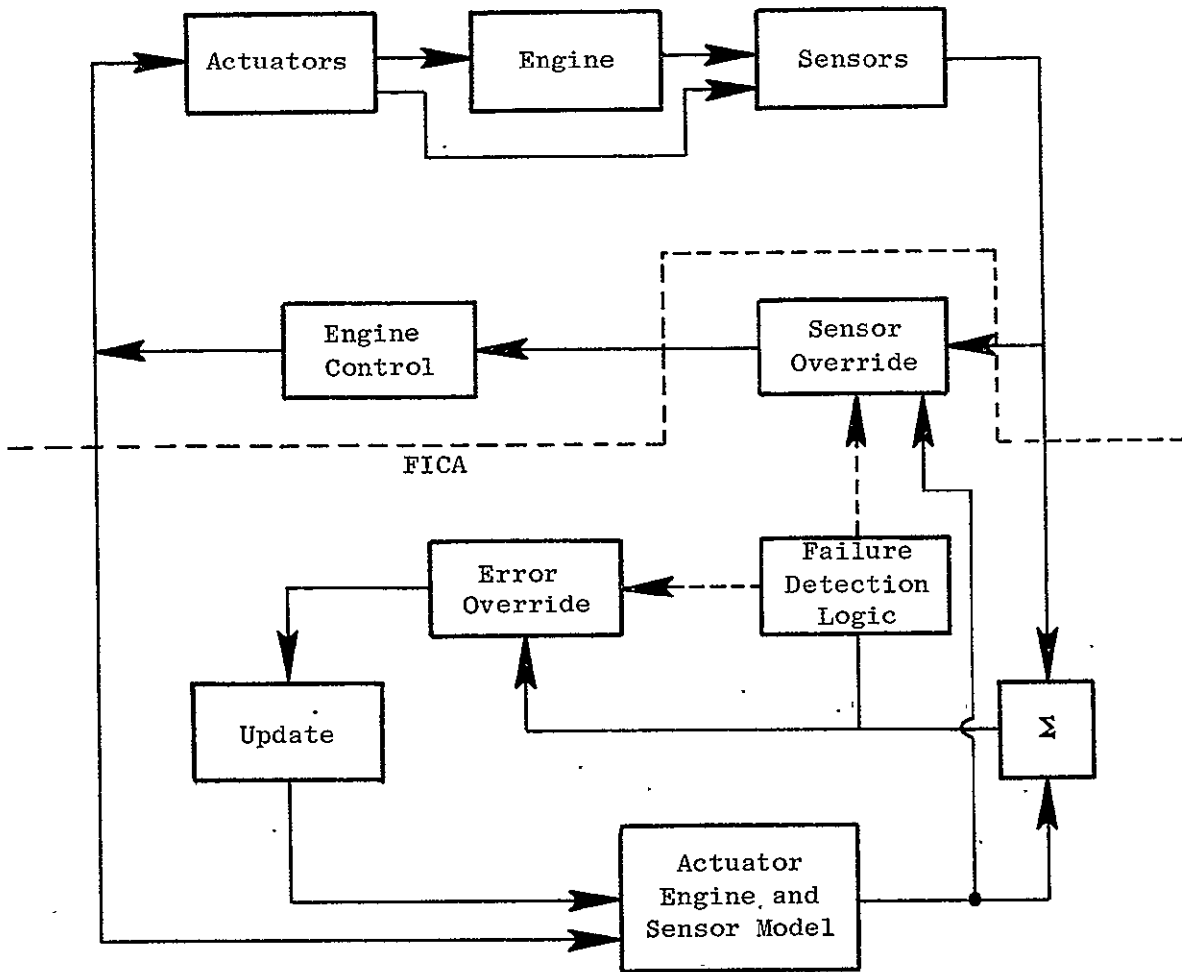


Figure 42. Block Diagram of the FICA Strategy.

The engine model for the subsonic transport is designed to be accurate for a power range from flight idle to maximum, over an inlet temperature range from about 65° F to 130° F and an inlet pressure range from about 0.2 atm to 1.3 atm to accommodate a sensor failure at any condition in flight.

The engine model has the same inputs and outputs as the actual engine, as indicated by Figure 41; plus the inlet air pressure and temperature and the ambient air pressure, which determine the external operating environment.

The form of the model follows the engine cycle schematically shown in Figure 41. It consists of a low-pressure-ratio fan driven by the low pressure turbine, which receives the exhaust gases from the high pressure turbine. Fuel is burned in a combustor, using air from the high pressure compressor and exiting into the high pressure turbine. Most of the fan discharge air bypasses the compressor, combustor, and turbines and is mixed with the low pressure turbine exhaust gases. The mixed gases are accelerated in the jet nozzle and exhausted.

The model must account for the steady-state and transient performance of the engine. This is done in a simplified accounting for the mass flows, pressures and temperatures in the engine, and for the power in the fan, compressor and turbines. The representation of the fans, compressors, and turbines is designed to approximate the operating line for steady-state and the off-operating line for transient response. The representations are in the form of polynomials and tables, and the choice in each case was made to get the simplest calculation with the desired accuracy. The basic engine relationships will be presented in functional form indicating the interrelationships between variables. The block diagram shown in Figure 43 shows how these relationships follow from the engine cycle of Figure 42. The nomenclature is: W - gas flow lb/sec, P - stagnation pressure, and T - stagnation temperature; the subscripts identify the station as shown in Figure 43. Since there is a significant lag in the temperature sensors, the output of these sensors is a state and is indicated by a terminal S in the subscript.

For the fan the airflow is of the form:

$$W_2 = (P_2/\sqrt{T_2}) \cdot f_{FW} (N_L/\sqrt{T_2}, P_{15}/P_2) \quad (1)$$

and the temperature rise across the fan is:

$$T_{15} = T_2 \cdot f_{FT} (N_L/\sqrt{T_2}, P_{15}/P_2) \quad (2)$$

The core inlet pressure and temperature are affected by the flow split and core inlet ducts.

$$T_{21} = f_{1T} (T_{15}, T_2) \quad (3)$$

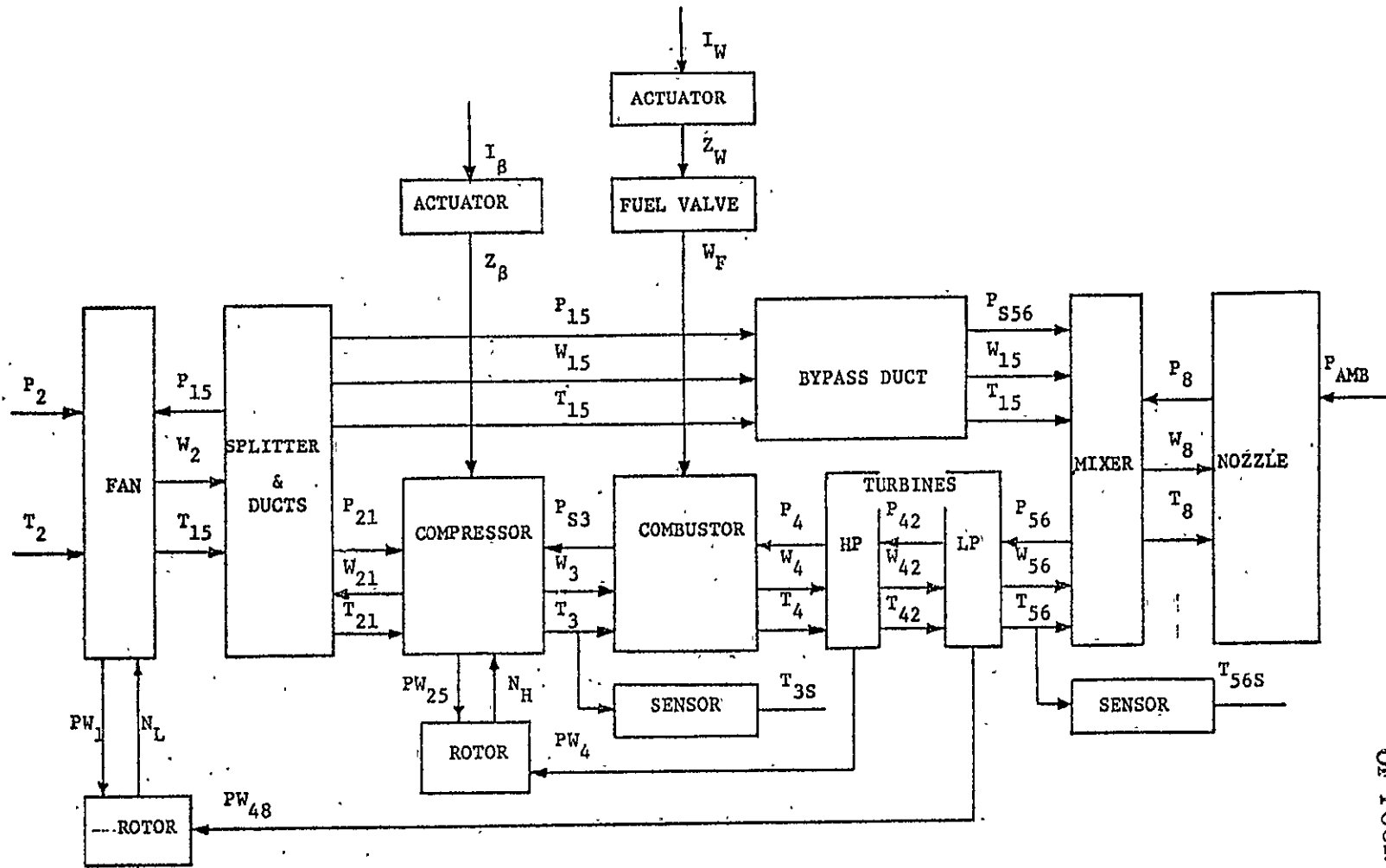


Figure 43. Block Diagram of Engine Model Computation.

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$$P_{21} = P_{15} \cdot f_{IP} (N_L/\sqrt{T_2}) \quad (4)$$

The high pressure compressor air flow is:

$$W_{21} = (P_{21}/\sqrt{T_{21}}) \cdot f_{CW} (N_H/\sqrt{T_2}, P_{S3}/P_{21}, Z_B) \quad (5)$$

where N_H is the high pressure rotor speed and Z_B is the stator position; the temperature rise is:

$$T_3 = T_{21} \cdot f_{CT} (N_H/\sqrt{T_2}, P_{S3}/P_{21}) \quad (6)$$

The combustor inlet air flow is:

$$W_3 = C_W \cdot W_{21} \quad (7)$$

where C_W is a constant.

The combustor temperature rise depends on fuel air ratio:

$$T_4 = T_3 + f_c (W_F/W_3) \quad (8)$$

where W_F is the fuel flow rate and discharge air flow is:

$$W_4 = W_3 + W_F \quad (9)$$

The high pressure turbine inlet pressure is based on a fixed area nozzle:

$$P_4 = C_{TN} \cdot W_4 \cdot \sqrt{T_4} \quad (10)$$

The combustor inlet static pressure is related to the turbine inlet pressure

$$P_{S3} = C_{BL} \cdot P_4 \quad (11)$$

The fuel flow is a function of the metering valve position

$$W_F = f_{MV} (Z_{WF}) \quad (12)$$

The bypass duct air flow is the fan flow less the compressor air flow

$$W_{15} = W_2 - W_{21} \quad (13)$$

The turbine discharge pressure is computed from the bypass duct pressure loss. At the mixing plane between the core gas flow and bypass air flow the approximation that the static pressures of the two streams are equal is used.

$$P_{S56} = P_{15} - f_{BL} (W_{15}, P_{15}, T_{15}) \quad (14)$$

$$W_{56} = W_{21} + W_f \quad (15)$$

The stagnation at the turbine discharge is

$$P_{56} = P_{S56} + f_{DL} (W_{56}, P_{S56}, T_{56}) \quad (16)$$

The inter turbine pressure and temperature are

$$P_{42} = P_{56} \cdot f_{LP} (P_4/P_{56}) \quad (17)$$

$$T_{42} = T_4 \cdot f_{NT} (P_4/P_{56}) \quad (18)$$

The low pressure turbine exit temperature is

$$T_{56} = T_{42} \cdot f_{LT} (P_{56}/P_{42}) \quad (19)$$

The total gas flow leaving the mixer and entering the nozzle is the fan flow plus the fuel flow

$$W_8 = W_2 + W_f \quad (20)$$

The gas temperature leaving the mixer is

$$T_8 = (W_{56} \cdot f_M (T_{56}) + W_{15} \cdot T_{15})/W_8 \quad (21)$$

The nozzle pressure is

$$P_8 = f_N (W_8, T_8, P_{AMB}) \quad (22)$$

The mixer inlet static pressure is

$$P_{S56} = C_M \cdot P_8 - C_{MH} \cdot W_8^2 \cdot T_8/P_8 \quad (23)$$

The fan power is

$$PW_1 = T_2 \cdot W_2 \cdot f_{FP} (P_{15}/P_2) \quad (24)$$

and the compressor power is

$$PW_{25} = C \cdot W_{21} \cdot (T_3 - T_{21}) \quad (25)$$

The high and low pressure turbine powers are

$$PW_4 = f_{HP} (T_4, P_4/P_{42}, W_3, W_f) \quad (26)$$

$$PW_{48} = f_{LP} (T_{42}, P_{42}/P_{56}, W_3, W_f) \quad (27)$$

The preceding equations describe the static relationships within the engine. The dynamic states of the engine within the frequency range of the controls are primarily the rotor accelerations, metering valve and compressor variable stator actuators, and the thermal inertia of the temperature sensors.

The rotor accelerations are proportional to the unbalanced power and inversely proportional to the polar moment of inertia and speed.

$$\dot{N}_L = C_R \cdot (PW_{48} - PW_1)/(J_L \cdot N_L) \quad (28)$$

$$\dot{N}_H = C_R \cdot (PWW_4 - PW_{25})/J_H \cdot N_H \quad (29)$$

The metering valve and compressor variable stator actuator velocities are proportional to the respective electrical currents from the control logic.

$$\dot{Z}_W = C_W \cdot I_W \quad (30)$$

$$\dot{Z}_B = C_B \cdot I_B \quad (31)$$

The rate of change of the temperature sensors is proportional to the weight flow of the gas past the sensor and the difference between the gas temperature and the sensor temperature.

$$\dot{T}_{3S} = C_{T3} \cdot W_3 \cdot (T_3 - T_{3S}) \quad (32)$$

$$\dot{T}_{56S} = C_{T56} \cdot W_{56} \cdot (T_{56} - T_{56S}) \quad (33)$$

The overall accuracy of the model cannot be simply stated because the accuracy as operated depends on which states are input. However, the accuracy of individual functions can be given. For example, on the operating line the accuracy of the fan and high pressure compressor flow are within 2 percent. Many of the fits are within 1 percent.

5.4 FEEDBACK GAIN DECISION LOGIC

One can recognize that the nonlinear model and the feedback gain matrix is actually the well-known extended Kalman Filter (Reference 1). Thus the feedback gain can be chosen to minimize the mean square error between the

actual and estimated outputs. The engine can be represented in compact form as:

$$x_{n+1} = x_n + f(x_n, u_n) \quad (34)$$

$$y_n = g(x_n, u_n) + \epsilon_n' \quad (35)$$

where at $t = n\tau$, x_n = state of the engine

u_n = input to the engine

y_n = measured output

ϵ_n' is the measurement noise with $E(\epsilon_n') = 0$ and

$$E(\epsilon_n' \epsilon_n'^T) = R_2'$$

The best estimate of the measured output y can be represented by:

$$\hat{x}_{n+1} = \hat{x}_n + f_M(\hat{x}_n, u_n) + K(y_n - \hat{y}_n) - v_n \quad (36)$$

$$\hat{y}_n = g_M(\hat{x}_n, u_n) - \epsilon_n'' \quad (37)$$

where at $t = n\tau$, f_M and g_M represent the nonlinearities in the model.

\hat{x}_n = estimated state of the engine given the past measurements

\hat{y}_n = expected measured output of the engine

u_n = error in the model which is assumed Gaussian $(0, R_2)$

ϵ_n'' = error in the measurement model which is assumed Gaussian $(0, R_2'')$

To obtain the best feedback gain, we look at the error, e_n , between the states of the engine and the model.

$$e_{n+1} = e_n + f(x_n, u_n) - f_m(\hat{x}_n, u_n) + v_n - K_n(y_n - \hat{y}_n) \quad (38)$$

$$y_n - \hat{y}_n = g(x_n, u_n) - g_m(\hat{x}_n, u_n) + \epsilon_n \quad (39)$$

For small errors:

$$e_{n+1} = \phi e_n + v_n - K_n(y_n - \hat{y}_n) \quad (40)$$

$$y_n - \hat{y}_n = C e_n + \epsilon_n \quad (41)$$

where $e_n = e_n' + e_n''$ is Gaussian $(0, R_2)$, $R_2 = R_2' + R_2''$. The gain K which minimizes this error is well known (Reference 1) and is given by the equations

$$K_n = \phi P_n C^T (R_2 + C P_n C^T)^{-1} \quad (42)$$

$$P_{n+1} = (\phi - K_n C) P_n (d - K_n C)^T + R_1 + K_n R_2 K_n^T \quad (43)$$

$$P_0 = E(e_0 e_0^T)$$

where

$$P_n = E(x_n - \hat{x}_n) (x_n - \hat{x}_n)^T \quad (44)$$

Obviously the gain matrix given by Equation 42 depends on the operating point of the engine.

Under the assumption of Gaussian noise and modeling errors, the error between the actual and estimated outputs will also be Gaussian with zero mean and covariance

$$R_y = R_2 + C P_n C^T \quad (45)$$

The expected variance of the error for the i^{th} individual sensed variable is:

$$E\{(y_{i,n} - \hat{y}_{i,n})(y_{i,n} - \hat{y}_{i,n})^T\} = R_{yii} \quad (46)$$

Where R_{yii} is the i^{th} diagonal element of R_y . Thus, the optimum detector for failure (2) is

$$|y_{i,n} - \hat{y}_{i,n}| \leq k_i R_{yii} \quad \text{No Failure} \quad (47)$$

$$|y_{i,n} - \hat{y}_{i,n}| > k_i R_{yii} \quad \text{Failure} \quad (48)$$

k is the threshold constant.

When a sensor failure is detected the output of that sensor is ignored until such time that it is again within the tolerance. In the computation of the feedback gain, this is equivalent to setting to zero the corresponding row of the matrix C and the row and column of R_2 in Equations 42 and 43. This

implies that the gain K should be computed at each time step that takes into account the available sensors and changes in flight conditions. However, the on-board calculation of the Riccati equation requires considerable more memory and computational speed than is conveniently available. Simplifying assumption have been made (as discussed in the next section) which allow the K matrix to be computed outside the engine and still maintain satisfactory performance.

5.5 ANALYSIS OF IMPLEMENTATION ASSUMPTIONS

From an implementation point of view, it is desirable to have as computationally simple a K matrix as possible, thereby allowing a more detailed nonlinear model to be used. Ideally, one would like to use only a single time invariant matrix. However, as sensors fail or flight conditions change, the response of the extended Kalman filter will shift from the optimum. Such degradation is acceptable if stability of the filter can be maintained by good tracking of the model with the actual engine.

The approach used to obtain the desired K matrix was empirical since no suitable analytical technique was available. Initially, optimal K matrices for various sensor failures were obtained for an operating point of 92% full thrust. It was noted that these K matrices reached steady state in approximately 0.3 to 0.4 second. Since this time is short compared to the transient time of the engine, the decision to use time invariant K matrices appeared reasonable.

The open and optimum closed loop eigenvalues of the linearized engine model for several sensor failures are shown in Table V. It can be seen that the response of the optimum filter with no sensor failures is considerably faster than the actual engine as indicated by the open loop eigenvalues. In general, as a sensor fails the optimum closed loop eigenvalues associated with that sensor tend to shift toward the open loop values. A large shift indicates a strong coupling between the sensor and that state in the unfailed case. For example, the eigenvalue associated with N_H and Z_{WF} shifts from 0.465 to 0.829 with a PS3 failure due to the lack of strong coupling between PS3 and N_H after the failure. As expected, the failure of a temperature sensor means that the filter model state for that temperature sensor becomes open loop since there is no way of determining the state of the failed sensor from the remaining measurements.

Even using steady-state gains, it would be impossible to have separate K matrices for each possible combination of sensor failure. One approximation is to use a fixed K and to set to zero the column corresponding to the failed sensor. In this manner, the effect of the failed sensor is no longer included in the update of the model. However, as indicated in Table VI, if the K designed for no failures is used, the filter becomes unstable if the PS3 sensor fails and the corresponding column is set to zero. This is again due to the high coupling between PS3 and N_H in the unfailed optimum case.

Table V. Open and Optimum Closed Loop Eigenvalues.

Open Loop	Corresponding Engine Variable	Optimum Closed Loop						Primary Engine Variables
		No Failures	N_L Failed	N_H Failed	PS3 Failed	N_L & PS3 Failed	N_H & PS3 Failed	
0.9684	N_L, N_H	0.0026	0.0405	0.0026	0.0026	0.0438	0.0027	N_L, N_H
0.9788	N_H	0.0716	0.0717	0.0940	0.0893	0.0930	0.1076	N_L, T_{35}
0.9971	T_{56S}	0.1543	0.2625	0.1931	0.1940	0.2809	0.9271	N_H, T_{3S}
0.9971	T_{12S}	0.3398	0.6616	0.3398	0.3398	0.6537	0.3397	N_L, T
0.9980	T_{25S}	0.4652	0.4563	0.8491	0.8289	0.8345	0.8323	$N_H,$
0.9989	T_{3S}	0.7883	0.7893	0.7881	0.7884	0.7894	0.7879	T_{125}
1.0	Z_W	0.8608	0.8608	0.8608	0.8610	0.8609	0.8606	Z_β
1.0	Z_β	0.9514	0.9515	0.9447	0.9519	0.9507	0.9661	T_{12S}, T_{25S}

Table VI. Shift of Eigenvalues with P_{g3} Sensor Failure.

Optimum Closed Loop		Optimum No Failure Feedback Matrix With P _{g3} Failed	Primary Engine Variables
No Failure	P _{g3} Failed		
0.0026	0.0026	0.0034	N _L , N _H
0.0716	0.0896	0.1144	N _L , T _{3S}
0.1543	0.1940	0.2821	N _H , T _{3S}
0.3398	0.3398	0.3399	N _L , T _{56S}
0.4652	0.8289	1.0142	N _H , Z _W
0.7883	0.7884	0.7883	T _{12S}
0.8608	0.8610	0.8608	Z _β
0.9514	0.9519	0.9515	T _{12S} , T _{25S}

It was found that the optimal K matrix designed for a PS3 failure provided good filter response for other combinations of failures as shown in Table VII. In order to allow correction of the model when PS3 is available, the PS3 column of the optimum K matrix with no failures was adjoined to the K matrix obtained under the assumption of a failed PS3. The negative root shown in Table VII is due to this additional column. Since it is a very fast root and was shown to have only slight transient effect on the overall behavior of the system, no adjustments of the gains were made.

The above discussion was for a flight condition of 92% full thrust. The change in open loop eigenvalues with change in thrust from flight idle to full thrust is shown in Figure 44. It can be seen that the response decreased by a factor of approximately three as the thrust increases. However, as shown in Figure 45, the closed loop response using the K matrix of Table VII which was designed at 92% thrust does not change much except for the smallest two eigenvalues. A shift of the eigenvalues similar to those of Table VII occurs at any thrust condition during sensor failure.

5.6. RESULTS OF NONLINEAR SIMULATION

To evaluate the stability and response of the failure detection and correction, it has been simulated on one hybrid computer with an accurate nonlinear cycle balance simulation of the QCSEE engine and nonlinear control system on a second hybrid computer. The failure detection and correction was connected into the accurate simulation between the sensor simulation and the controls simulation. In this manner, the performance of the system as it would operate the actual engine could be predicted.

The typical results obtained are shown in Figures 46 through 50 in which the power demand to the controls is stepped between 70% of takeoff power and all takeoff power. The response shown in Figure 46 for the system with all sensors functioning, and with the failure detection and correction functioning. The simulation showed that the Kalman filter tracked the simulation so that at no point in the transient did any sensor errors exceed the tolerances. This is indicated by the event trace in the margin next to the core turbine inlet temperature. When this trace steps outward one or more sensors are indicated as failed.

The traces in Figures 47, 48 and 49 show that PS3, NL, and NH pulled (failed) separately. When PS3 is pulled at takeoff power there is no shift in the operating point, but there is a change in the transient response. The explanation for this is: PS3 is the primary variable for transient fuel flow scheduling, but it is not used for steady-state control. With NL pulled there is a slight shift in the operating point, and the settling transient is changed because this is a controlled variable at takeoff power and 70 percent of takeoff power. With NH pulled, the speed input to the transient fuel scheduling and the compressor variable stator control are estimated. As a result there is a small shift in the core stator position.

Table VII. Closed Loop Eigenvalues with Nonoptimal Feedback Matrix.

No Failure	N_L Failed	N_H Failed	PS3 Failed	Z_W Failed	N_L & PS3 Failed	N_H & PS3 Failed	N_L , PS3 & Z_W Failed
0.0042	0.9640	0.0041	0.0026	0.0044	0.9570	0.0041	$0.9729 + j 0.0362$
-0.2152	-0.2153	0.1207	0.0893	-0.1776	0.0891	0.1226	0.0891
0.1283	0.1234	0.9520	0.1940	0.1309	0.1872	0.9757	0.1872
0.3398	0.3363	0.3398	0.3398	0.3398	0.3398	0.3398	0.3364
0.4772	0.4799	0.1768	0.8491	0.5864	0.8396	0.8350	$0.9729 - j 0.0362$
0.7883	0.7882	0.7882	0.7881	0.7881	0.7882	0.7882	0.7882
0.8608	0.8608	0.8608	0.8608	0.8617	0.8610	0.8610	0.8610
0.9520	0.9519	0.9520	0.9447	0.9519	0.9512	0.9518	0.9523

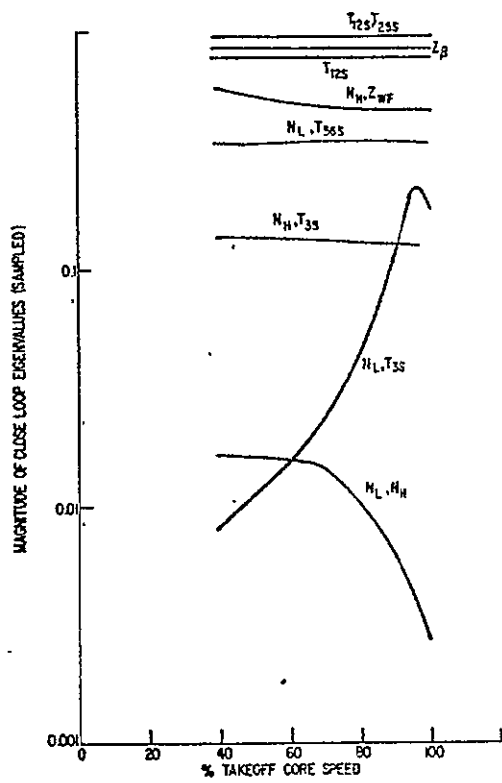


Figure 44. Closed Loop Eigenvalue Variations.

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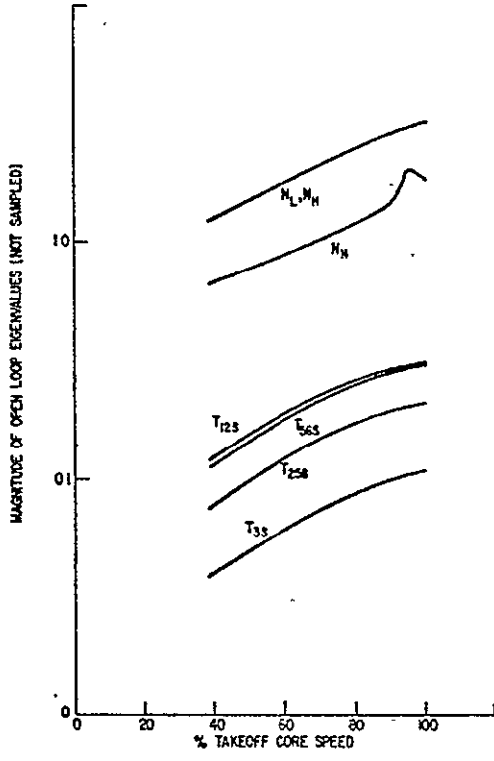


Figure 45. Open Loop Eigenvalue Variations.

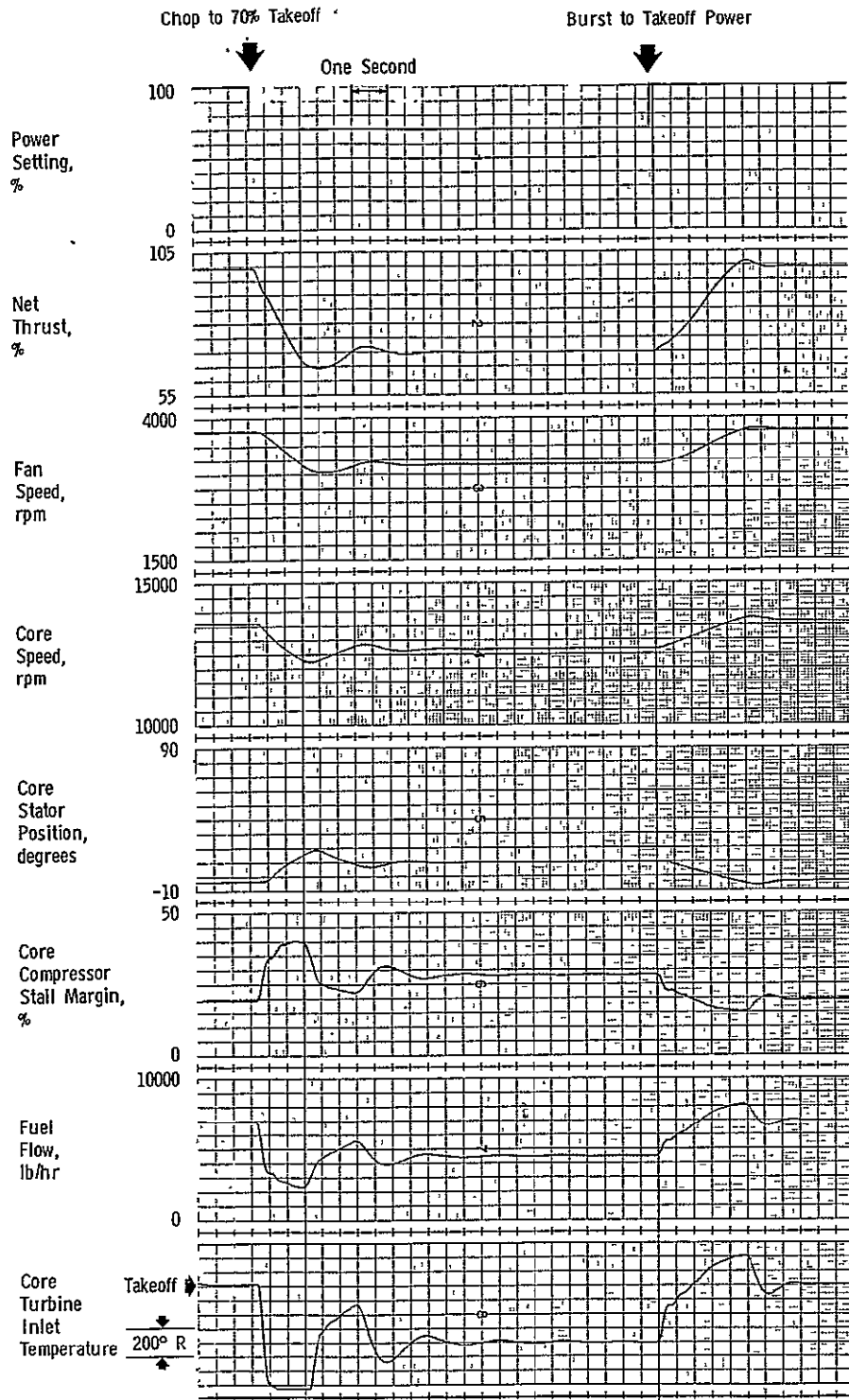


Figure 46. Computer Trace with All Sensors Functioning.

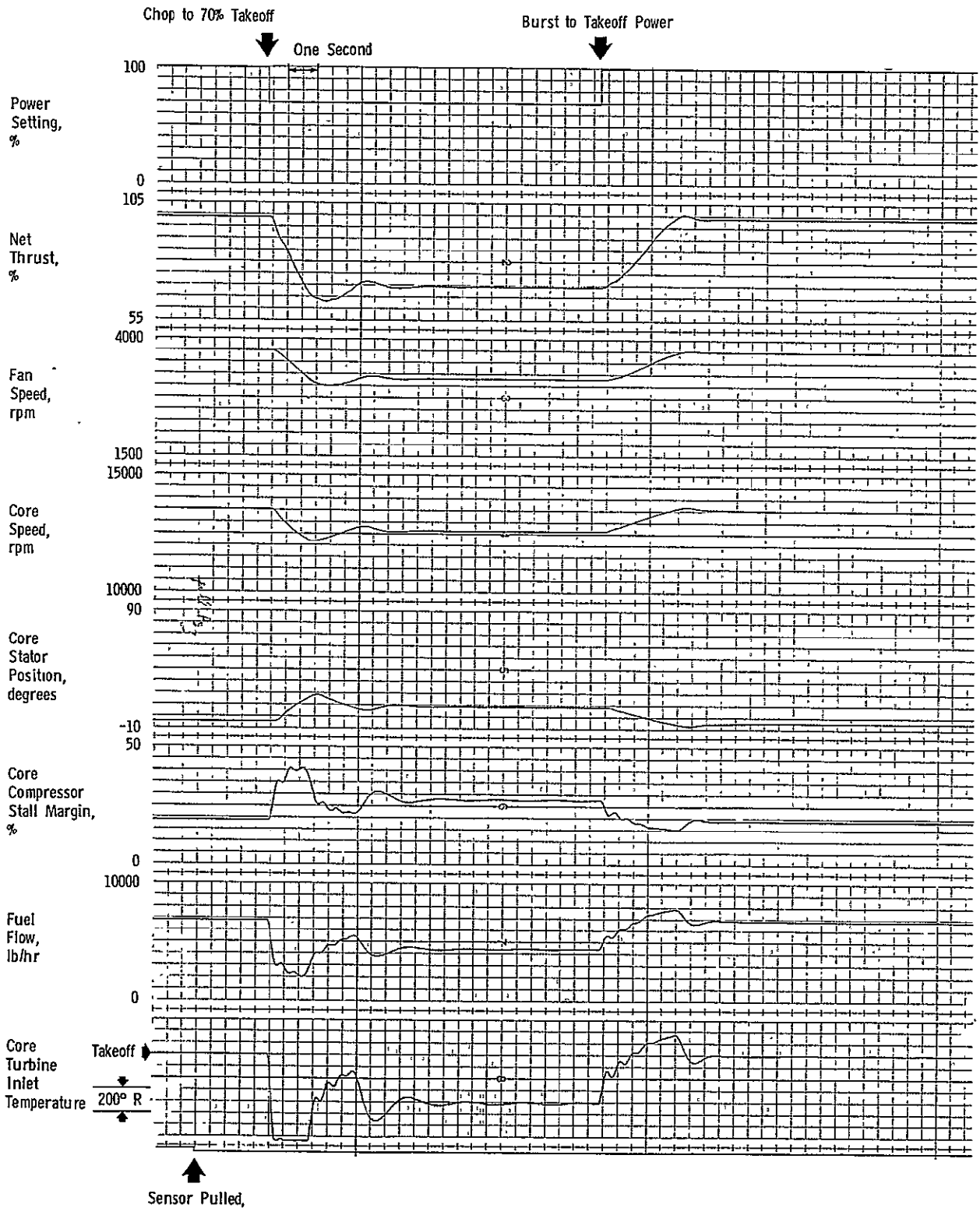


Figure 47. Computer Trace with PS3 Sensor Pulled.

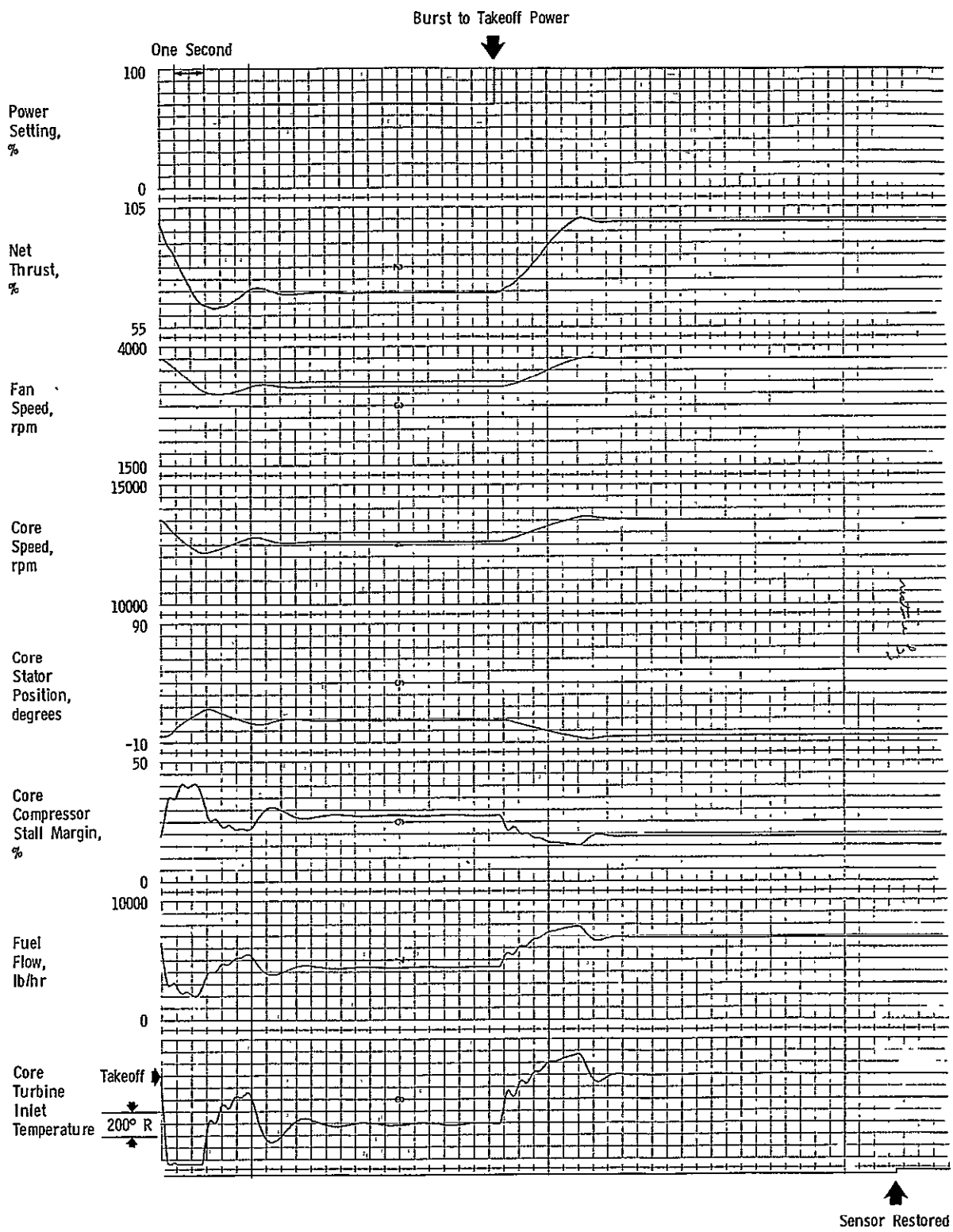


Figure 47. Computer Trace with PS3 Sensor Pulled (Concluded).

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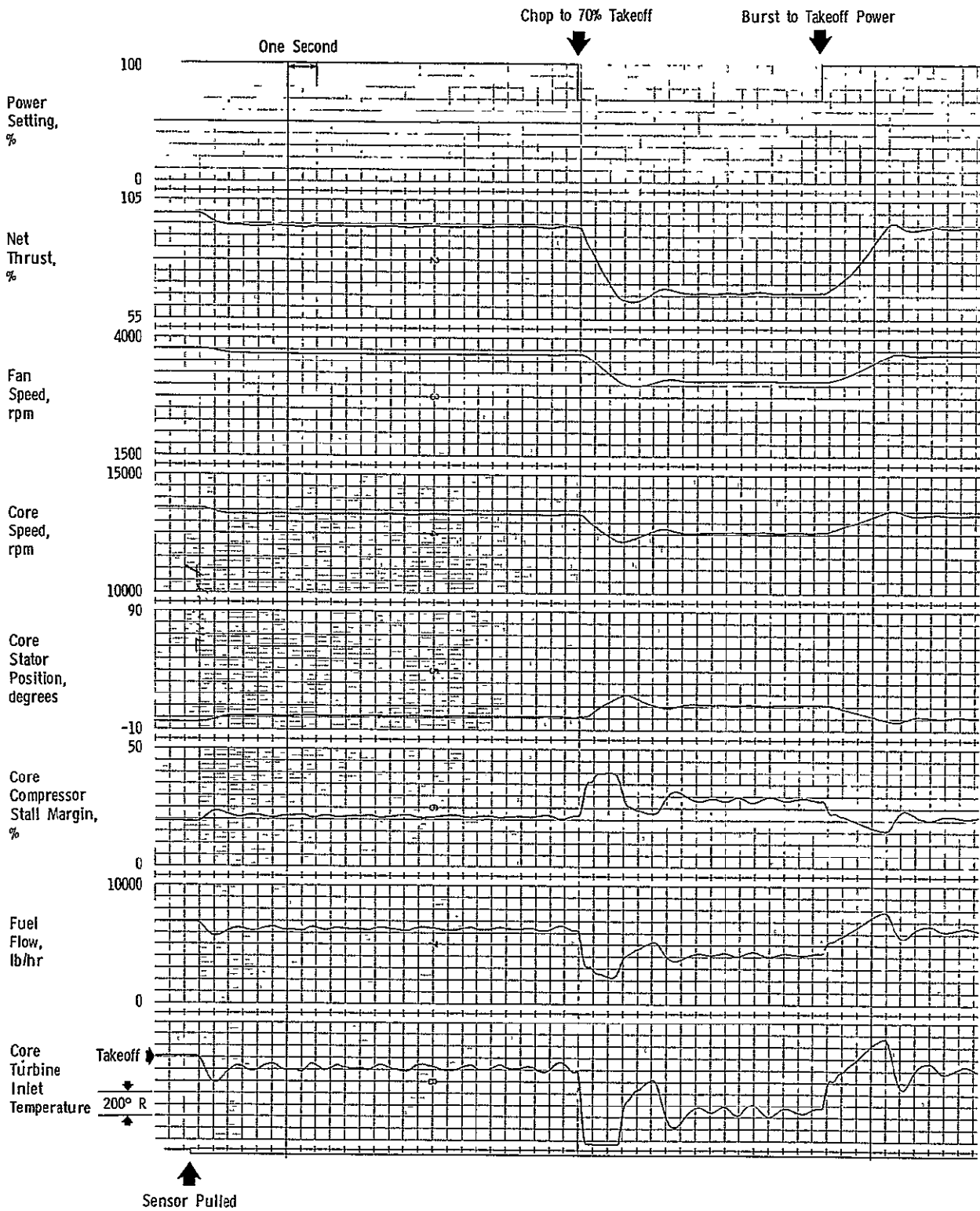


Figure 48. Computer Trace with XNL Sensor Pulled.

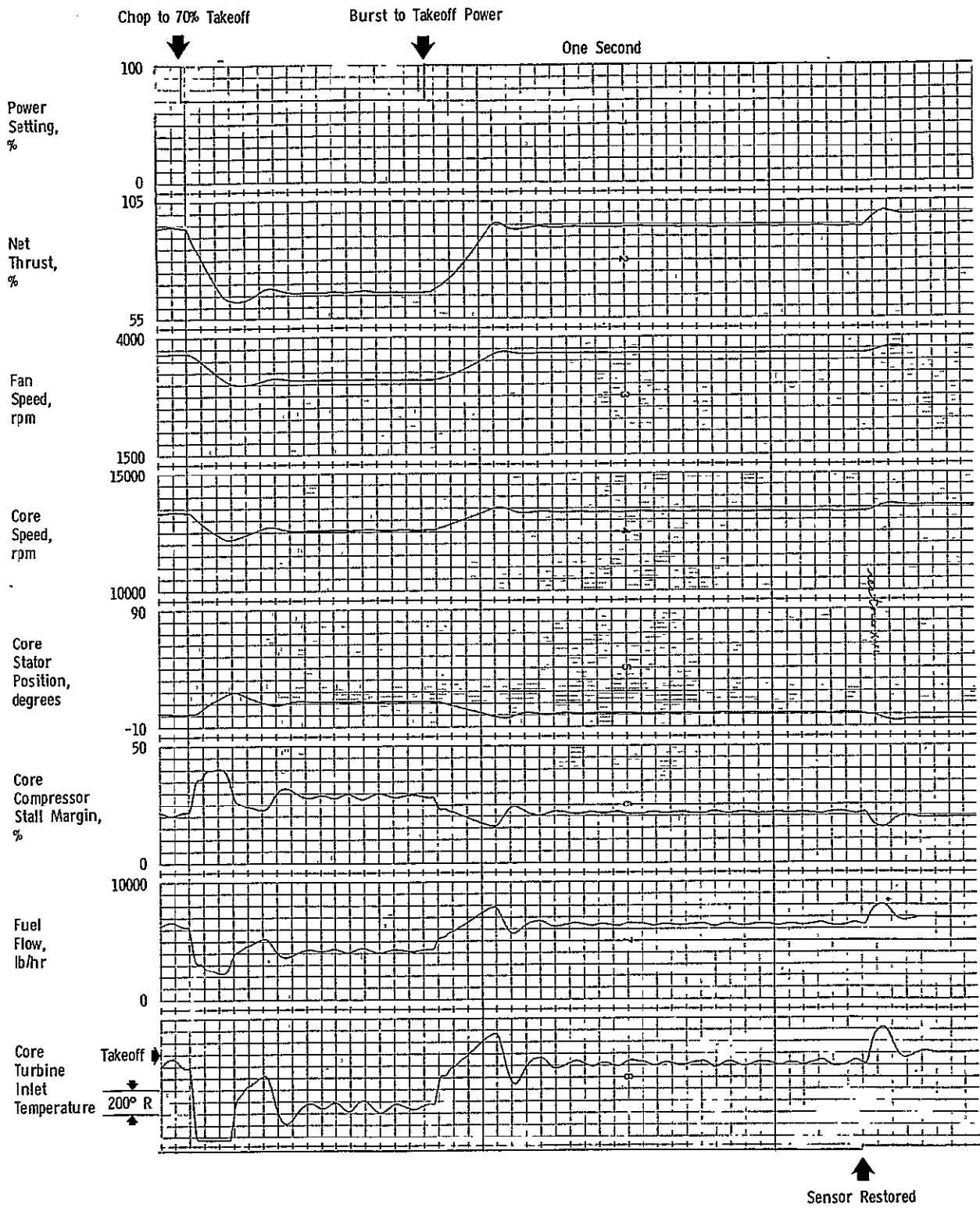


Figure 48. Computer Trace with XNL Sensor Pulled (Concluded).

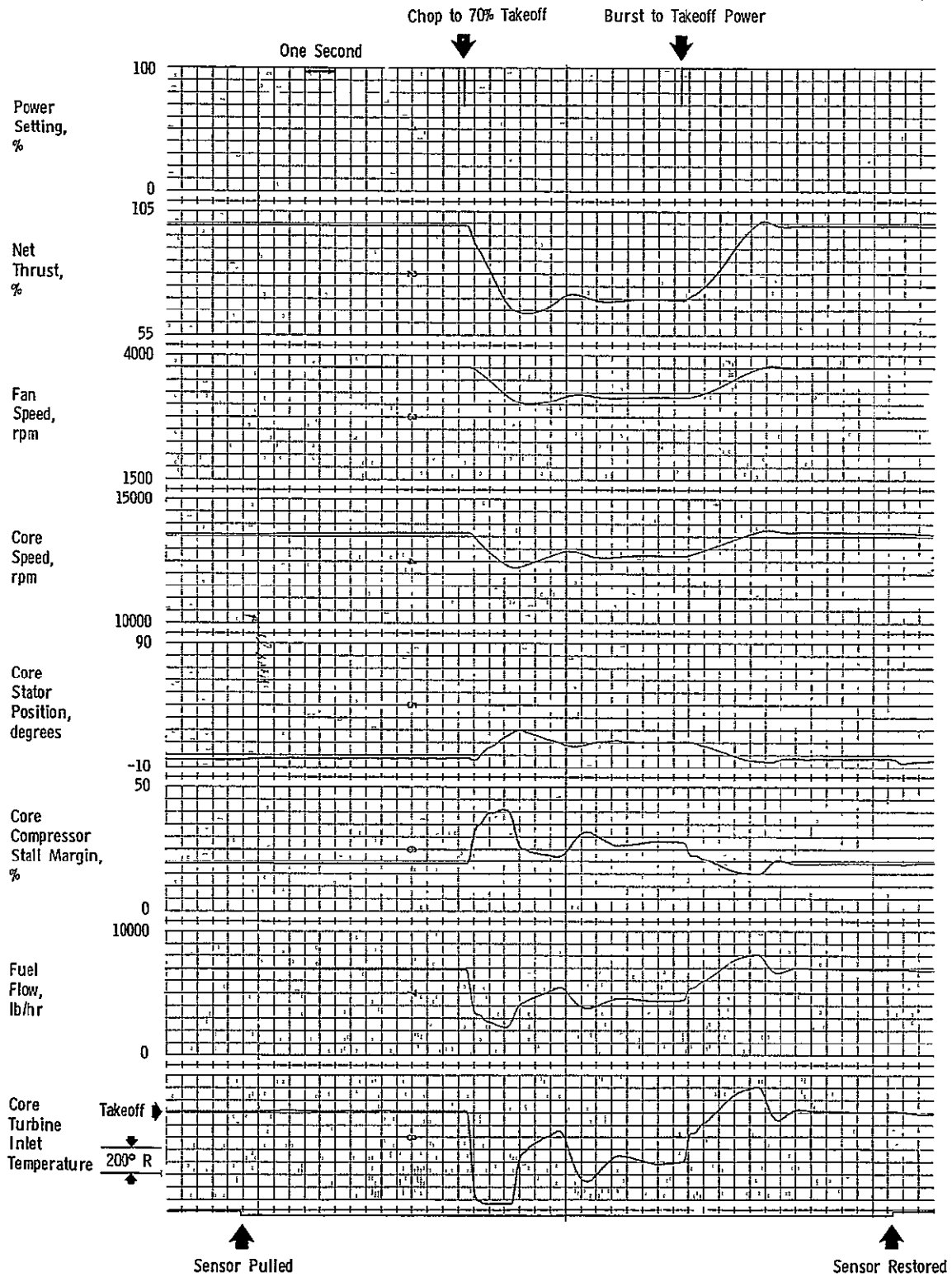


Figure 49. Computer Trace with XNH Sensor Pulled.

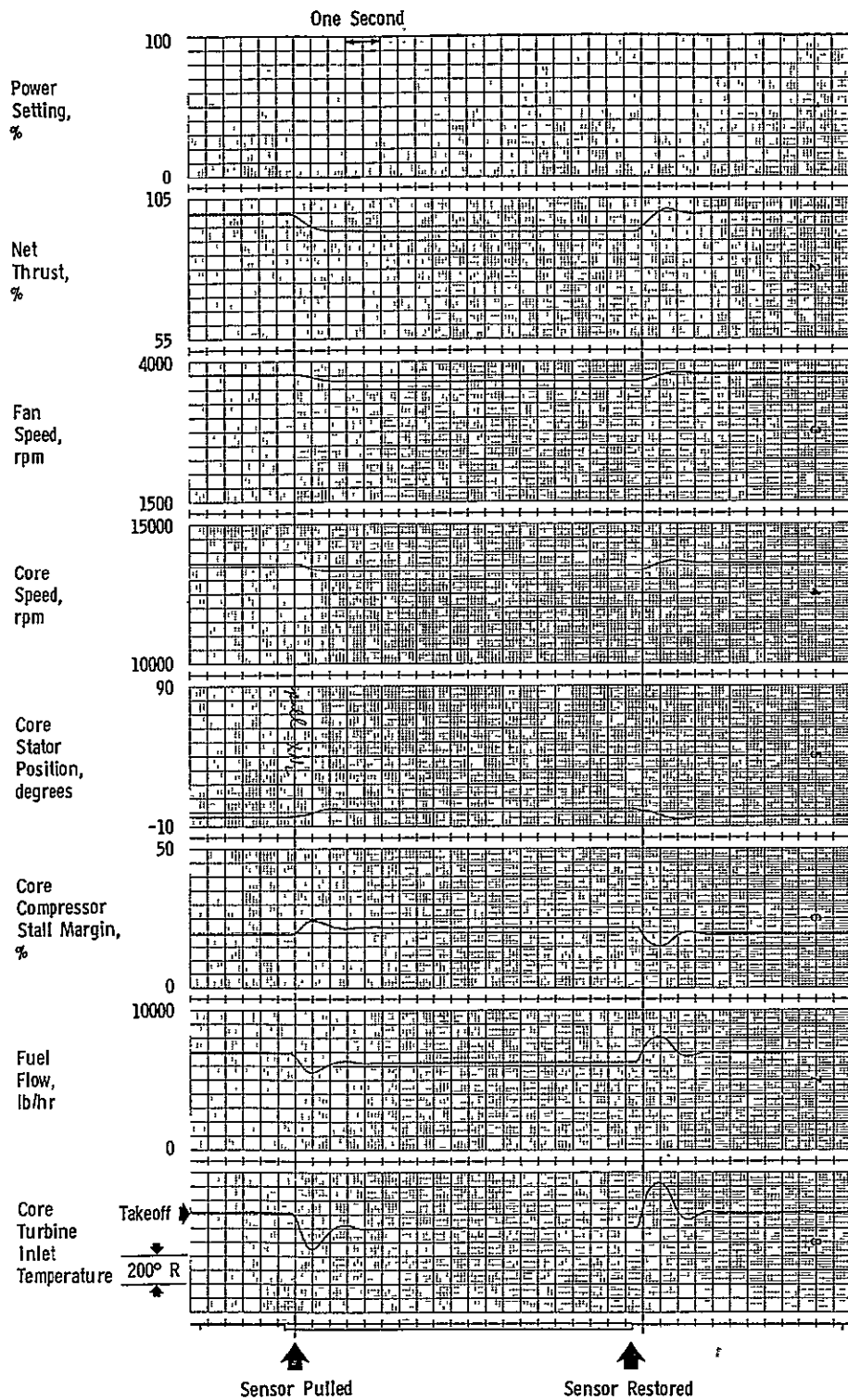


Figure 50. Computer Trace with XNL Sensor Pulled and with 16-Bit Control Computer Simulated.

The on-engine digital control computer has a 12-bit word with double precision capability. The hybrid computer has a 16-bit word with double precision capability, but software is used to mask the least significant bits to simulate the digital computer controller's 12-bit word. Comparisons between these two computers have been made of accuracy (as indicated by the shift set point with a sensor pulled) and steady-state hunting with a sensor pulled. The results indicate that there is a substantial improvement in the hunting with a 16-bit computation. This hunting is shown most strongly in the core turbine inlet temperature channel as is shown in Figures 48 and 50. The former is with a simulated 12-bit control computer; the later, a 16-bit. Both are with the XNL sensor pulled. These two traces indicate that there is no significant difference in accuracy or stability amid disturbances.

It can be seen from the figures that while the transient is altered for failed sensors good engine control is maintained. For all of these runs a fixed gain feedback matrix has been used, demonstrating that it is not necessary to supply a separate feedback matrix for each sensor failure and each power range for the engine. Although not shown in the computer traces herein included, multiple sensor failures have been demonstrated in which chop and burst transients have been controlled adequately. This further demonstrates the advantage of the extended Kalman filter technique, in which a fixed gain feedback matrix is satisfactory for a wide range of conditions.

5.7 CONCLUSION

Based on an extended Kalman filter, a failure detection and correction strategy for turbofan engines has been developed. It has been shown that continuing control can be maintained even with multiple sensor failures. Key to this development is the model of the engine, which provides reasonable estimates of engine behavior yet is compact enough to be implemented in an on-engine digital computer. An empirical approach to obtain a suitable feedback matrix was used. Although the design procedures are not fully systematic, nor all the problems of implementation solved, the results show that the failure and correction strategy maintains good control for steady state and transients in the hybrid simulation. The strategy has been implemented in the on-engine digital computer in a form identical to the FORTRAN used in the hybrid computer. The failure detection and correction strategy is to be tested with a simulated sensor failure on the engine.

6.0 DIGITAL CONTROL SUBSYSTEM

6.1 GENERAL DESCRIPTION

The digital control subsystem, shown in Figure 51, is comprised of 1) an engine-mounted digital control, and 2) command and monitor peripheral equipment located in the control room.

The digital control performs the computational requirements for the overall engine control system according to the demands received from the command and monitor equipment and other parameters received from engine-mounted sensors. In addition to generating control signals to manipulate fuel flow and core compressor stator position, the digital control transmits engine and control data to the command and monitor equipment in the control room.

The command and monitor equipment approximates an aircraft interface in that it provides the command inputs to operate the engine. Likewise, the transmission process is similar from a hardware viewpoint to a flight-type system. That is, all command data are transmitted to the digital control in a time-shared digital format over a data link that could be adapted for a flight-type system. However, the command and monitor equipment also provides selected adjustment inputs to modify steady-state and dynamic characteristics of the control strategy, indication of system faults, and a comprehensive control and engine parameter display system.

Fault indication and corrective action are part of the digital control strategy and are described in Section 3.3.3 and Section 5.0 of this report. Also, the control includes provisions for readout of 48 control and engine variables from the command and monitor equipment in the control room. These variables are listed in Table VIII. (Also see Table IX.)

The Table VIII data may be read out from a number of stations in the control room. Any one of the forty-eight parameters may be selected for display on a binary-coded decimal readout on the engineering control panel, and all parameters are transmitted serially to the remote (NASA) computer in binary form. Parameters 00 through 14 are available for real time analog recording through instrumentation connections on the interconnect panel and any of the forty-eight channels may be selected for analog recording through a sixteenth instrumentation connection. In addition, Parameters 05, 07, 10, 12, and 13, along with inlet Mach number calculated from 08; percent fan corrected speed calculated from 12 and 19; and turbine temperature calculated from 35, are displayed in engineering units on the operator control panel to aid in engine operation. Also, sensor failure signals from the FICA function are displayed as an octal code number on the operator control panel; and the torque motor currents, Items 00, 01, and 02, are displayed on engineering panel meters.

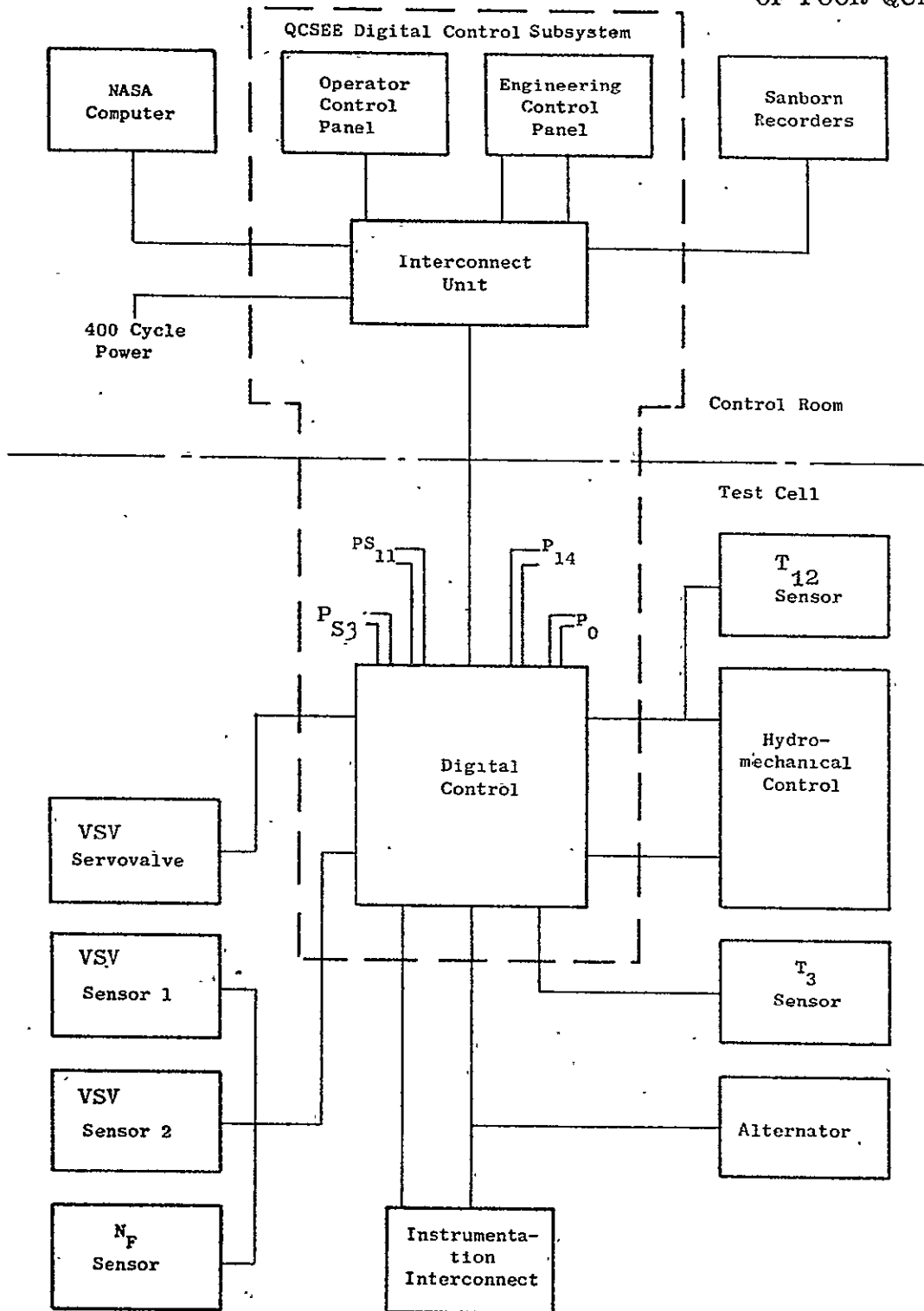


Figure 51. A Block Diagram of Digital Control System.

Table VIII. Control and Engine Monitor Data.

Thumb Wheel Switch Position	Parameter	Full-Scale Range
00	A18 TMC	±100 mA
01	βF TMC	±100 mA
02	WF TMC	±100 mA
03	WF	0 - 10K pph
04	A18	-0.247 to 4.753 in.
05	βF	-0.414 to +0.414 v/v exc.
06	FMP	0 to 800 psia
07	T41C	-0 to 3460 R
08	(PTO-PS11)/PTO	-0 to 1.0
09	PS3/PTO	-0 to 20.47
10	Power Demand	-0 to 100
11	PLA	-0 to 130
12	N1	0 to 3893 rpm
13	N2	-0 to 15,492 rpm
14	VSV	-5 to 60 Degrees
15	WF Control Mode	
16	βF Control Mode	
17	A18 Control Mode	
18	F.I. (See Table IX)	
19	T12	-40° to 160° F
20	PTO	0 to 19 psia
21	P14-PTO	0 to 12 psid
22	PTO-PS11	0 to 12 psid
23	PS3	0 to 300 psia
24	MVP	0 - 813 in.
25	βF1	-0.414 to +0.414 v/v exc.
26	βF2	-0.414 to +0.414 v/v exc.
27	βF Demand (auto mode)	0 to 3893 rpm N1
28	A18 Dem. (auto mode)	±6 in./sec
29	T3	-65 to 1090° F
30	VSV Reset TMC	Normal/Reset
31	Mode Word	
32	Hyd. Pump Disc. Press	0 to 5000 psia
33	WF Temp.	0 to 300° F
34	βF Rate	-30.8 to +30.8 v/v sec.
35	EGT	0 to 2000° F
36	Engine Oil Inlet Temp.	0 to 250° F
37	Scav. Oil Temp.	0 to 350° F
38	Eng. Oil Inlet Press.	0 to 150 psig
39	Scav. Oil Press.	0 to 150 psig
40	T25	0 to 200° F
41	P5	0 to 25 psia
42	Gearbox Innerrace Bearing Temperature	0 to 300° F
43	Horizontal Vib.	0 to 50 mils
44	Vertical Vib.	0 to 50 mils
45-47	Spares	

Table IX. Fault Indication (F.I.)*.

No.	Fault	Data Word No. 18 Digital Output Valve	Fault Indication
1	No Fault	0000	Off
2	Vib Hor. & Vert. > 40 mils	1024	On
3	Loss of Command Data Link	512	On
4	Computer Fault Test	255	On
5	ESTMC > -60 ma	128	On
6	Lube Supply Temp. > 180° F	64	On
7	Lube Supply Pressure < 30 psia and N2 80%	32	On
8	G/B Bearing Temp. > 264° F	16	On
9	-0.0854 v/v < VSV 1 - VSV 2 > +0.0854 v/v	4	On
10	Computer Timing Oscillator Failure	1	On

Sanborn Recorder Output (No. 16) Voltage = $\frac{\text{Digital Output}}{4095} \times 10 \text{ Volts}$

For multiple fault indication, the sum of the digital output values of the indicated failures shall be displayed.

*Parameter 18 on Table VIII.

6.2 DIGITAL CONTROL DESCRIPTION

The digital control is an engine-mounted assembly that includes a special-purpose digital computer. The control accepts operational input demands and engine variable information in the form of a.c. and d.c. analog signals and digital signals and uses this information to generate engine control signals and engine conditions monitoring data. Control inputs and outputs are given in Table X; a block diagram is shown in Figure 52.

The digital computer is composed of three major sections: the program memory, the central processor, and the input-output unit. Basic operation is described below, followed by a description of the key elements shown in Figure 52.

A group of instructions comprising one control cycle is stored in the program memory. Each instruction is sequentially transmitted to the central processor for execution. The central processor generates timing to operate the computer, executes the instruction, and transmits a ready-for-next-instruction command back to the program memory at the completion of each instruction except for the jump-and-branch instructions; in which case the central processor also provides a new address for the program counter. When all of the instructions are executed, the program is repeated. The flow of information into and out of the computer is handled by the input-output section under commands from the central processor. The input-output unit receives command digital data from the control room and analog input control parameter signals. Under the command of the central processor, the input-output unit digitizes the signals as they are required in the computational sequence and transmits them to the central processor as binary encoded numbers. The outputs to drive the servovalves are received in the input-output unit as binary encoded numbers from the central processor. Again, under the command of the central processor, the numbers are converted from digital to analog signals are loaded and stored in sample-and-hold networks that are uniquely designated for each output. The sample-and-hold network outputs are processed using standard analog techniques to provide the output interface with the other components in the control system. The information contained in the sample-and-hold networks is updated once each cycle.

The basic sections of the digital control are described separately below.

6.2.1 Program Memory

The memory has been organized to provide 16-bit words to the central processor. Each word contains four bits of operational code which, when decoded in the central processor, direct the central processor to perform one of the basic instructions. The specific instructions indicated by the operational codes are shown in Appendix C. The remaining twelve bits may be used to transmit binary numbers from the memory, address the scratch pad memory, or provide an additional bit of operational code depending on which instruction is contained in the operational code. The memory is comprised of sixteen 512X8 chips to provide a 4,096 word capacity.

Table X. Digital Control Inputs and Outputs.

I. INPUTS	II. OUTPUTS
<p>A. <u>Engine and Control Inputs</u></p> <ol style="list-style-type: none"> 1. Alternator - Power and Core Speed Sensing 2. Primary LP Turbine Speed Signal 3. Secondary LP Turbine Speed Signal 4. T12 Sensor 5. Compressor Disch. Gas Temperature Sensor 6. Fuel Metering Valve Position Transducer 7. Throttle Position Transducer 8. Core Stator Vane (VSV) 9. Core Stator Vane (VSV) 10. PS11 Sensor 11. PTO Pressure 12. P14 Pressure 13. PS3 Pressure <p>B. <u>Instrumentation Inputs (0-10V)</u></p> <ol style="list-style-type: none"> 1. Spare 2. Fuel Temperature - ° F 3. Fuel Manifold Pressure - psia 4. Exhaust Gas Temperature - ° F 5. Fuel Flow - PPH 6. Engine Lube Oil Out Pressure - psig 7. Engine Lube Scavenge Pressure - psig 8. Engine Lube Oil Inlet Temperature - ° F 9. Engine Scavenge Oil Disch. Temperature - ° F 10. T25 - ° F 11. Pressure Station 5 - psia 12. Gearbox Interface Bearing Temperature - ° F 13. Engine Horizontal Vibration 14. Engine Vertical Vibration 15. Core Stator Position VSV, Degrees 16-20. Spares <p>C. <u>Operator Inputs</u></p> <p>Multiplex Digital Signals Ability to Receive Any Number</p>	<p>A. <u>Torque Motors</u></p> <ol style="list-style-type: none"> 1. WFTMC - Fuel Control 2. VSVTMC - Core Stator Vane Control 3. ESTMC - Emergency Shutdown <p>B. <u>LVDT Drives</u></p> <ol style="list-style-type: none"> 1. MVP 2. VSV 1 3. VSV 2 4. PLA <p>C. <u>Other Inputs</u></p> <ol style="list-style-type: none"> 1. T12 Sensor Excitation 2. LPT Speed Indication 3. Multiplex Digital Data Link Transmit any number of data words

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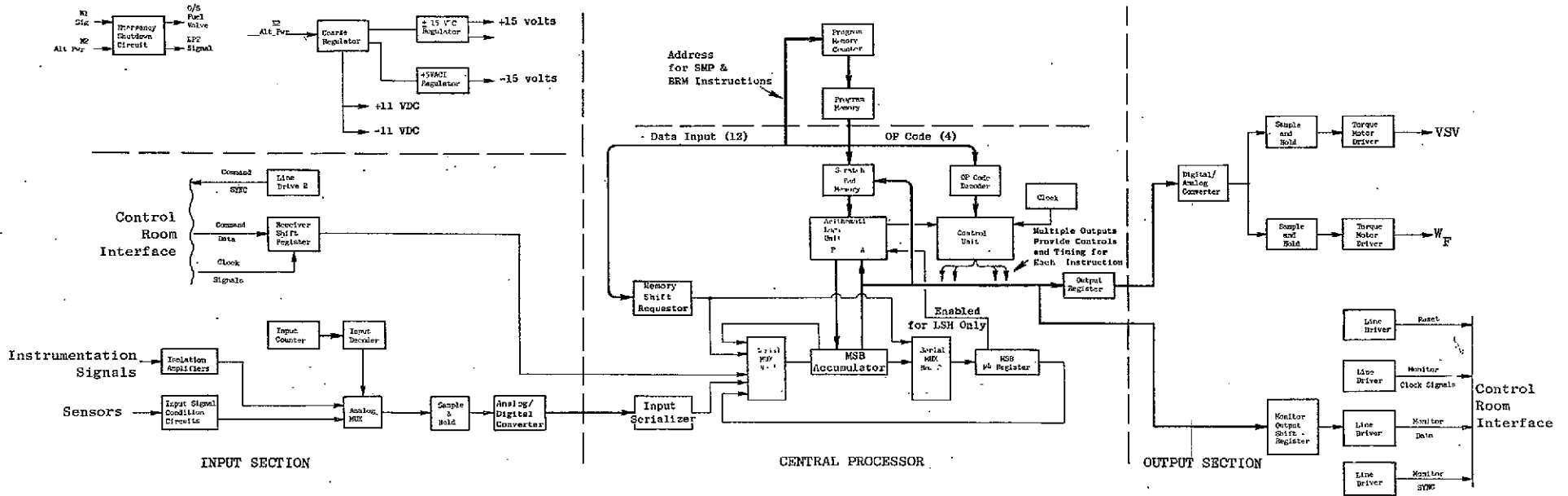


Figure 52. Digital Control Block Diagram.

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When each instruction is complete, the program counter receives from the central processor an advance-to-the-"next memory address" signal for the jump-and-branch instructions. Each combination of high and low states of the counter outputs is decoded as a unique location in the program memory. The memory then outputs the word contained at that location. The last (OUT 15) instruction in the program memory is decoded in the central processor to reset all of the counters in the computer to zero and start the control cycle over.

6.2.2 Central Processor

The major functional blocks of the central processor are the Arithmetic and Logic Unit (ALU), the scratch pad memory, the control unit, the accumulator, and the MQ register. Figure 53 is a schematic showing the ALU, the accumulator register, and the MQ register.

The function of the central processor is to carry out the instructions received from the program memory. The operational code portion of each word received from the program memory is decoded (op-code decoder) into one of the various instructions that the central processor has been designed to perform. The major elements of the central processor are described below.

1. Control Unit - The control unit contains the circuitry that generates control signals in the proper sequence to execute the instructions received from the op-code decoder. Control unit outputs are disbursed throughout the digital control to perform the required operations.
2. Arithmetic Logic Unit - The ALU is the heart of the digital control. All arithmetic operations employ the ALU in their execution. The ALU is comprised of D1, A1, and A14, as shown in Figure 53. The ALU operates on data received from the scratch pad memory at the "B" terminals and from the accumulator at the "A" terminals in accordance with control unit inputs received at the "S" terminals. Tables of the arithmetic and logic operation performed by the ALU are shown in Table XI. The results of the operations performed are presented at the "F" terminals of the ALU.
3. Scratch Pad Memory - The scratch pad memory is a 256-word random access memory (RAM) with read/write capability. The scratch pad memory is addressed from the program memory at the "A" terminals (Reference Figure 52). When the read mode is enabled from the control unit, data are output at terminal "O" to the ALU from the location addressed, and data at terminal "O" are read into the location addressed.

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Table XI. Arithmetic Logic Unit (ALU) Operations.

Control CN ₄				Output Function With Mode Control CN ₄ & CN Low		Control, CN ₄				Output Function With Mode Control CN ₄ High: CN Irrelevant	
S ₀	S ₁	S ₂	S ₃	Low Levels Active	High Levels Active	S ₀	S ₁	S ₂	S ₃	Negative Logic	Positive Logic
L	L	L	L	F = A minus 1	F = A	L	L	L	L	F = \bar{A}	F = \bar{A}
L	L	L	L	F = AB minus 1	F = A+B	L	L	L	L	F = \overline{AB}	F = $\overline{A+B}$
L	L	H	L	F = $A\bar{B}$ minus 1	F = A+B	L	L	H	L	F = $\overline{A+B}$	F = \overline{AB}
L	L	H	H	F = minus 1 (2's complements)	F = minus 1 (2's complement)	L	L	H	H	F = Logical 1	F = Logical 0
L	H	L	L	F = A plus (A+B)	F = A plus $A\bar{B}$	L	H	L	L	F = $\overline{A+B}$	F = \overline{AB}
L	H	L	H	F = AB plus (A+B)	F = (A+B) plus $A\bar{B}$	L	H	L	H	F = \bar{B}	F = \bar{B}
L	H	H	L	F = A minus B minus 1	F = A minus B minus 1	L	H	H	L	F = $\overline{A+B}$	F = A+B
L	H	H	H	F = A+B	F = $A\bar{B}$ minus 1	L	H	H	H	F = A+B	F = $A\bar{B}$
H	L	L	L	F = A plus (A+B)	F = A plus AB	H	L	L	L	F = \overline{AB}	F = $\overline{A+B}$
H	L	L	H	F = A plus B	F = A plus B	H	L	L	H	F = A+B	F = $\overline{A+B}$
H	L	H	L	F = $A\bar{B}$ plus (A+B)	F = (A+B) plus AB	H	L	H	L	F = B	F = B
H	L	H	H	F = A+B	F = $A\bar{B}$ minus 1	H	L	H	H	F = A+B	F = AB
H	H	L	L	F = A plus A*	F = A plus A*	H	H	L	L	F = Logical 0	F = Logical 1
H	H	L	H	F = AB plus A	F = (A+B) plus A	H	H	L	H	F = $A\bar{B}$	F = A+B
H	H	H	L	F = $A\bar{B}$ plus A	F = (A+B) plus A	H	H	H	L	F = AB	F = A+B
H	H	H	H	F = A	F = A minus 1	H	H	H	H	F = A	F = A

*Each bit is shifted to the next more significant position

For Positive Logic: Logical 1 = High Voltage
Logical 0 = Low Voltage

For Negative Logic: Logical 1 = Low Voltage
Logical 0 = High Voltage

4. Accumulator Register - The accumulator register, composed of devices G1, G10, and G19 on Figure 53, is a highly versatile register that is programmed by the control unit to accept inputs and provide outputs in either parallel or serial form. It accepts serial inputs from the sensors, MQ register, and program memory, plus instrumentation command inputs, and provides parallel outputs to the ALU, the scratch pad memory, and the output register, as well as serial output to the MQ register. Data can be both left- and right-shifted in serial transmission of data through the accumulator. Point of input origin, destination of data outputs, as well as mode of operation, are established signals provided by the control unit.
5. MQ Register - The MQ register, comprised of devices G28, E28, and C28 as shown in Figure 53, is used as a shift register in conjunction with the accumulator. It is employed as a repository for data during the multiply, divide, and rotate instructions.

The remainder of the circuitry shown in Figure 53, and not discussed above, is a portion of the control unit circuitry.

6.2.3 Instructions

The digital control is programmed using the set of instructions defined below.

Out 0 - The function of this instruction is to consume time while other functions are being performed in the control. No operation results from the Out-0 command. When the Out-0 instruction word is received from the program memory the control unit generates the following:

- A signal to the program memory instruction counter that advances the count, sequencing the memory to the next instruction.

Out 1 - The function of the Out-1 instruction is to transfer calculated output data from the accumulator to the DA output register in the input-output unit to start the output process. When the Out-1 instruction word is received from the memory, the control unit generates two signals:

- A signal to the DA output register then enables a parallel transfer of data from the accumulator register.
- A signal to the program memory instruction counter that advances the count, sequencing the memory to the next instruction. The value in the output register is continuously converted to analog value by the digital-to-analog converter.

Outs 2 through 6 - The function of these instructions is to load the output of the digital-to-analog converter into unique sample-and-hold networks designated for the data contained in the output register.

When one of these instructions is received, the control unit generates a signal to advance the output address counter and advance the program memory counter. Each output address count signal will be decoded to select a specifically designated sample-and-hold network.

Out 13 - The purpose of this instruction is to transmit data to the off-engine equipment (simulated aircraft interface). When the Out-13 instruction is received the control unit generates the following signals:

- 12 clock pulses to the monitor output shift register to transmit the data serially to the off-engine equipment.
- 12 clock signals to the off-engine equipment to enable the off-engine equipment to receive the data.
- A monitor sync-pulse to the off-engine equipment at the conclusion of the message to update the off-engine message identification counter.
- A reset pulse signal to the off-engine equipment if the message transmitted was the last message of that control iteration to reset the off-engine message identification counter to zero.
- A signal to the program memory instruction counter that advances the program count.

Out 14 - When an Out-14 instruction is received, the control unit generates 1) a command pulse signal to start an AD conversion, and 2) a command to advance the program memory instruction counter. The AD converter is a successive approximation type and requires $24\mu\text{s}$ to perform an AD conversion. Therefore, an Out-14 instruction will be inserted into the program far enough in advance of when the data are required to ensure that $24\mu\text{s}$ have lapsed before it is required in a given computation. At the completion of the AD conversion, the converter generates a signal to advance the input counter. The input counter outputs are decoded to select one of thirty-two outputs. The counter outputs are coded by the order in which they will be used in the control cycle.

Out 15 - This instruction is used at the end of each computer cycle to recycle the computer. When an Out-15 command is received from the instruction decoder, the control unit generates a signal to reset the input, output, and instruction counters to zero and the computer cycle begins again. This positive reset at the end of each cycle ensures that an occasional false trigger in the computer will not degrade the control system's overall performance.

INP 0 - The purpose of this instruction is to bring control inputs into the computer. This is accomplished in the following manner. After an AD conversion has been completed, the control parameter to be input to the computer is stored as a 12-bit binary number in an output register in the AD converter. The binary word is transmitted serially from the AD converter to the accumulator register through the use of a parallel serial converter via serial MUX No. 1. When an INP 0 instruction is received, the control unit generates the following signals to control the operation:

- A mode control signal (low level) to enable the accumulator to operate in the shift-right serial input mode.
- A strobe signal of the input serializer to enable the output.
- Four signals encoded to address the input serializer so as to cause the serializer output to be sequenced through its input one bit at a time to transfer the 12-bit number serially from the DA converter in the order of least significant bit first.
- An enable signal to establish the gating path from the input serializer to the accumulator.
- A twelve-pulse clock signal to the accumulator that lets the serial data be input from the multiplexer.
- An "advance the program memory" instruction countercommand signal.

INP 1 - The purpose of this instruction is to transfer data from the control room receiver shift register to the accumulator. When an INP 1 instruction is received the control unit generates the following signals to control the operation:

- Two enable signals to establish the gating path to the accumulator at serial MUX No. 1.
- A mode control signal (low level) to the accumulator to operate in the shift-right serial mode.
- A twelve-pulse clock signal to the control room receiver shift register and the accumulator, to transfer the information from the shift register to the accumulator.
- An advance in the program memory instruction countercommand signal.

LAI - The purpose of the LAI instruction is to bring numerical constants from the program memory into the accumulator for use in a computational process. As in the previous instruction, a parallel-to-serial data conversion is made using the memory serial converter to transfer the data in the accumulator via MUX No. 1. When the LAI instruction is received, the control unit generates the following signals:

- A mode control signal (low level) to enable the accumulator to operate in the shift register-serial input mode.
- Three signals encoded to address the program memory serial converter so as to cause the output to be sequenced through its inputs one bit at a time to transfer the 12-bit binary number serially from the program memory, least significant bit first.
- Enable signals to the serial MUX No. 1 that establish a transmission path from the memory serial converter to the accumulator.
- A twelve-pulse clock signal to the accumulator that lets the serial data be input from the multiplexer.
- An advance in the instruction counter signal to the program memory.

LMI - The purpose of the LMI instruction is to transfer a numerical constant from the program memory to the MQ register for use in a computational process. The process is the same as the LAI instruction. The data are transferred serially using the program memory serializer except that the data are routed into the MQ register instead of the accumulator, via serial MUX No. 2. The MQ register is a shift register with a shift-right or shift-left capability. When data are being transferred from program memory unit to the MQ register, zeros are loaded into the accumulator.

When an LMI instruction is received, the control unit generates the following signals that are applicable to this operation:

- An enable signal to serial MUX No. 2 that establishes the transmission path from the program memory serializer and the MQ register.
- A signal to the MQ register that places the register in the shift-right mode.
- A twelve-pulse clock signal to the MQ register that lets the serial data be input from the multiplexer.
- Three signals encoded to address the program memory serializer causing the serializer output to be sequenced through its inputs one bit at a time to transfer the 12-bit binary number serially from the program memory, least significant bit first.
- A signal to advance the program memory to the next instruction.

LDA - The purpose of this instruction is to transfer data from a specific scratch pad memory location to the accumulator. The specific location in the scratch pad memory from which the data are to be transferred is determined by the data portion of the program memory instruction word. This is a parallel data transfer using the arithmetic and logic unit (ALU) as a transmission link.

Upon receipt of the LDA instruction, the control unit sends five control signals to the ALU to set up the control mode that will enable the ALU that is to serve as a transmission link between the scratch pad memory and the accumulator. This control mode enables each of the 12 output lines of the ALU that are to be equal to the ALU "B" inputs only. In addition, the control unit generates the following signals that control the operation.

- A low-level signal to the accumulator that enables the parallel input mode of the accumulator.
- A signal to the scratch pad memory that enables the read mode of operation.
- A pulse signal to the accumulator that enters the data into the accumulator.

STO - The function of this instruction is to store a 12-bit number that is currently in the accumulator in the 256-word read/write scratch pad memory. The scratch pad memory work location at which the number is to be stored is selected by the program memory. The data portion of the program memory word is used to address the scratch pad memory and designate the scratch pad memory location. The transfer of data from the accumulator to the scratch pad memory is a parallel operation. When an STO instruction is received from the program memory, the control unit generates the following signals:

- A write command (low level) to the scratch pad memory, enabling the write mode of operation of the scratch pad memory.
- An advance in the instruction counter signal to the program memory.

ROT - The purpose of this instruction is to interchange the data in the accumulator and the MQ register so that at the end of the operation the number once contained in the accumulator will be in the MQ register and vice versa. To accomplish this, data paths are established between the serial outputs and inputs of the accumulator and MQ register. The accumulator and MQ register are placed in the serial right-shift mode of operation and the data are transferred by 12-pulse clock input.

When the ROT instruction is received, the control unit generates the following signals to control the operation:

- An enable signal that establishes the data transmission path between the serial output of the accumulator and the serial input of the MQ register via serial MUX No. 2.
- An enable signal that establishes the data transmission between the serial output of the MQ register and the serial input of the accumulator via serial MUX No. 1.

- Twelve-pulse clock signal to the accumulator and MQ register to shift the data on both of them one bit to the right for each clock pulse.
- An advance-the-counter signal to the program memory.

RSHM - The purpose of this instruction is to shift the data in the accumulator and MQ register one bit to the right. Execution of this instruction will cause the least significant bit in the accumulator to be shifted to the most significant bit location in the MQ register, the least significant bit in the MQ register to be lost, and a zero to be put into the most significant bit of the accumulator. When the RSHM instruction is received, the control unit generates the following signals to control the operation:

- A signal to the accumulator that enables the right-shift serial mode of operation of the accumulator.
- A signal to the MQ register that enables the right-shift serial mode of operation of the register.
- A transfer pulse to the accumulator and MQ register that transfers the data in both one bit to the right.
- An instruction counter advance signal to the program memory to start the next instruction.

RSH - This instruction is the same as RSHM except that it causes the most significant bit to be repeated in the accumulator in order to preserve the sign of the number. Control signals are also the same as with RSHM except that there is a signal to shift the most significant bit in the MQ register back to the accumulator.

LSH - The purpose of this instruction is to shift data in the accumulator and the four most significant bits in the MQ register one bit to the left. Execution of this instruction will result in the most significant bit in the MQ register being transferred to the least significant location in the accumulator and the most significant bit in the accumulator to be lost. The left shift is accomplished in the following manner. External wiring on the four most significant bits of the MQ register permits MQ register left-shift operation. The accumulator left-shift operation is achieved by operating in the parallel load mode and employing the arithmetic and logic unit in the $F = A+A$ mode. To obtain a left shift of the most significant bit in the MQ register to the least significant bit in the accumulator, a data path is established to carry the (CN) input of the ALU.

The control unit generates the following signals upon receipt of the LSH instruction.

- A high-level signal to the MQ register to enable the shift-left mode of operation.

- A low-level signal to the accumulator enabling the parallel load mode of operation.
- Five signals to the ALU establishing the $F = A+A$ of operation.
- A high-level signal to establish data path from MQ register to ALU through serial MUX No. 1.
- A clock pulse signal to the accumulator to transfer ALU outputs to the accumulator (left shift).
- A clock pulse signal to the MQ register to left-shift data in the MQ register.
- A signal to the instruction counter to advance to the next instruction.

ADD -- The purpose of this instruction is to add a number stored in the scratch pad memory to a number stored in the accumulator using the ALU. The sum will be entered in the accumulator when the instruction is complete.

Add instructions are accomplished in the following manner. The data portion of the program memory word for this instruction is used to address the scratch pad memory location is then placed in the read mode and the number is presented at the "B" inputs of the ALU. The other number contained in the accumulator is present at the "A" inputs of the ALU. The CN output will be set to indicate no carry. The ALU control inputs will be set to place the ALU in the ADD mode, $F = A+B$, whereupon the sum will then be gated into the accumulator, replacing the "A" number.

When an ADD instruction is received, the control unit generates the following signals to control the operation.

- A high-level signal to the scratch pad memory enabling the read mode of operation.
- Five control mode signals to the ALU enabling the add mode of operation.
- A signal to the ALU carry input indicating zero carry input into this add function.
- A signal to the accumulator placing the accumulator in the parallel load mode of operation.
- A clock pulse signal to the accumulator that enters the sum from the ALU.
- A signal to the program memory to advance to the next instruction.

ADDC - The ADDC instruction is executed in the same manner as the ADD instruction. It is used to transfer a carry bit if one is generated in double-precision addition. Double-precision numbers (24 bits) are generated as a result of multiplications. To increase computational accuracy, it is sometimes necessary to add or subtract double-precision numbers. Addition of double-precision numbers is a two-step operation because the ALU can only accommodate 12-bit numbers at one time. The 12 least significant bits are added first. If a carry is generated from this addition at the carry output of ALU, it will be stored in a flip-flop in the control unit and will be added at the CN input of the ALU during the next instruction when the most significant bits are added. The only change in the control unit's functions, as shown in the AD instructions, is that ALU carry input may be high or low depending on the last carry to come out of the ALU.

SUB - The purpose of this instruction is to subtract a number stored in the scratch pad memory from a number in the accumulator. This instruction is accomplished in the same manner as the ADD instruction except that the ALU is placed in the subtract mode, $F = A - B - 1$, and the CN input of the ALU set to add a "one" to the result.

SUBC - This instruction is analogous to the ADDC instruction except that an overflow at the ALU carry output at the end of a subtraction now represents a "borrow" instead of a "carry".

MPYM - The purpose of this instruction is to multiply an unsigned number stored in the scratch pad memory by an unsigned number stored in the MQ register. At the end of this operation, a 24-bit product will be contained in the accumulator and MQ register combination.

The method of multiplying is as follows: The multiplicand, which is contained in scratch pad memory, is addressed by the data bits of the MPYM instruction and is present at the "B" inputs to ALU. At the start of multiplication, zero's are stored in the accumulator. Binary multiplication is accomplished through cumulative addition, with a running total contained in the accumulator MQ register.

If the number stored in the least significant bit location in the MQ register is one, the number stored in both the accumulator and the MQ register is shifted one bit to the right. A zero will be shifted into the most significant location of the accumulator except if the sum of the accumulated total in the accumulator and the number stored in the scratch pad memory is greater than one. In this case, a one is generated at the ALU carry and is stored in the overflow flip-flop in the control unit. If the overflow flip-flop indicates a one, a one will serially input to the most significant bit of the accumulator during the shift-right operation.

If the number at the least significant bit of the MQ register is zero, then the addition does not take place and the numbers in the accumulator and MQ registers are right-shifted only. After 12 add-shift operations, the product, a 24-bit number, will be contained in the combination accumulator/MQ register with the 12 most significant bits in the accumulator.

In order to perform the add-shift operation, the accumulator is placed first in the parallel mode of operation to add and then the serial mode of operation to right shift.

The control unit generates the following signals to control the operation:

- An accumulator mode control signal to add or shift. This signal is $12\mu\text{s}$ long and is 180° out of phase with IMC timing signal.
- A signal to establish the shift-right transmission path between the accumulator and the MQ register.
- A 12-pulse shift-right signal to the accumulator.
- An add signal to the accumulator each time the least significant bit in the MQ register is one. This signal is synchronized with the timing signal delayed by 0.5 seconds from the right-shift operation.
- A zero to the CN input of ALU.
- Five control signal inputs to the ALU to set up the ADD, $F = A+B$ mode of operation.
- A signal to the scratch pad memory to enable the read mode of operation.
- A signal to the overflow flip-flop unit to zero output prior to each ADD in the ALU.
- A clock signal that sets a one in the overflow flip-flop if the ALU generates a carryout signal during the last add.
- A signal to the serial input of the accumulator when the overflow flip-flop output is one.

MPY - The purpose of this instruction is to multiply signed numbers. The manner in which this is accomplished is exactly the same as the MPYM instruction except for the following: For negative multiplicands (the number stored in the scratch pad memory), a one will be serially input to the accumulator whenever the most significant bit of the partial product in the accumulator and the most significant bit of the scratch pad memory are one.

DIV - The purpose of this instruction is to divide the signed, combined contents of the accumulator and MQ register by a number stored in the scratch pad memory. The DIV instruction is an accumulative subtraction.

shift-left operation that is performed in a manner similar to that of the multiplication instruction. The result is in the MQ register with a invalid remainder in the accumulator. The division is integer. Negative results are in one's complement - except even division, which is in two's complement.

BRMA XXXX - The purpose of this instruction is to perform branching capability in the program when a BRMA (Branch on Minus Absolute) instruction is received. If the result of the last subtraction was negative, the program memory counter will be jumped to the address indicated by the data bits associated with BRM instruction denoted by XXXX. If the result of the last subtraction was positive, the program counter is simply incremented by one to the next instruction. The branching capability utilizes a timing signal delayed by 50% of the duty cycle of the normal clocking. When a BRM signal is received an "advance the counter" signal is generated by the control in time with the delayed signal if the result of the last subtraction was positive. Last subtraction resultant polarity was determined by a flip-flop in the control unit which monitors the carry out of the Arithmetic Logic Unit being set at the last subtraction instruction. If, however, the result of the last subtraction was negative the control unit generates the following signals to implement the branching in time with the normal clock.

A control mode signal to place the program memory counter in the parallel load mode, and an enable signal that loads the data bit information to jump the memory address to that required.

BRMR XXXX - An instruction included for programming convenience, (BRMR = Branch on Minus Relative) executed as BRMA.

JMP XXXX - The purpose of the jump instruction is to provide unconditional branching in the program address. It is executed identically to the BRM instruction, in which the result of the last subtraction was negative.

6.2.4 Input-Output Section

The input-output section of the digital control contains the signal condition circuits for inputs plus distribution circuits for outputs, and provides an interface with the central processor in an acceptable digital format. All data transfers to and from the central processor take place under the command of signals received from the control unit of the central processor.

Referring to Figure 52, the signal flow in the digital control is as follows: The instrumentation and sensor input signals are fed to an analog multiplexer circuit that is controlled by the central processor control unit. The input counter provides an address to the input decoder from which a single input signal is selected. The inputs are selected in a fixed order by increasing the count by one at the end of an analog-to-digital conversion. At the end of each control iteration cycle the counter is reset to zero.

The sample-and-hold output is connected to the analog-to-digital (AD) converter. The AD converter changes the analog signal to a 12-bit digital word representing the analog signal. The 12-bit digital word is fed to the digital computer circuit via a serial digital multiplexer No. 1. Other signals into the digital multiplexer provide communication between the digital control and remote units located in the control room. The 12-bit word from the AD converter is operated according to the program instructions stored in the digital computer program memory.

Upon completion of this portion of the program, the central processor feeds the result of the computation to a digital-to-analog (DA) converter circuit and a data multiplexer circuit. The data multiplexer provides another communication link between the digital control and the control room. The DA converter signal goes to the analog output circuits, which consist of flip-flops, sample and hold circuits, torque motor amplifiers, and driver circuits.

6.2.5 Other Circuits

Other circuits in the digital control include 1) a power supply that provides the necessary regulated voltages for the control, and 2) circuits which provide transducer excitation. There is also an emergency shutdown circuit that cuts back fuel flow if the low-pressure turbine (LPT) acceleration rate is excessive or the LPT speed exceeds a given limit.

Figure 54 is an example of an analog signal conditioning circuit showing a pressure amplifier circuit, a typical analog circuit used in the digital control. The input to the amplifier is the output from a strain gauge bridge transducer. The excitation for the transducer is provided by the +15 volt power supply in the digital control. IC1 is used as a differential amplifier to provide some preamplification of the pressure signal. Resistors R13 through R19 comprise a temperature compensation network used to compensate offset and offset-drift over the temperature range. The output of IC1 goes to R7, the input resistor of IC2. IC2 is the second stage of the amplifier and sets the desired overall gain of the amplifier by selecting resistor R9, R10, and R11.

Another digital network, which deserves mention here because it is part of a new development being applied to the QCSEE, is the driver amplifier used to operate the fail-fixed servovalve described in Section 7.3. This is a unique application of digital technology in that it drives a hydraulic output power device without the need for digital-to-analog conversion.

As shown in Figure 55, a 12-bit word is generated and held by the processor as a function of the flow demand. The least significant bit (LSB) is ignored to generate an 11-bit signal, "B". Simultaneously, the 2.048-MHz clock signal and the 4-bit series counters generate a continuously changing 12-bit word. The most significant bit (MSB) is excluded to create 11-bit word "A" that periodically counts from 0 to 2,047. Signals A and B are compared by the three series 4-bit comparators to generate an output signal when $B > A$. The MSB (2^{12}) from the clock counter, through an inverter, and the next most significant bit (2^{11}) are fed to an AND gate to generate the 25% "on" signal; that is, a signal that pulses on for 25% of the time of each count cycle from 0 to 4,097.

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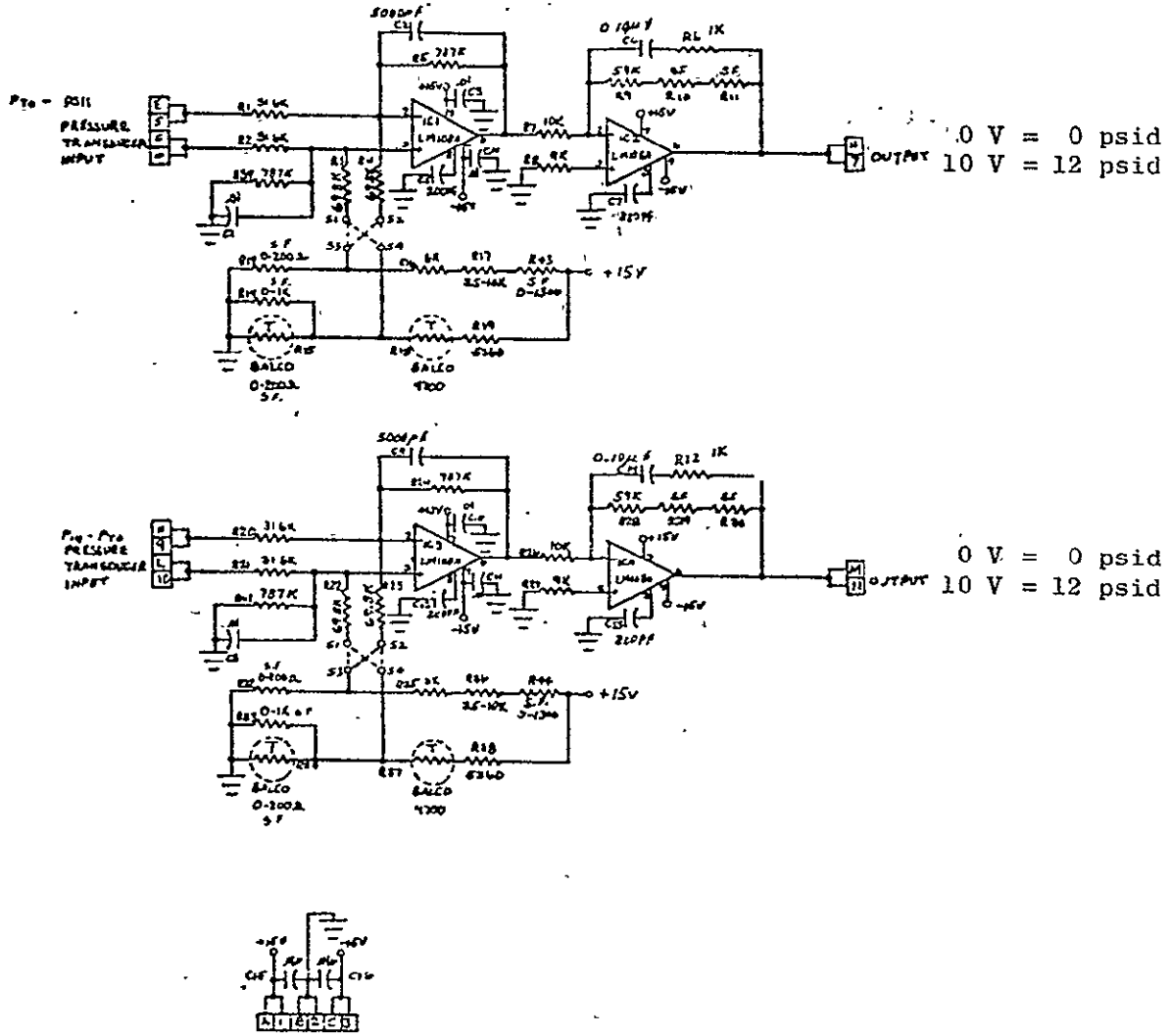


Figure 54. Typical Analog Circuit.

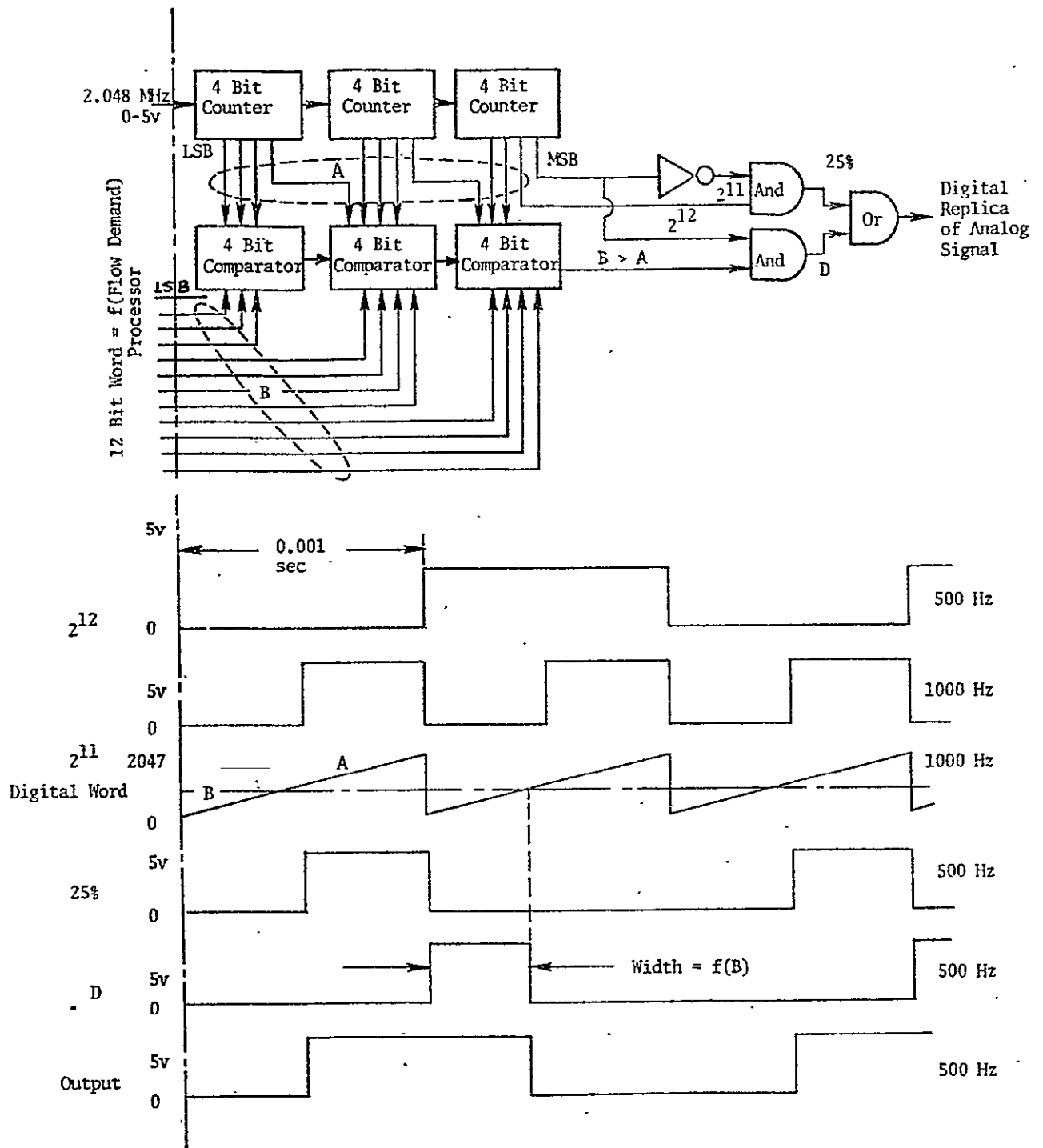


Figure 55. Digital Driver Amplifier for Fail-Fixed Servovalve.

The MSB (2^{12}) signal from the counter circuit and the $B > A$ signal from the comparator circuit are coupled through an AND gate to generate signal "D". As shown in Figure 55, the width of signal "D" is a function of "B", varying from 0% to 50% on time. The 25% signal and the "D" signal are logically summed through an OR gate to generate an output signal that is the replica of an analog signal of the flow demand. This signal is then treated by a conventional torque motor current amplifier stage to drive the servo-valve with a -80 mA to +80 mA, 500 Hz signal, whose "on" time varies from 25% to 75% as a function of the digital flow word.

6.2.6 Circuit Components

Circuit components used in the digital control were selected primarily on the basis of their ability to maintain the desired circuit accuracy under the stringent environmental conditions imposed upon them. Other considerations were cost, weight, power consumption, and availability. In order to achieve a state-of-the-art design, new components were investigated and were used where possible. The major components are described below:

Low-Power Schottky TTL - Digital components used are primarily low-power Schottky TTL devices. These devices presently offer the best speed-power product of any high-speed family. Table XII shows a comparison of the TTL circuits. The low-power Schottky family (54LS/74LS) features both Schottky-barrier-diode inputs and emitter inputs. Full Schottky-barrier-diode clamping is utilized to achieve speeds comparable to series 54/74 TTL at one-fifth the power. The Schottky-barrier-diode is connected in parallel with the base collector junction of the normal TTL transistor. Schottky-barrier-diodes have a lower forward voltage than the base collector junction and it clamps the transistor as base drive increases. Most of the excess base current is diverted and this prevents the transistor from reaching classic saturation. This effectively eliminates charge storage and subsequent recovery times.

Digital Memory Devices - Two other new integrated circuit devices are used in the computer section of the digital control. These are the 5340 programmable read-only memory (PROM) and the L5531D read/write random access memory (RAM). A description of each follows:

- The 5340 PROM is a 4096-bit memory arranged as 512 eight-bit words. The PROM contains logic circuits, decoders, buffers, and data storage circuits. The device is manufactured with all outputs high in all storage locations. Device programming is accomplished by making an output low for a particular word. To do this a Nichrome fusible link is changed from a low resistance to a high resistance. The outputs are programmed one at a time by applying the appropriate TTL levels to the enable and applying a voltage pulse to the output that is to be programmed. The voltage source must supply sufficient current to complete programming of the output. Since pulse techniques are used to program the PROM and these techniques involve the use of the enable inputs and the output pins, the timing is critical and the pulses must occur as described by the device.

Table XII. 54/74 Family Typical Performance Characteristics (TTL).

Series	GATES		
	Propagation Delay Time	Power Dissipation	Speed-Power Product
54LS/74LS	9.5 ns	2 mW	19 pJ
54L/74L	33.0 ns	1 mW	33 pJ
54S/74S	3.0 ns	19 mW	57 pJ
54/74	10.0 ns	10 mW	100 pJ
54H/74H	6.0 ns	22 mW	132 pJ

specification sheet. Programming equipment is available to simplify the procedure. Several PROMS can be connected to a common output bus. Since the outputs are the open collector-type, pullup resistors must be used. The value of the resistor is determined in part by the number of PROMS used and the number of TTL loads the memory must drive. Sixteen PROMS are used in the digital control and are connected to form a 4096-by-16-bit word memory. The digital control program is stored in this memory and contains the instructions for the computations and data manipulations of the digital control.

- The L5531D RAM is a 256-bit memory device arranged in a 256-by-1 array. That is, there are 256 memory locations, each containing one bit of information. The RAM circuit chip contains logic circuits, decoders, buffers, and a memory array. The L5531D is a three-state device and is so called because the output has the high and low TTL states and third high impedance state. This third high impedance state allows the outputs of several L5531D's to be connected to a common bus. The memory is addressed using an 8-bit address word to select one of the 256-bit locations. With the write enable low, the data on the input pin of the RAM are written in the selected memory location. If the write enable is high and the RAM is enabled, the stored data are read out on the data-out pin. The data read-out is the complement of the data written into the memory location during the write cycle. The data will be retained in the selected memory location until new data are written in or the power is removed from the RAM. There are twelve L5531D's used in the digital control to form a 256-word memory with each word 12-bits long. These RAM's form the scratch pad memory of the computer and are used for temporary storage during computations and data manipulations.

Other New Components - Another device used is the Hewlett-Packard 5082-4365 optically coupled isolator. This is used as an interface component between the digital control and other circuitry where electrical isolation is desirable. The 4365 consists of a pair of inverting optically-isolated gates each with a light-emitting diode and high-gain integrated photo detector. The output of the detector is an open collector Schottky clamped transistor. The input and output are TTL compatible.

Other new components used in the digital control consist of sample and hold circuits, a voltage follower, and power op-amps, all of which are standard op-amp-type circuits. They were selected because of improved characteristics (temperature drift, speed, etc.) over previously used components of the same type.

6.3 ELECTRICAL CIRCUIT CONSTRUCTION

6.3.1 General Description

In the QCSEE digital control, the signal processing and control are accomplished with a collection of interconnected electrical assemblies called modules. A module is a functional assembly of electronic components specifically designed to perform a precise sequence of desirable operations on one or more specified electrical inputs.

In general, modules constructed to meet on-engine environmental requirements consist of electrical components whose leads are soldered into printed circuit board (PCB) assemblies. The PCB provides the necessary electrical connections between components. These PCB assemblies are installed into an anodized aluminum module can with 0.81-cm (0.032-in.)-thick walls and encapsulated with filled, resilient potting compounds. The primary advantages of the potting compounds are: (1) they damp vibrate and protect against moisture; (2) they improve steady-state and transient module thermal characteristics; and (3) they protect the circuitry from contaminants.

QCSEE digital control modules are of three basic types:

- (1) Analog modules
- (2) Digital modules
- (3) Combination analog/digital modules

Each of the above designs is directed toward the packaging of a specific type or set of components. The analog module handles standard electrical components such as operational amplifiers, transistors, diodes, transformers, resistors, capacitors, and so on. The digital module is specifically designed to handle digital components in dual-inline package form. The analog/digital module is a necessary design compromise used where a separation of the analog and digital circuitry is not functionally possible due to electrical requirements.

All of the module design approaches described below have been utilized on one or more successful engine programs. They are considered more than adequate to meet the QCSEE digital control design requirements.

6.3.2 Analog Module Design

An analog module consists of electrical analog components mounted to printed circuit boards (PCB's). A typical analog module requires two PCB's. All QCSEE analog PCB's utilizes a 2 oz., double-sided copper, 0.079-cm (0.031-in.)-thick polyimide boards bonded to an anodized heat sink made from aluminum sheet. The anodized aluminum heat sink is located between the bodies of the electrical components and the PCB component side surface and

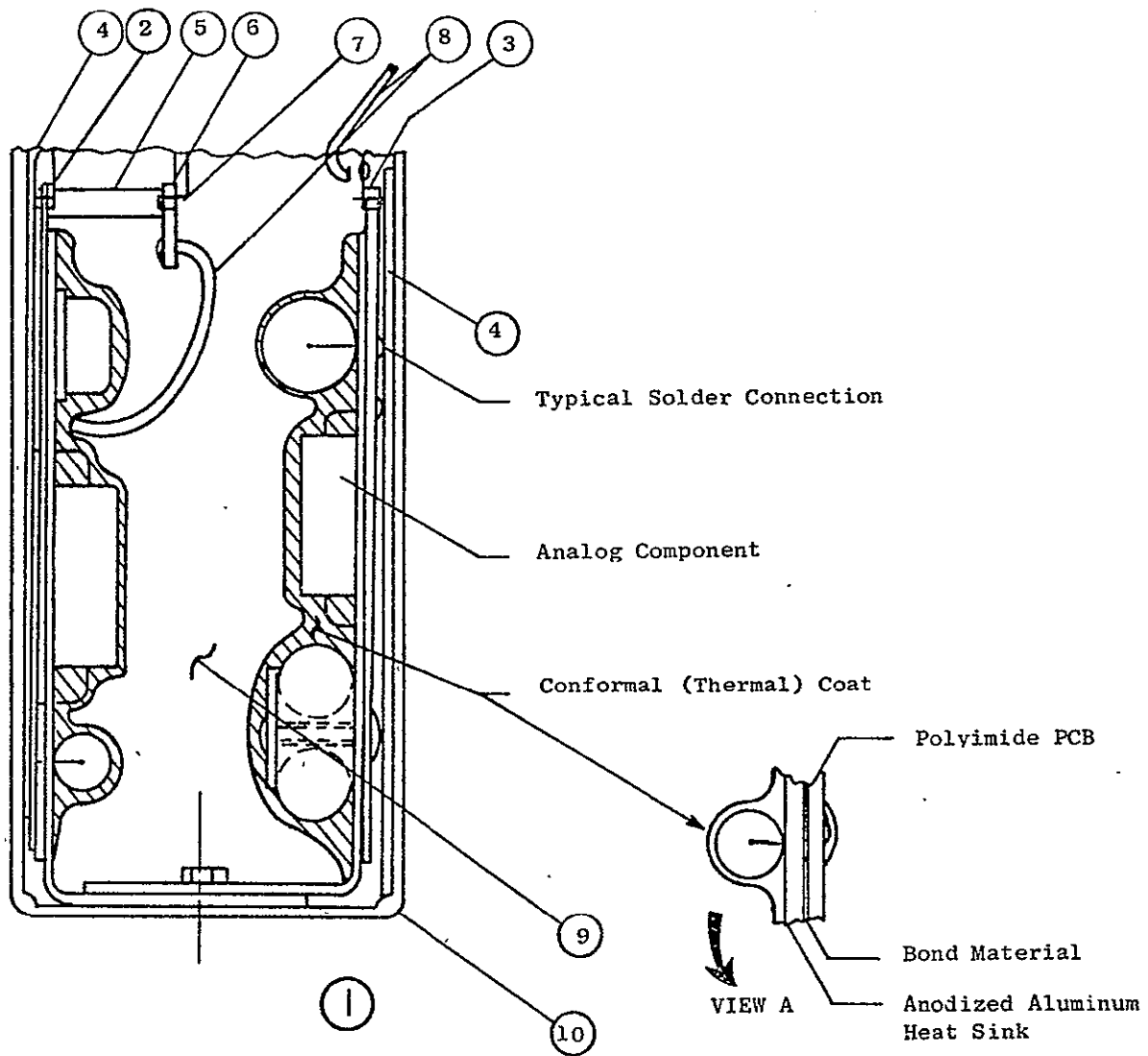
provides, via a nonanodized aluminum mounting flange, a low-thermal-resistance path to the module's mounting surface (see Figure 56). The incorporation of the relatively-low-thermal-resistance path permits the use of a lower density (lower thermal conductivity) potting compound which results in an overall weight reduction. The microsphere-filled RTV potting being used has a specific gravity of 0.7 compared to a specific gravity of 1.5 for the alumina-filled RTV potting compound normally used to thermally compensate module configurations not utilizing an anodized aluminum heat sink. Generally, these two module configurations are thermally equivalent and for most typical analog modules yield component-to-mounting-surface hot-spot temperature differences of less than 25° F. Components having hot-spot temperature differences greater than this are provided with additional heat-sinking capability to achieve the-less-than 25° F differential goal.

6.3.3 Digital Module Design

A digital module consists of digital electronic components mounted to automatically wire-wrappable digital boards. A typical digital module requires two wire-wrap boards. All QCSEE digital boards utilize 4-oz. copper for power and ground planes and are made from double-sided 0.127-cm (0.050-in.)-thick glass-epoxy PCB stock. The electrical connections required by the circuit being packaged are made with socket pins for digital component leads and Kapton insulated wire routed from pin to pin (see Figure 57). To reduce electrical noise and improve circuit reliability during operation, all electrical interfaces are soldered prior to final test and encapsulation. A typical digital module may have as many as 8 to 10 times more internal board-to-board common connections than a typical analog module. A special flexible interconnection circuit (see Figure 57) is designed to handle the relatively large number of common connection inherent in a digital module. The flexible connector carries common signals and is routed around either end of the digital board. All flexible connector electrical interfaces are soldered in place prior to final test and encapsulation. Digital board assemblies are bracket-mounted to the base of the module can and the final module assembly is encapsulated in an alumina-filled potting compound. This compound is used in all digital and analog/digital modules to thermally compensate for the lack of an integral heat sink similar to the anodized aluminum heat sink utilized for analog PCB's. As in the case of analog modules, component-to-mounting-surface hot-spot temperature differences are held to less than 25° F with additional heat sinking capability added if necessary to achieve this goal.

6.3.4 Analog/Digital Module Design

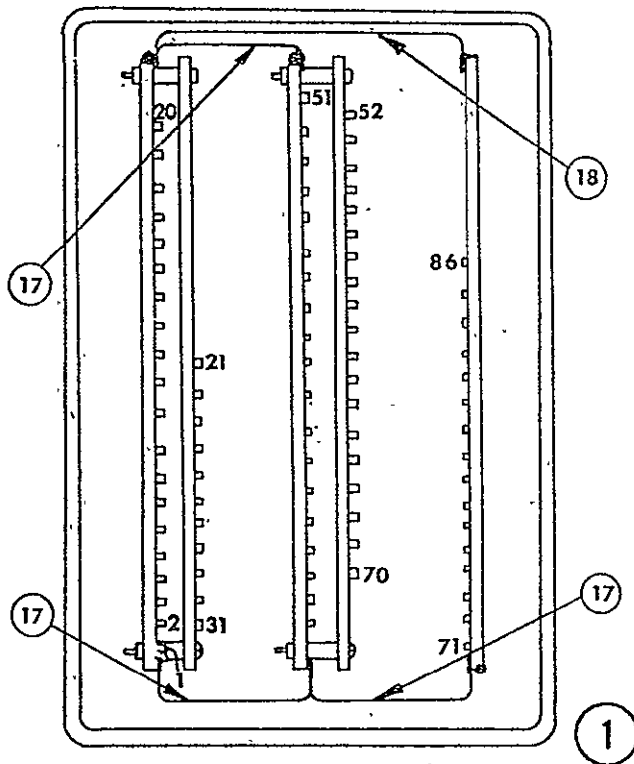
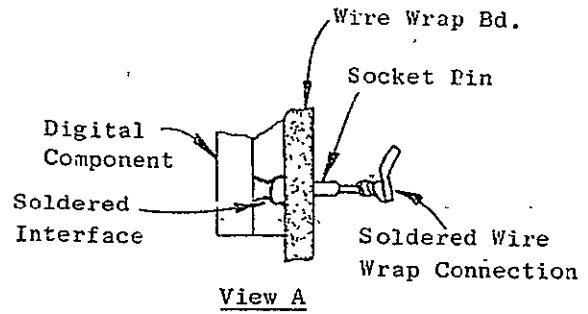
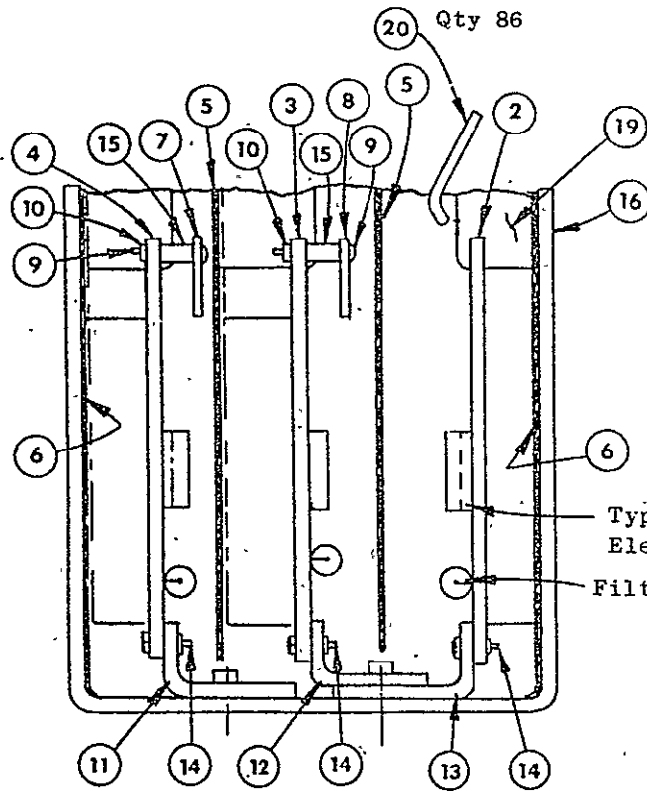
An analog/digital module consists of one analog based coupled with one digital board. As in the digital module case the large number of board-to-board connections are made via a specially designed analog/digital board flexible connector and; as before, are soldered in place prior to final test and encapsulation. The final module assembly is encapsulated in an alumina-filled potting compound and subjected to the same component-to-mounting-surface hot-spot temperature evaluation as described for both the analog and digital modules.



- Item.
- 1----- Typical Module Assembly
 - 2----- Printed Wiring Bd. Assy.
 - 3----- Printed Wiring Bd. Assy.
 - 4----- Insulator (Electrical)
 - 5----- Satellite Bd. Spacer
 - 6----- Satellite Bd.
 - 7----- Satellite Bd. Mounting Screw
 - 8----- 24 AWG. Hookup Wire
 - 9----- Lightweight Potting Compound
 - 10----- Module Can

Figure 56. Typical Analog Module.

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Item	Description
1	Module Assembly
2	Digital Bd. EC877
3	Digital Bd. EC878
4	Digital Bd. EC879
5	Insulator
6	Insulator
7	Satellite Bd.
8	Satellite Bd.
9	Satellite Bd. Mounting Screw
10	Satellite Bd. Mounting Nut
11	Mounting Bracket
12	Mounting Bracket
13	Mounting Bracket
14	Mounting Bracket Screw
15	Satellite Bd. Spacer
16	Module Can
17	Flexible Connector
18	Flexible Connector
19	Potting Compound
20	Hookup Wire

Figure 57. Typical Digital Module.

6.4 DIGITAL CONTROL PRODUCT DESIGN

This section describes the manner in which the digital control circuit modules and other internal elements are mounted and enclosed to provide a unit suitable for engine-mounting and a means for connection of external inputs and outputs.

6.4.1 Installation

Figure 58 is a sketch showing the digital control and the manner in which it is mounted on the engine.

The control is basically a rectangular box with a raised section which incorporates the provisions for external electrical and pressure-sensing connections. The approximate dimensions are 33.0 x 38.1 x 12.7 cm (13 x 15 x 5 in.) - length, height, and thickness as installed - with 5.08 cm (2.0 in.) additional thickness at the raised section. (It should be noted that for this experimental control, excess space has been included for possible future experimental use.)

Flanges are provided on the front and back surface of the control for mounting to two triangular brackets which in turn mount to pads on the engine fan frame. Four pads are provided, two for each triangular bracket.

A handle on top of the control is provided for carrying, installing, and removing the control. Resting tabs on the mounting surfaces help steady and support the weight of the control during installation or removal of mounting screws.

6.4.2 Vibration Consideration

Early in the control packaging design process a vibration study was performed assuming a 10-g vibratory input at the unit's calculated center of gravity, well above that expected on the engine (see Figure 59). The analysis identified weakness at several points in the initial design and changes were made to correct these weaknesses. The resulting design is anticipated to be satisfactory from a vibration standpoint.

To prove the vibratory capability of the unit, a chassis vibration test was performed over the spectrum shown on Figure 59 which is based on dynamic analyses performed on the complete engine.

6.4.3 Internal Construction

Choosing the internal construction details of the digital control primarily involved deciding how best to arrange and mount the electrical circuit modules. The primary factors considered were: (1) module dimensions, (2) heat dissipation, (3) intermodular connections, and (4) module connections to control inputs and outputs.

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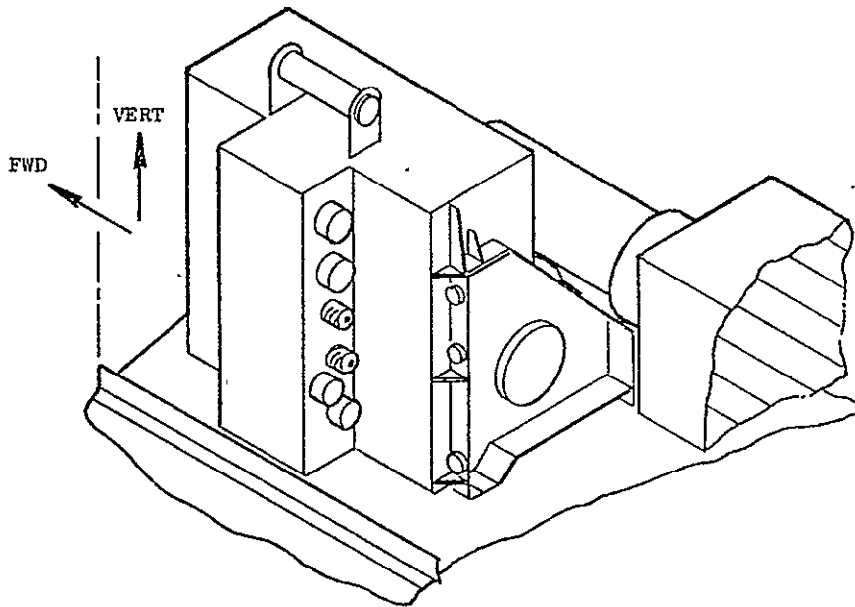
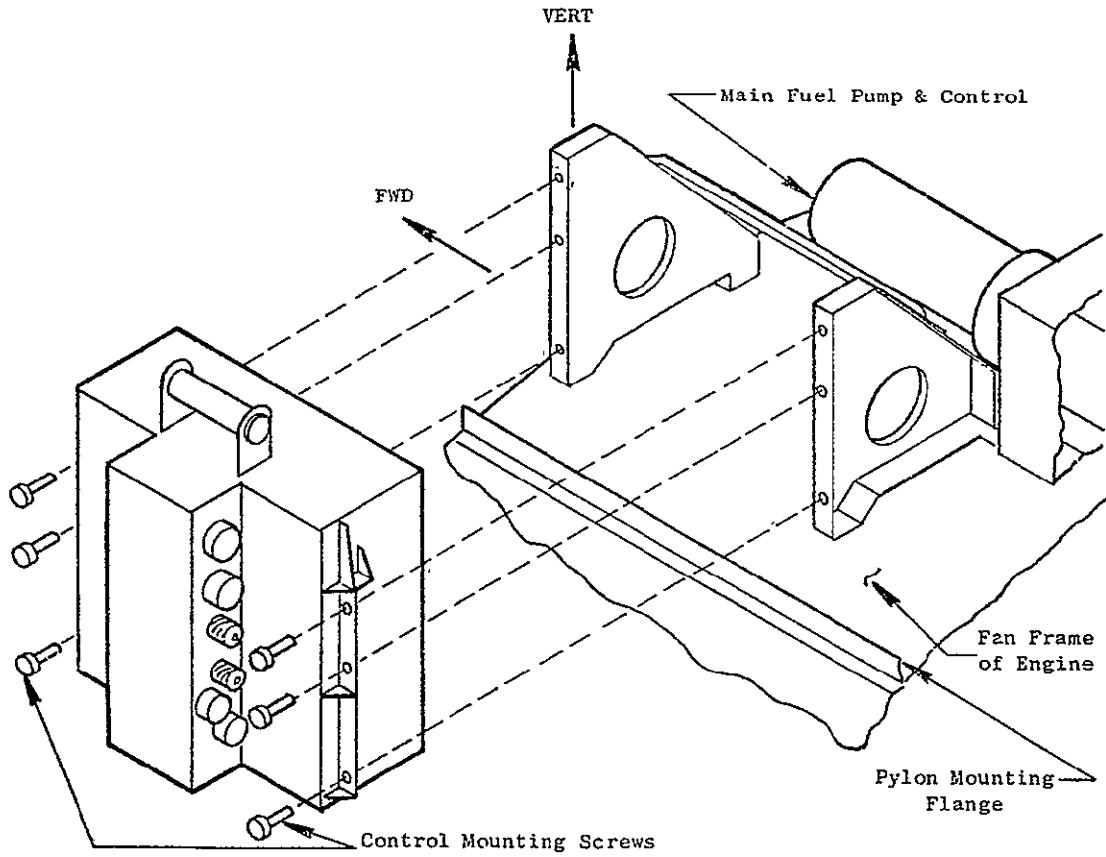


Figure 58. Digital Control Installation.

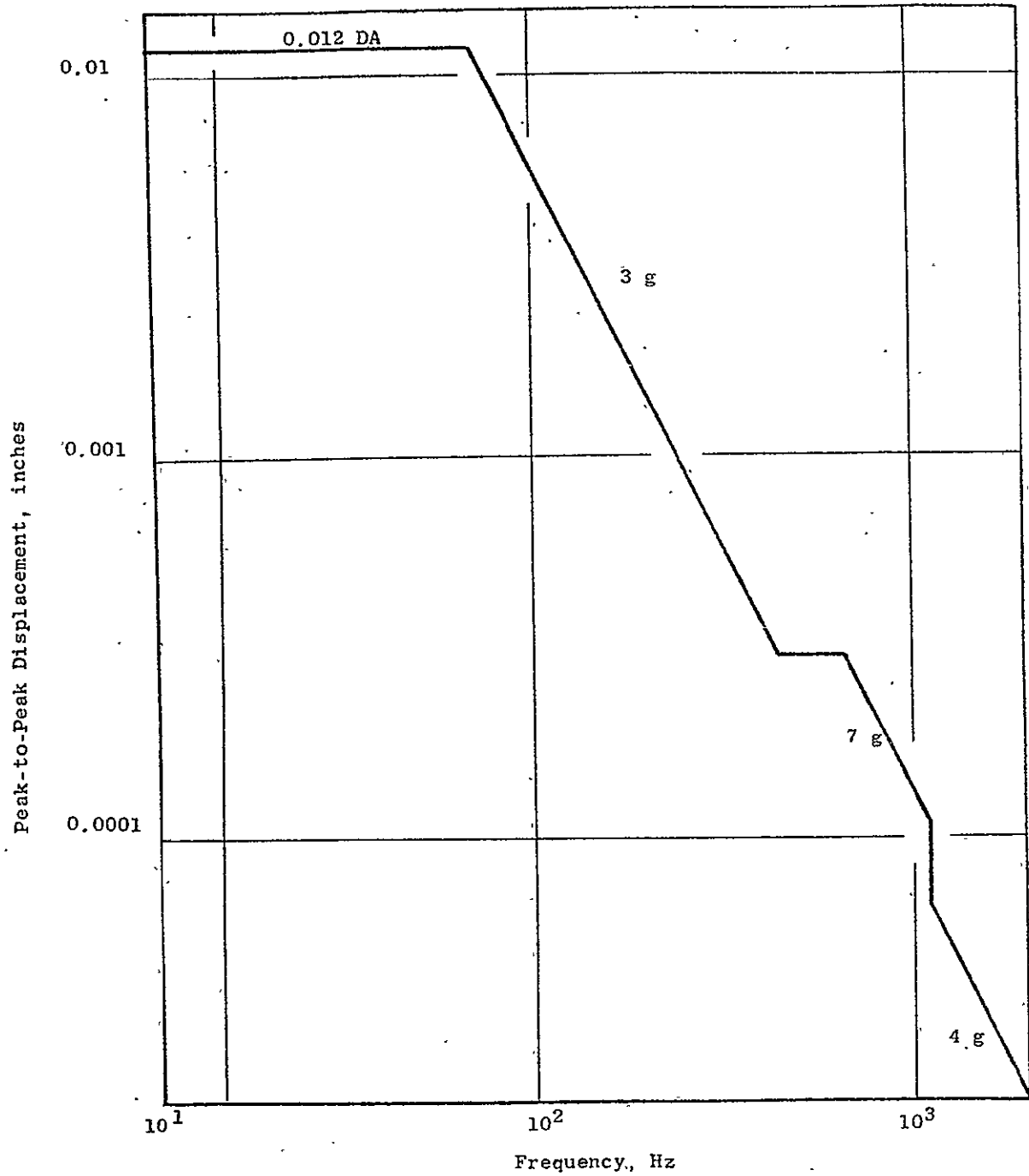


Figure 59. Vibration Testing.

The arrangement finally chosen is shown in Figure 60, which is a view looking toward the side opposite the connector side with a cover removed. As noted previously, ample excess space has been provided for the addition of possible future experimental circuits.

The modules are bolted to aluminum plates which are part of the chassis and which serve to carry away heat as explained in more detail later. U-shaped channels between the rows of modules at their upper end furnish further support and also serve as channels for interconnecting wiring. Wires between modules are attached to pins at each module, routed through the appropriate channels, and tacked down with a clear silicon adhesive which provides waterproofing and reduces the chances of handling and/or vibration damage. Wires to external connections are passed through slots in the two channels and routed to the external connectors, input pressure transducers, or electrical input filters where they are connected. These wire bundles are coated with clear RTV.

6.4.4 Cooling

Approximately 100 watts of heat are generated by operation of the modules in the digital control. This heat is dissipated by conduction and convection utilizing air from outside the engine nacelle.

As noted earlier in the module design section, the heat generated by elements within each module flows through the thermally conductive potting compound and anodized aluminum heat sink in the module till it reaches the mounting surface (see Figure 57). From here the heat is conducted through the bolted module mounting surface into the aluminum mounting plate, its transfer aided by a thermal grease applied at their interface. Finally, the heat is conducted through the mounting plates and carried away by air passing over the plates on the side opposite the modules.

The air-cooling flowpath is shown in Figure 61. Air enters at the top (as mounted on the engine) and divides into three parallel ducts under the top rows of modules. The air from these ducts is collected, passed back across the lower portion of the module mounting surfaces, and discharged near the bottom of the control. Use is made of machined fins in parts of the cooling flowpath to get maximum heat transfer.

The air-cooling system is designed for an installed engine. An air scoop outside the nacelle serves as an inlet; a hole in the engine inlet duct flush with the duct wall serves as an exit. The pressure differential resulting from the lowered static pressure that will exist in the inlet duct during all forward operation will produce a flow sufficient to meet the design objective of having no elements in the control more than 43° F hotter than the cooling air supplied.

If any installation conditions are encountered during the experimental engine test program that are unusual enough to prevent the normal cooling air differential pressure, a pressurized air source will be used to cool the control.

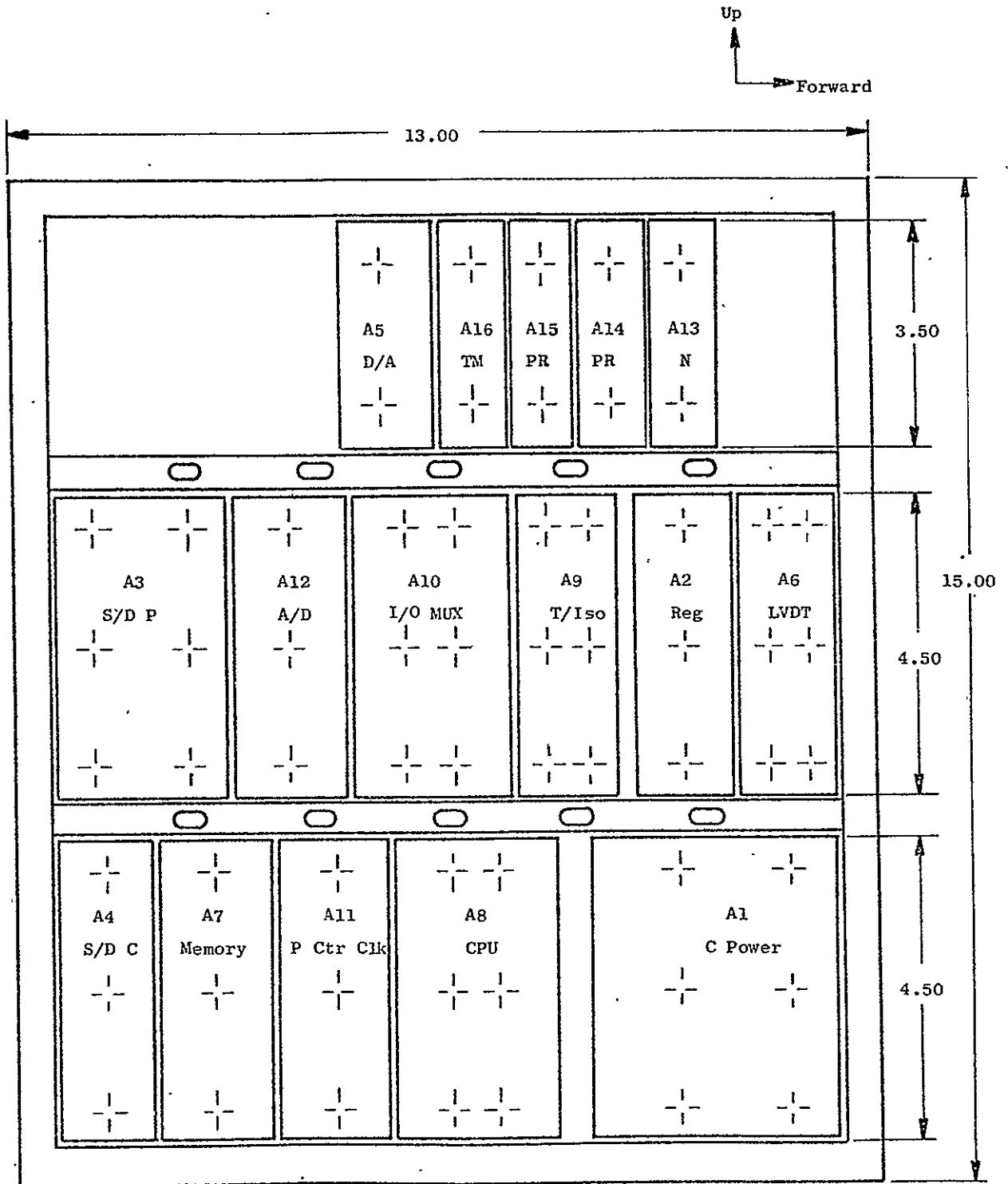
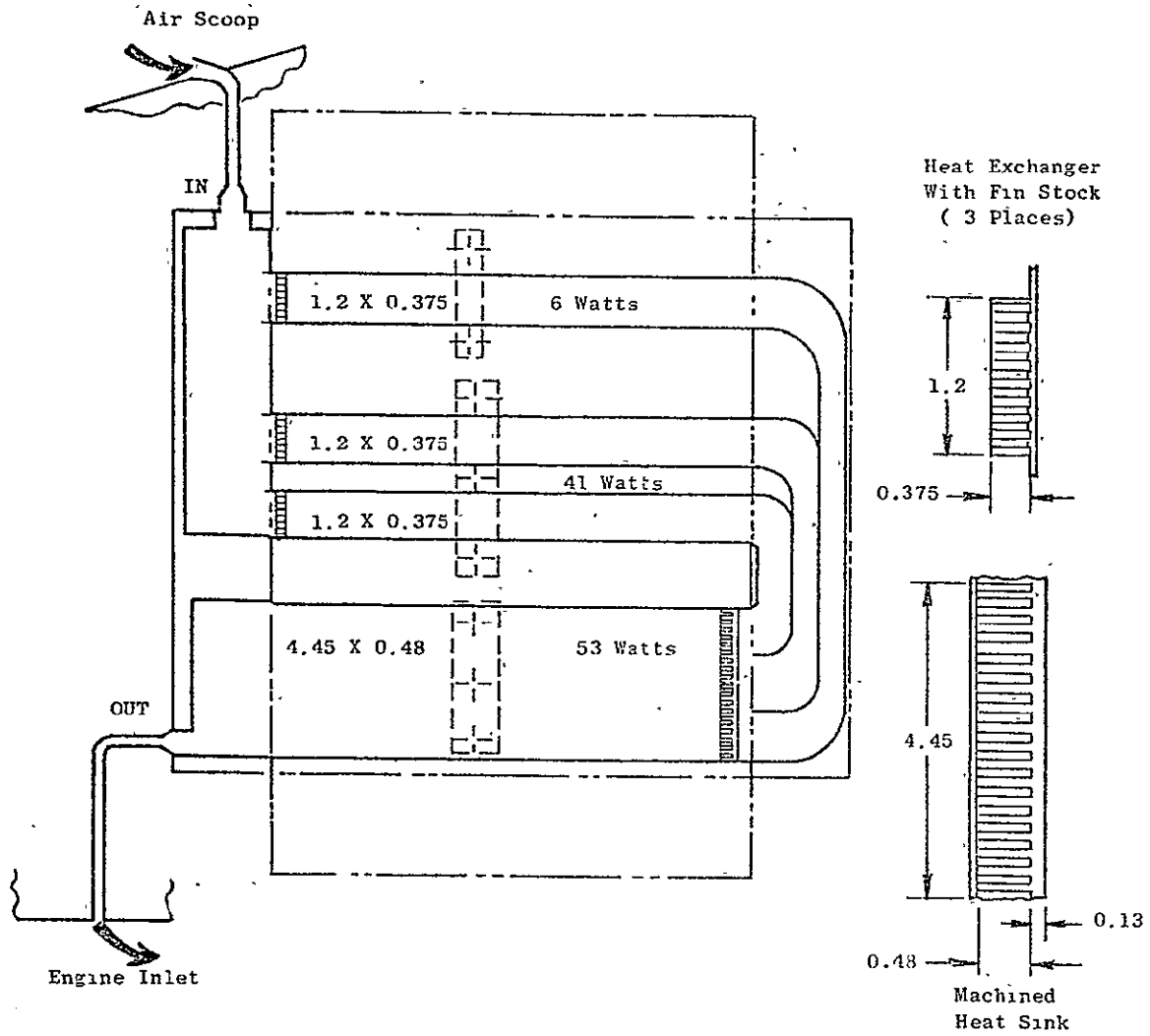


Figure 60. Module Arrangement Digital Control.

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Minimum Pressure Drop.....0.288 psid
 Minimum Flow Rate.....0.026 lbm/sec
 Estimated Maximum ΔT43° F

Figure 61. Cooling Air Flow Path.

6.5 SOFTWARE DESIGN

The computational section of the digital control described in the previous paragraphs is a special-purpose, stored-program, single-address computer. Through appropriate electrical circuitry the central processor receives and processes input information to form the required outputs according to the instructions defined in the program memory. The computer has the capability to add, subtract, multiply, divide, and branch upon command. It is a fractional machine except for division, which is done in integer form. The machine data word is twelve bits in length and may be treated as an unsigned binary or a signed two's complement number.

The term "software" applies to the set of statements which are contained in the program memory. The statements are made up using the set of instructions described in Section 6.1 and listed again in Appendix C, in which is also shown the execution time for each instruction.

The complete software program is listed in Appendix C with notes indicating key elements. The program basically follows the block diagrams in Appendix C, with statements generally grouped to correspond to the separate block diagrams and auxiliary functions. The major groups of statements are as follows:

- 0 - 126 Self-check and initialize for start of computations.
- 73 - 146 Decode and store input commands for future use.
- 147 - 327 Portion of Fuel Flow Block Diagram
- 338 - 1854 Failure Indication and Corrective Action
- 1855 - 3248 Remainder of Fuel Flow Block Diagram
- 3249 - 3627 Core Stator Block Diagram
- 3628 - 3693 Fault Detection
- 3694 - 3798 Data Transfer
- 3799 - 4073 Subroutines

Interwoven within these groups are operations related to engine sensor inputs and inputs from the off-engine equipment. Processing of information from the engine sensors is noted by the instruction INP 0 which transfers data in the AD register to the accumulator and STO XXX which stores the information in the accumulator in a selected location in the scratch pad memory. This action is followed by the instruction OUT 14 which initiates the next AD conversion. The rate at which these engine data are read and stored is controlled by the speed of the AD converter. A software program spacing of approximately 25 to 30 microseconds is allowed for the conversion between reading and storing input data. Processing of information from the off-engine

equipment is noted by the instruction INP 1 which transfers data from the command link register to the accumulator and STO XXX which transfers the data to the scratch pad memory for future use. This information is read into the scratch pad memory before it is required for use in the basic software program.

Transmittal of engine and control system operating point or condition information from the control to the off-engine equipment is also interwoven into the basic control software program. This processing is noted by two instructions: LDA XXX, which loads the accumulator with the data in scratch pad memory location XXX; and OUT 13, which transmits the data in the accumulator to the off-engine equipment.

Execution time for the complete 4073 statement QCSEE OTW program as shown in Appendix C is 0.0135 seconds.

The following example of a small program segment is described in more detail to aid in understanding program procedures. (Note: Circled numbers in the examples below refer to scratch pad memory addresses.)

This example shows steps leading up to calculation of main fuel channel output from input stored in (6) and the desired gain, K_{WT} , of 2.8172 bits/bit. Because numbers cannot fall below -2048 or above +2047, the input signal must be limited to $2047/K_{WT}$, or 726; a value stored in 11. The steps in this computation are outlined below and charted in Figures 62 and 63.

<u>Line No</u>	<u>Mnemonic</u>	<u>Comment</u>	<u>Min Value</u>	<u>Max Value</u>
		(First, limit to +726. See chart in Figure 50)		
3006	LAI 726	Load positive limit in accumulator		
3007	STO (9)	Store positive limit in (9)		
3008	LDA (6)	Load input signal in accumulator	-2048	+2047
3009	SUB (0)	Subtract zero (stored in (0))		
3010	BRMR (5)	Branch ahead 5 steps if previous result is negative		
3011	SUB (9)	Subtract positive limit	- 726	+1321
3012	BRMR 4	Branch ahead 4 steps if previous result is negative		
3012	LDA (9)	Load positive limit in accumulator		
3014	JMPR 4	Jump ahead 4 steps		

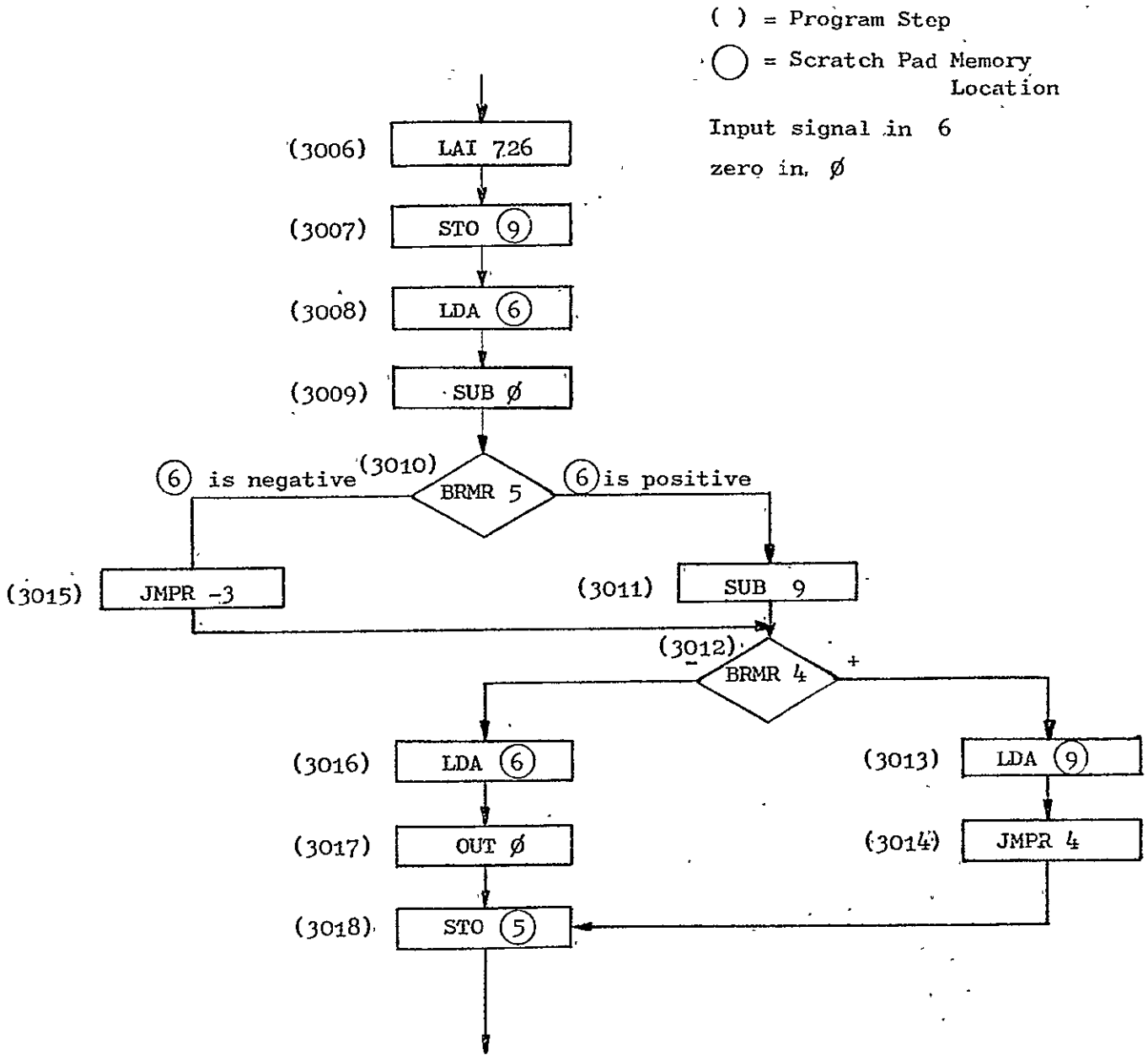
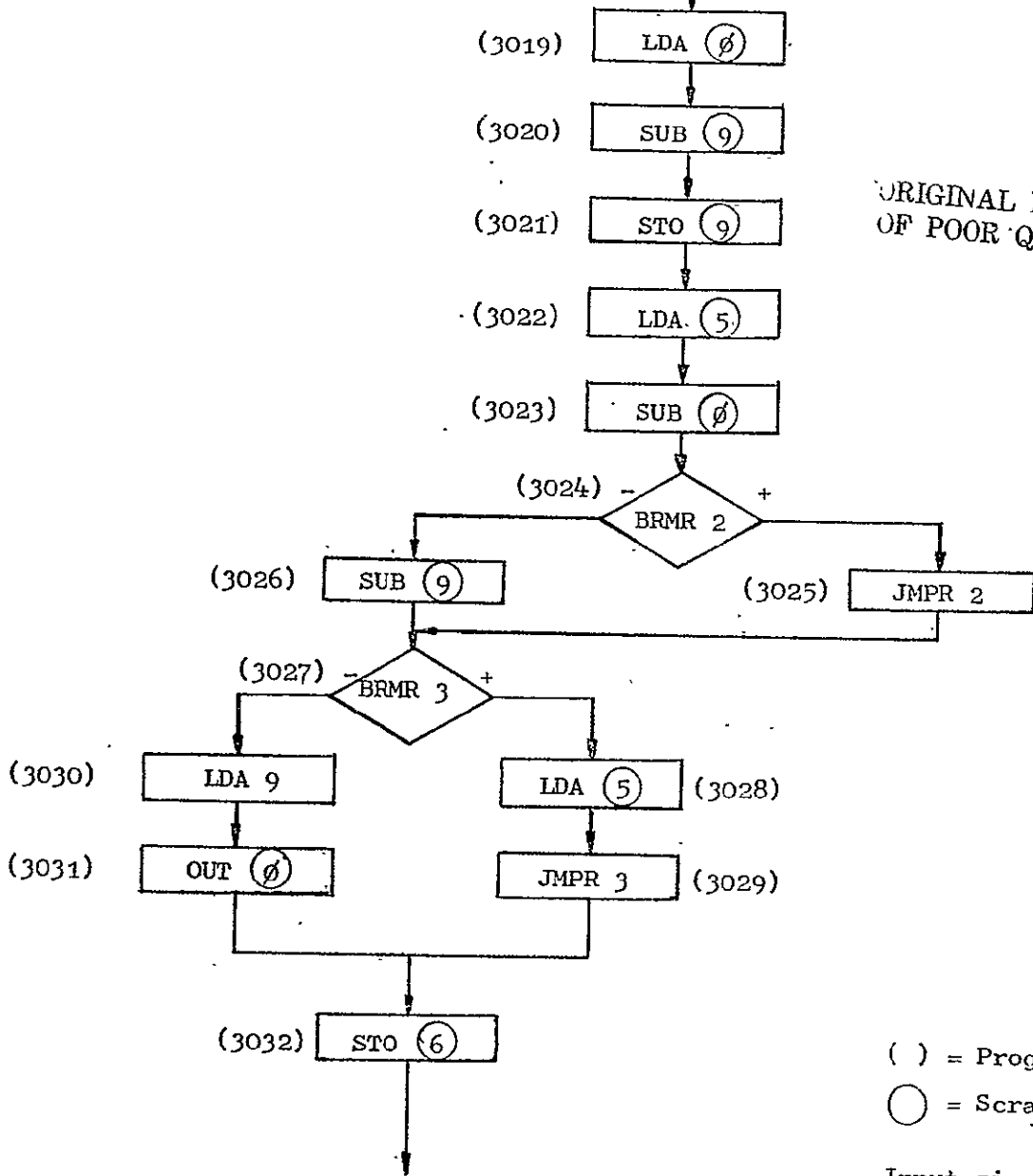


Figure 62. Flow Chart of Positive Limit Check in Fuel Flow Channel.

Input signal with positive limit applied
(Output of Figure 62)



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() = Program Step
 () = Scratch Pad Memory Location
 Input signal in (5)
 limit (726) in (9)

Figure 63. Flow Chart of Negative Limit Check in Fuel Flow Channel.

<u>Line No</u>	<u>Mnemonic</u>	<u>Comment</u>	<u>Min Value</u>	<u>Max Value</u>
(First, limit to +726. See chart in Figure 50)				
3015	JMPR -3	Jump back 3 steps		
3016	LDA (9)	Load positive limit in accumulator		
3017	OUT (∅)	No operation - kills time so path length remain equal		
3018	STO 5	Store accumulator contents in (5) (input signal except limited to 726 max.)	-2048	+ 726
(Next, limit to -726, see chart in Figure 51)				
3019	LDA (∅)	Load zero in accumulator		
3020	SUB (9)	Result is negative limit (-726)		
3021	STO (9)	Store negative limit in (9)		
3022	LDA (5)	Load accumulator with input signal limited to 726 max.	-2048	+ 726
3023	SUB (∅)	Subtract zero		
3024	BRMR 2	Branch ahead 5 steps if previous result is negative		
3025	JMPR 2	Jump ahead 2 steps		
3026	SUB (9)	Subtract negative limit	-1322	+ 726
3027	BRMR 3	Branch ahead 3 steps if previous subtraction was negative		
DO NOT PASS "GO", DO NOT COLLECT \$200				
3028	LDA (5)	Load accumulator with input signal limited to 726 max.	-2048	+ 726
3029	JMPR 3	Jump ahead 3 steps		
3030	LDA (9)	Load negative limit in accumulator		
3031	OUT (∅)	No operation - kill time to equalize path lengths		
3032	STO (6)	Store accumulator contents in 6 (input signal with +726 limits applied)	- 726	+ 726

6.6 VARIATIONS FOR FLIGHT DESIGN

For a flight design, the digital control would change significantly. One obvious change would be the elimination of the many extra functional features included in the experimental control providing testing flexibility and adjustability.

Also, development programs are currently being conducted to define advanced designs which take advantage of medium- and large-scale integrated chips (MSI and LSI) and advanced hybrid packaging techniques uniquely suited for on-engine environment.

Work is currently being done on an advanced packaging development program aimed at reducing the amount of internal wiring by using MSI and LSI chips and mounting them on alumina multilayer interconnection boards. The program also includes development of improved methods of transferring heat from electrical elements. This program is aimed primarily at improved reliability but will also offer weight and volume payoffs.

All things considered, it is estimated that the weight and volume of a flight-design digital control would be reduced approximately 40% from the current experimental design.

6.7 OFF-DESIGN DIGITAL CONTROL ELEMENTS

6.7.1 Description

The QCSEE digital control subsystem includes three off-engine components which furnish command and adjustment inputs to the engine-mounted digital control and display data transmitted from that unit. These three components, which will be located in the engine test control room, are designated the Interconnect Unit, the Operator Control Panel, and the Engineering Control Panel. The basic functions of these units are outlined below. It should be noted that these units were designed for the QCSEE UTW as well as OTW and thus incorporate some elements not used for the OTW.

6.7.2 Interconnect Unit

This unit serves as a signal-processing, -coordination, and -switching device between a remote digital computer supplied by NASA, the outer two off-engine digital control units, transient data recorders, and the engine-mounted digital control.

6.7.3 Operator Control Panel

This unit is intended for use by the engine operating crew. The panel is arranged as shown on Figure 64 and includes the following features:

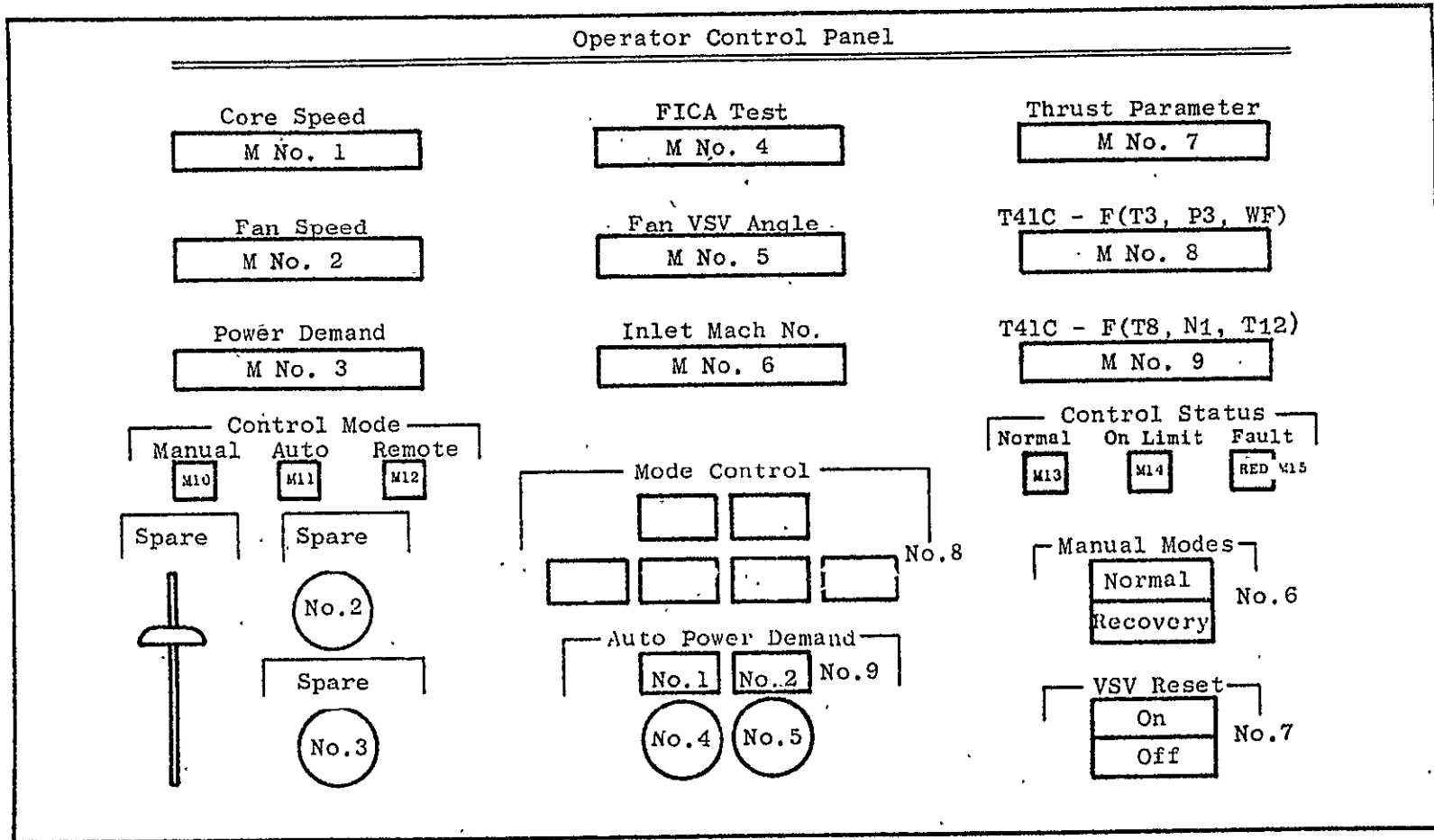


Figure 64. Operator Control Panel.

- Nine digital indicators which continuously display the variable shows.
- Six lighted segment pushbuttons for selecting the digital control operating mode (only one used for OTW).
- A light that indicates when digital control commands are originating from the remote NASA computer.
- Lights that indicate whether all manipulated variables are being controlled normally or if one or more is on a limit. When operation on a limit is indicated, the limit can be identified by means of a selectable digital readout on the Engineering Control Panel.
- A light that indicates when any of the faults of Table XIII have occurred. The fault(s) can be identified by means of a selectable digital readout on the Engineering Control Panel.
- A two-element pushbutton switch for switching to a recovery position which quickly introduces a predetermined set of control commands in case of emergency - or when desired for rapid transients during manual operation.
- A two-element pushbutton switch for operation of the VSV reset.
- Two potentiometers for automatic mode power demand with push-buttons to allow instantaneous switching from one to the other, thus allowing power-demand step changes.

6.7.4 Engineering Control Panel

This unit is intended for use by an engineering test monitor. The panel is arranged as shown on Figure 65 and includes the following features.

- A selected digital display for indicating any one of the variables listed in Table VIII.
- Twenty potentiometers for making on-line adjustments to the digital control logic.
- Three milliammeters which continuously indicate current to the torque motor servovalves controlling the manipulated variables. (Only two are used on the OTW.)
- A fault light equivalent to the one on the Operator Control Panel.
- Five toggle switches, one for selecting the type of servovalve output (i.e., normal or fail-fixed), one to activate FICA computation without introduction into control channels (switch FICA 1), one to activate FICA fully (switch FICA 2), one to activate the automatic fault correction features (switch FICA 3), and one to select input source (i.e., "local" off-engine units or "remote" NASA computer).

Table XIII. Fuel Pump Characteristics (F101).

	Main Fuel Pump	
	Boost Element	Vane Element
Rated Speed, rpm	6690	6690
Maximum S.S. Speed, rpm	6891	6891
Rated Flow (Delivered Flow at Service Limit at Rated Speed)	$2.7 \times 10^3 \text{ m}^3/\text{sec}$ (42.8 gpm) at 107.2° C (225° F)	$2.7 \times 10^{-3} \text{ m}^3/\text{sec}$ (42.8 gpm) at 107.2° C (225° F)
Rated ΔP at Rated Flow	$2.76 \times 10^5 \text{ N/m}^2$ (40 psi) min.	$\approx 6.65 \times 10^6 \text{ N/m}^2$ (≈ 964 psia)
Rated Inlet Pressure at Rated flow and Speed	$3.45 \times 10^5 \text{ N/m}^2$ (50 psia)	$6.21 \times 10^5 \text{ N/m}^2$ (90 psia)
Power Loss at Rated Speed	$1.49 \times 10^3 \text{ W}$ (2 hp) max.	Overall Efficiency = 0.72 at Design Point

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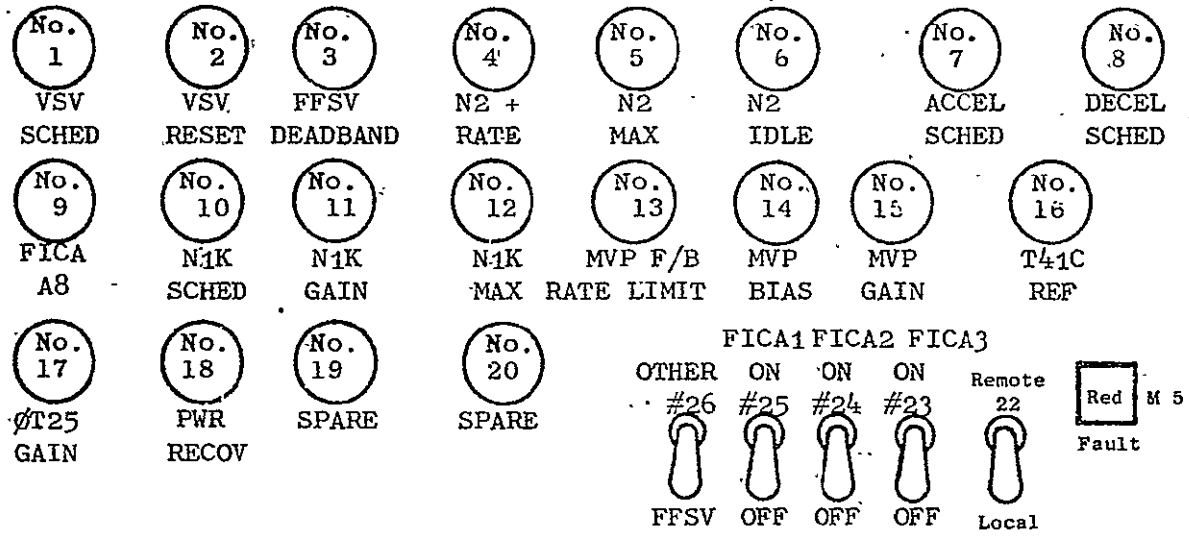
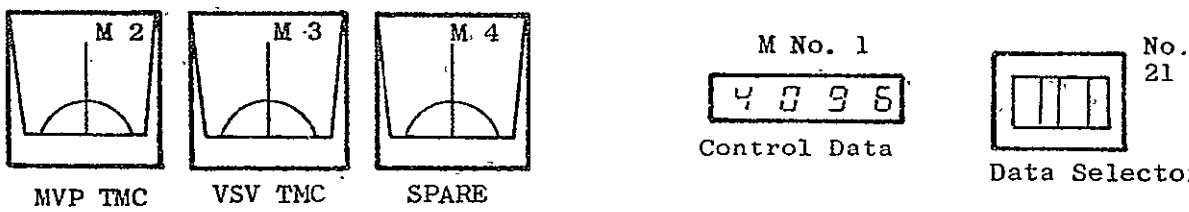


Figure 65. Engineering Control Panel.

6.7.5 Functional Design

A functional block diagram of the off-engine digital control components is shown on Figure 66 and a general functional description is given below.

Input signals to the off-engine components are in both analog and digital form. All digital signals are transmitted by differential line drivers and received by a differential line receiver over twisted wire pairs. All analog signals transmitted are buffered by low-output impedance amplifiers and received by operational amplifiers in a differential configuration.

The analog multiplexer located in the Interconnect Unit consists of two 16-channel multiplexer chips capable of handling all the analog inputs from the Engineering Control Unit and the Operator Control Unit. Each of the inputs are capable of being addressed separately in a predetermined sequence at a particular time determined by the digital control. The output of the multiplexer circuit goes to a sample-and-hold circuit and awaits AD conversion.

All analog signals coming into the Interconnect Unit are converted to a digital word upon command from the digital control just prior to being transmitted to the digital control.

Digital multiplexing at the data bus is accomplished by employing tri-state logic devices to provide inputs to the bus. The three states are high output, low output, and high impedance. Placed in the high-impedance state, the devices can be essentially deactivated, while the other two states are used to define logic levels in the transmission mode. All but one of the devices whose outputs are connected to the data bus shown in Figure 66 are placed in the high-impedance state; the remaining device will be in the transmission mode. In this manner, a single input to the data bus is made available to the digital serializer as a 12-bit parallel data word.

The digital serializer is a 12-bit shift register which is parallel loaded upon command. Subsequently, the data are shifted one bit at a time into the transmission system.

The isolation of signal and signal grounds is accomplished by means of optical isolators. These devices convert electrical signals into light internally, and then reconvert the light signal back into electrical signals. This process breaks all electrical connection from input to output while maintaining the signal information. The purpose of the isolators is to assure that ground loops, power differences between systems, and signal noise are reduced to a minimum.

The power supply for the off-engine units is derived from a 400-Hz source of 300 volt-amps or more. In the Interconnect Unit, plus and minus fifteen volts are developed and routed to the Engineering Control Unit and the Operator Control Unit. Analog circuits requiring the use of ± 15 volts in any of the three units use this regulated supply.

The +5 volts supply is generated separately and used as a logic supply in each of the three units.

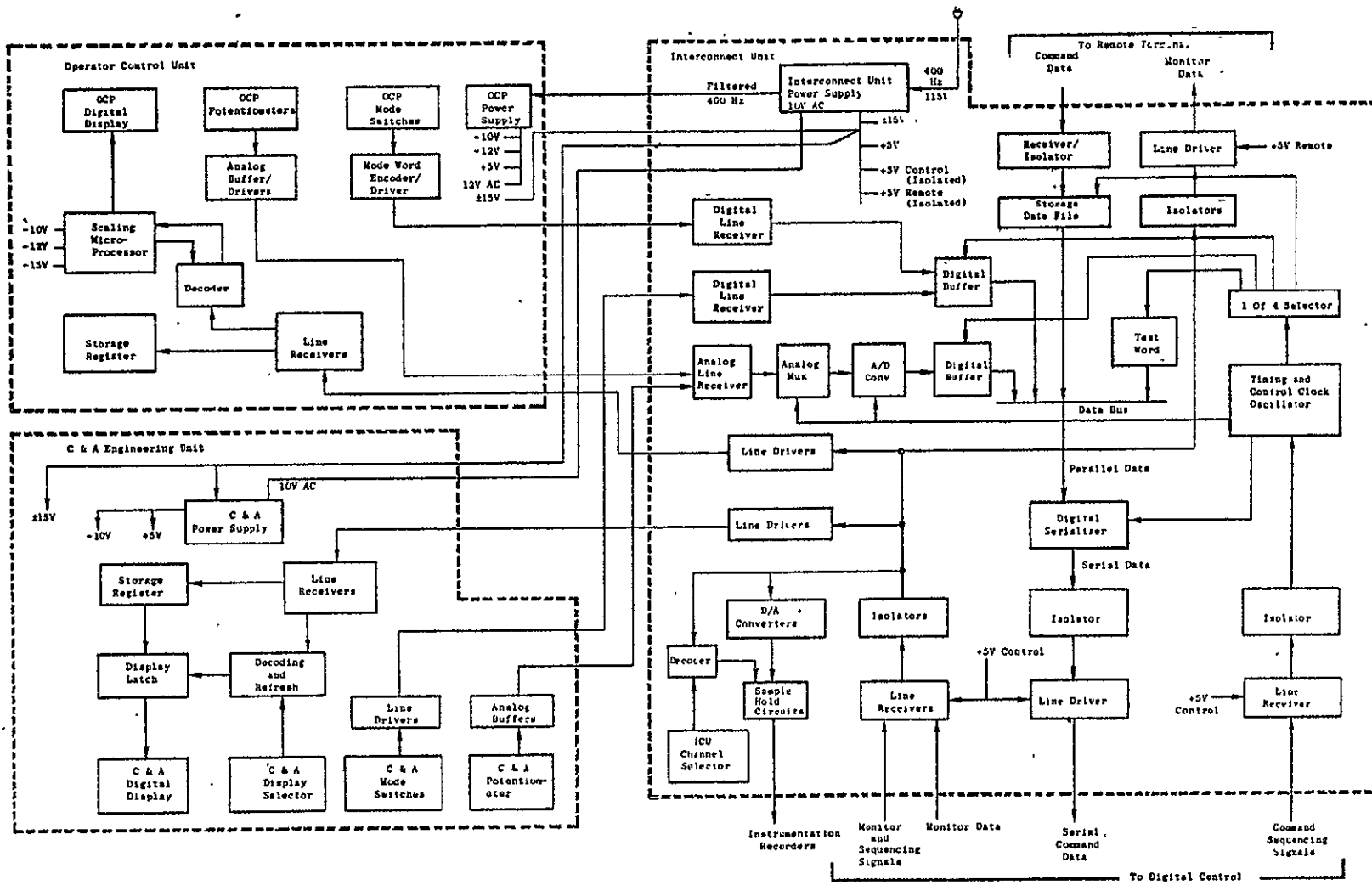


Figure 66. Off-Engine Block Diagram.

There are two isolated +5 volt logic supplies in the Interconnect Unit derived specifically to be used in the isolation technique used in this system.

The Operator Control Unit develops -10V and -12V for the scaling microprocessor. The +5 volts are developed for a logic supply and the 12-volts a.c. used to light the front panel pushbutton switches and indicators.

The Engineering Control Unit develops -10V to reference the potentiometers. The +5 volts are used as a logic supply while the 10-volts a.c. is the deriving source as well as the supplier of the one lighted indicator on the front panel. The ± 15 volts are used to derive the -10 volts as well as operating analog circuits.

The packaging of the off-engine digital control components is designed to operate in a control room environment. Both mechanical and electrical systems are designed for control room use only.

7.0 HYDROMECHANICAL CONTROL

7.1 PURPOSE

The purpose of the hydromechanical control is to provide backup control of engine fuel flow and to provide the fuel-handling interface for operation of several engine limits utilized in the control system. The basic fuel flow control is provided by electrical signals to a torque motor on the hydromechanical control.

7.2 DESCRIPTION

The QCSEE hydromechanical control is an F101 main engine control containing modifications appropriate to the unique requirements of the QCSEE control system and engine. The control for the OTW has many of its normal hydromechanical computational elements disabled in order to let the digital control have essentially full control authority. Woodward Governor Company is the vendor source for this control. The modified control is identified by General Electric Source Control Drawing 4013177-403 P02.

The modified F101 control will perform the following subsystem functions:

- Modulate core engine fuel flow to govern core speed as a backup to the digital control.
- Reduce fuel flow in proportion to electrical signal from the digital control as the primary fuel control method.
- Provide power lever position intelligence to the digital control.
- Provide minimum fuel system pressurization.
- Provide fuel flow shutoff to limit fan overspeed in response to electrical control signals from the digital control.
- Provide electrical metering valve position intelligence to the digital control.

Hydromechanical Control Inputs and Outputs

The inputs to and outputs from the hydromechanical control that have been retained for use on the QCSEE OTW are listed below:

<u>Inputs</u>	<u>Outputs</u>
● Pump discharge fuel flow	● Metered engine fuel flow
● Power lever angle	● Bypass fuel flow
● Core engine drive speed	● Power lever electrical position signal
● Electrical fuel flow control signal	● Metering valve electrical position signal
● Electrical fan overspeed signal	

7.3 OPERATION

The hydromechanical control mechanization arrangement which indicates implementation of the various control functions is depicted on Figure 67 for the modified F101 fuel control. The zones mentioned in following description are shown in Figure 67.

Backup engine speed control is accomplished with an assembly of the same basic governing components that have been used in previous Woodward Governor Company units: a flyweight system that provides isochronous speed governing (Zone C-14) at a level set by a power lever drive command linkage assembly. In normal operation, this system is overridden by use of a two-state torque motor servovalve to control engine speed in response to the electrical signal from the digital control (Zone B-15). The electrical override is only effective at speeds below the governor speed setting, thereby requiring the power lever to be set at 100% to permit full range electrical control. This is important because, should any malfunction occur in the electrical subsystem in the increase speed direction, full range governing of engine speed is still available with the hydromechanical system.

As noted previously, the OTW control system is designed for optional use of two different types of torque motor servovalves for fuel flow, the standard type and a fail-fixed type that, for the most probable electrical malfunctions (i.e., zero signal or maximum signal), will cause the metering valve to remain fixed. This is described in more detail later.

The fuel metering system is designed to use simple control elements for multiple functions. The main metering valve is a variable-area shoe and rotor (Zone D-10). A constant pressure drop is maintained across the metering valve by a bypass-type proportional-plus-integral regulator (Zones C, D, and E-10). The bypass system also provides the pump unloading function during shutdown (windmilling) conditions (Zone B-12). For reliability purposes, the unloading function is positively locked out during the normal engine operation between idle and maximum speed. The fuel shutoff valve (Zone B-12), similar to the fuel valve rotor, is integral with and actuated by the power

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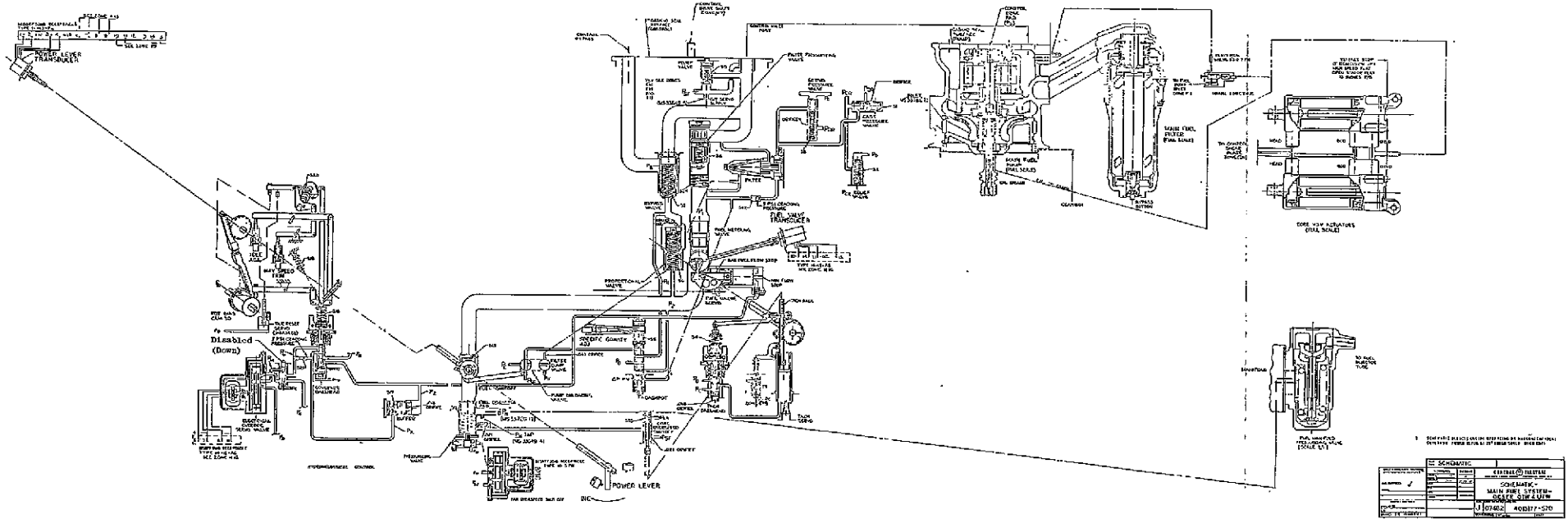


Figure 67. Hydromechanical Control Schematic.

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lever shaft (Zone A-11). Movement of the power lever to the "off" position mechanically actuates the pump unloading function which provides a 1.72×10^6 N/m² (250 psi) pump discharge pressure during windmilling conditions for servosystem regulation purposes.

A pressurization valve (Zone B-12), used to provide minimum back pressure to ensure adequate servosystem pressure during low metered flow conditions, is provided as part of the control package.

Modifications to the control incorporated for the QCSEE OTW include the following:

- Accel/Decel Schedules - These functions are disconnected so they cannot interfere with the operation of the electrical fuel control signal or backup governor.
- Core Stator Section - The core stator scheduling mechanism is de-activated and the stator control ports blocked by an electro-hydraulic servovalve physically mounted to the control but functionally isolated from it. This valve is described in Section 9.0.
- Emergency Fuel Shutoff - An electrical-to-hydraulic torque motor servovalve has been added to the control to accomplish shutoff of engine fuel flow in response to an electric fan overspeed signal. This function is accomplished by switching the pump discharge pressure into the reference chamber of the system pressurizing valve (Zone B-12). A similar action is taken in the event of core engine overspeed through the action of the existing overspeed shutoff valve (Zone B-10). A low-power torque motor-operated switching valve is mounted on the pressurizing valve cover to accomplish the fan overspeed protection. The flow gain of the output stage of the shutdown device has been selected to cause closure of the pressurizing piston within 20 milliseconds after the electrical overspeed signal is sensed. This shutdown action will temporarily place the fuel pump on pressure relief during the engine coast down.
- Metering Valve Position Signal - The control provides an electrical rotary position transducer on the metering valve shaft to signal metering valve angle (Zone E-9). For the QCSEE units, a position transducer identical to the power lever position transducer (Zone H-17) is used for the metering valve transducer.
- Electrical Fuel Override Authority - The present F101 controls provide a core speed floor limitation on the electrical fuel flow override through the action of a speed switch valve (Zone C-14) which is actuated by the core speed tachometer (Zone B-9). This speed floor setting will be disabled for QCSEE by blocking the speed switch valve (Zone C-14) to the desired position, thereby providing for full fuel control by the digital control.

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- Fail-Fixed Servovalve - As seen by Figure 68, the fail-fixed servovalve is basically a standard two-stage electrohydraulic servovalve. It differs only in the configuration of the second-stage spool valve and its attendant portion. As with a conventional servovalve, spool position is a function of input current.
- The valve is shown in the zero current condition. Both load lands of the spool valve have 0.015 cm (0.006 in.) overlaps thus hydraulically locking the actuator in position. As current is increased, the spool valve will stroke through the overlap and begin porting high-pressure flow to the metering valve actuator. Valve porting is timed so that at 50% rated current the areas of the metering valve port are equal to the areas of the supply and return ports, and will flow to and from the actuator effectively through two equal orifices in series. Flow is at a maximum. As current is further increased the metering valve land closes off: flow to the metering valve goes to zero, and a new fluid lock on the actuator is established. As the input current is reduced to zero, flow is again established to the actuator, causing motion in the same direction, as with increasing current. The actuator will be driven in small steps in one direction if the input is a series of square waves stepping from zero to rated current and back to zero. If the polarity of the input current is changed, the actuator will move in the opposite direction.

The preferred mode of operation is to drive the servovalve at a constant input frequency (from -80 mA to +80 mA) above the frequency to which the valve can fully respond. The valve will average the plus and minus "on" time. By limiting the minimum and maximum "on" time to 25% and 75%, the valve will behave as an analog device in response to pulse-width modulation. Flow will be proportional from zero to maximum for a 25% to 75% pulse-width demand. Control of the electrical signal to this valve is discussed in 6.2.3.

Should the valve receive a d.c. level zero current or a +80 mA current signal, indicative of an electrical failure, flow to or from the actuator will be stopped and a fluid lock condition established to hold the actuator to its position at the time of failure.

- Core Inlet Temperature Sensing - This function is not required. The sensor normally used with the control on the F101 is not used on the QCSEE OTW and the control ports to it are capped.

7.4 INSTALLATION

The hydromechanical control will be mounted on the F101 fuel pump similar to Figure 69. The pump is V-band flange-mounted to an F101 gearbox pump drive pad. Through-shafting is used to provide core speed input to the control drive spline. Fuel and power lever connections to the control will be essentially the same as the F101 configuration.

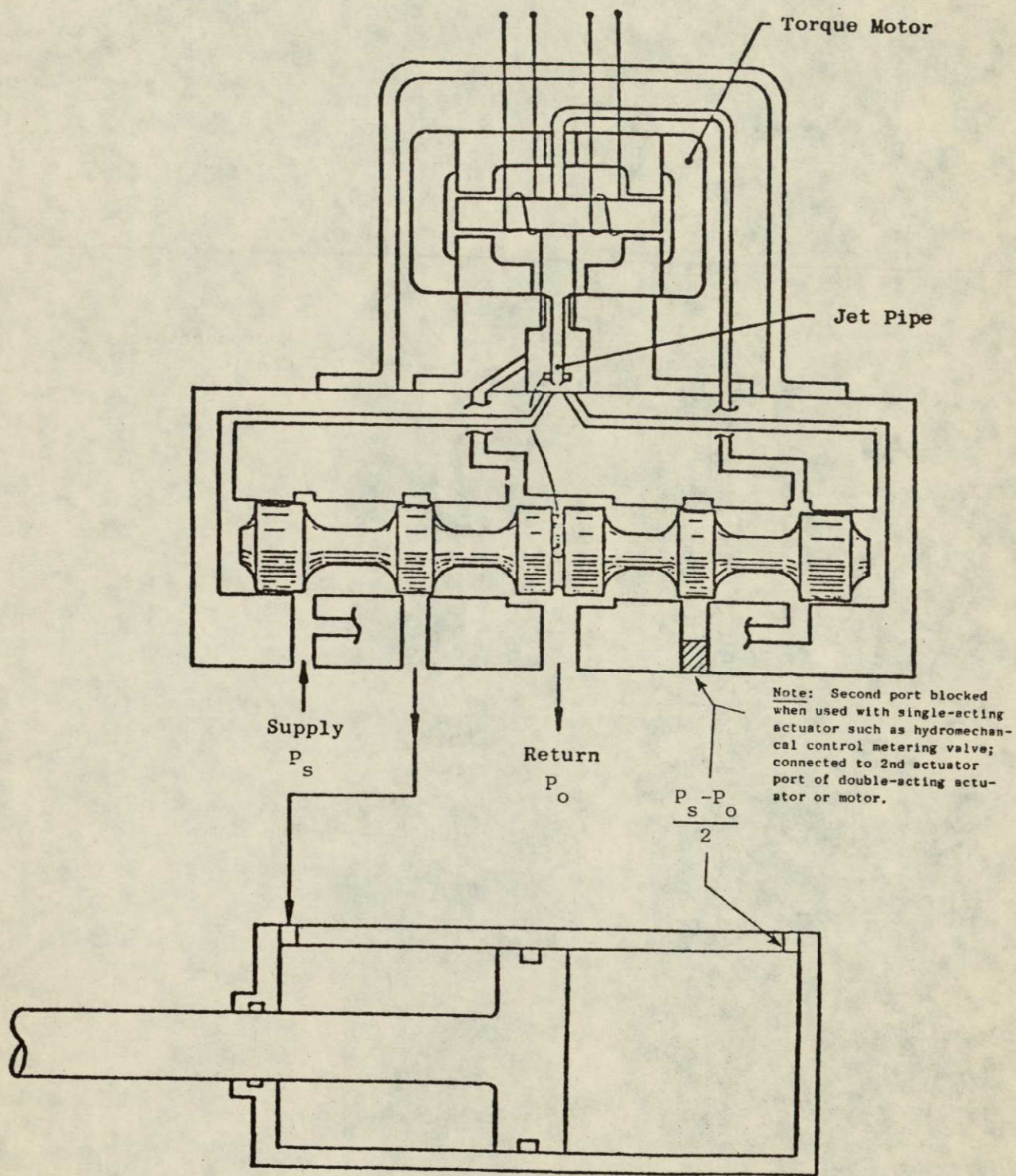
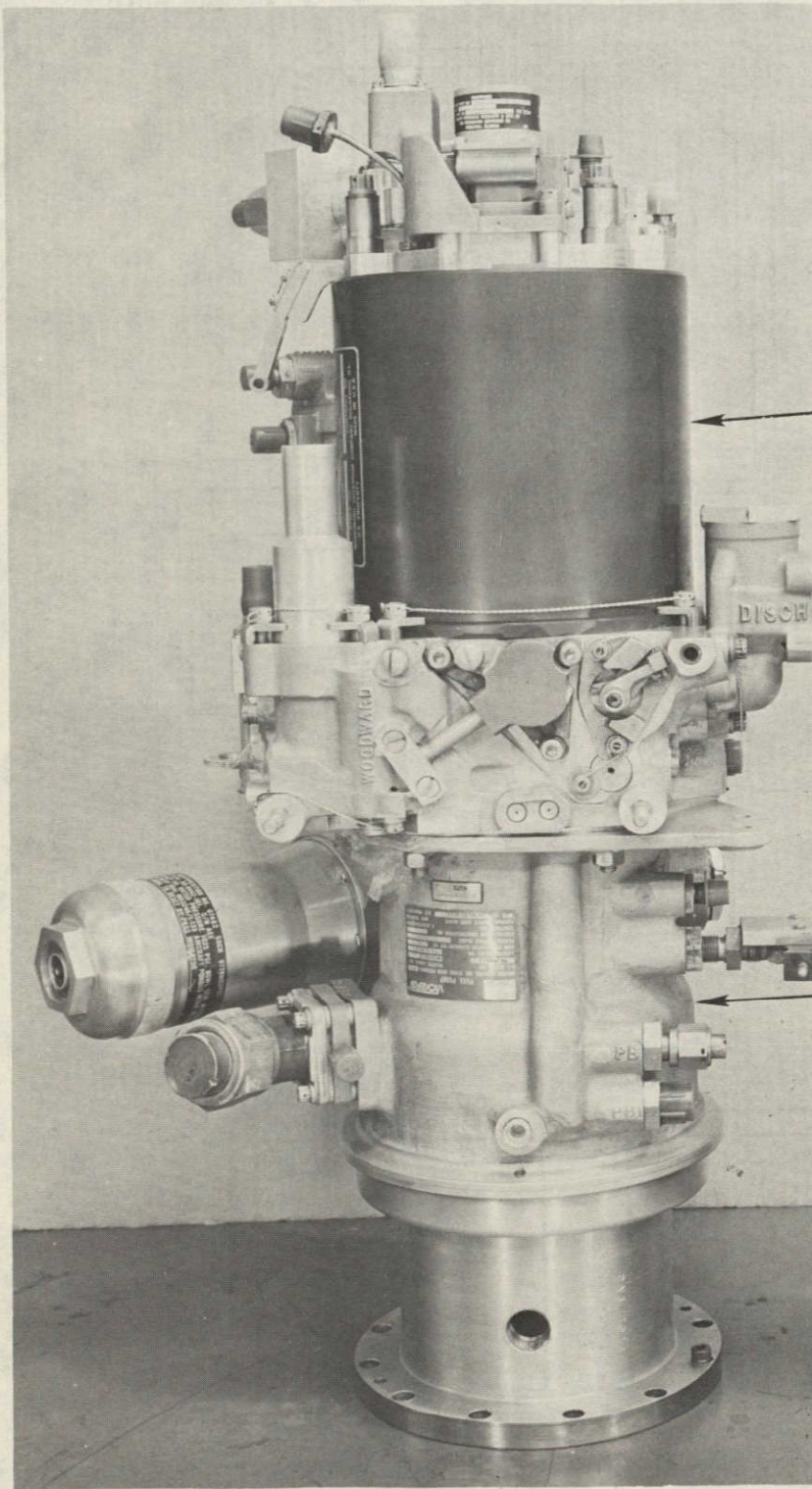


Figure 68. Fail-Fixed Servovalve.



Hydromechanical
Control

Fuel Pump

Figure 69. Hydromechanical Control and Fuel Pump.

7.5 VARIATION FOR FLIGHT DESIGN

The initial flight design QCSEE would have a hydromechanical backup to the primary digital electronic control. The exact nature of the simplified backup hydromechanical unit will be the subject of further study. Simplified elements will be devised for speed governing, transient fuel control, and VSV control.

For a second-generation QCSEE, it is expected that digital electronic technology will have developed (and been proven by operational experience) to be sufficiently better and more reliable than current hydromechanical controls that the hydromechanical backup would be eliminated altogether.

8.0 FUEL DELIVERY SYSTEM

8.1 PURPOSES

The purposes of the fuel delivery system are to pump, filter, and meter the fuel flow required for core engine combustion at the pressures dictated by engine burner conditions; and to provide a means of preventing fuel component overboard drain leakage.

8.2 DESCRIPTION

The QCSEE fuel delivery system is primarily based on F101 engine main fuel system components and includes the hydromechanical control described in Section 7.0. The fuel delivery system includes the following elements:

- Fuel Control (Metering Section)
- Main Fuel Pump
- Fuel Filter
- Drain Eductor and Flow Regulator

These elements are interconnected as shown in the schematic of Figure 70.

8.3 OPERATION

The fuel delivery system accepts fuel flow and pressure provided to the system pump intake by the test facility or aircraft fuel feed system and provides the pumping pressure rise required to deliver metered flow to the engine combustor as described in Section 8.6. Pump discharge flow is filtered by a 74 μm absolute full-flow barrier filter prior to entering the hydromechanical control inlet. The metering section of the hydromechanical control sets the metering valve area in response to control signals and limits as described in Sections 6.0 and 7.0. Flow is metered by establishing a constant metering pressure drop across the metering valve area through the action of a fuel bypassing regulator which returns to the fuel pump interstage pressure any excess intake flow not required for metered demand.

8.4 MAIN FUEL PUMP

The purpose of the fuel pump is to raise the pressure of metered system flow to a level suitable for metering control and delivery into the engine combustor.

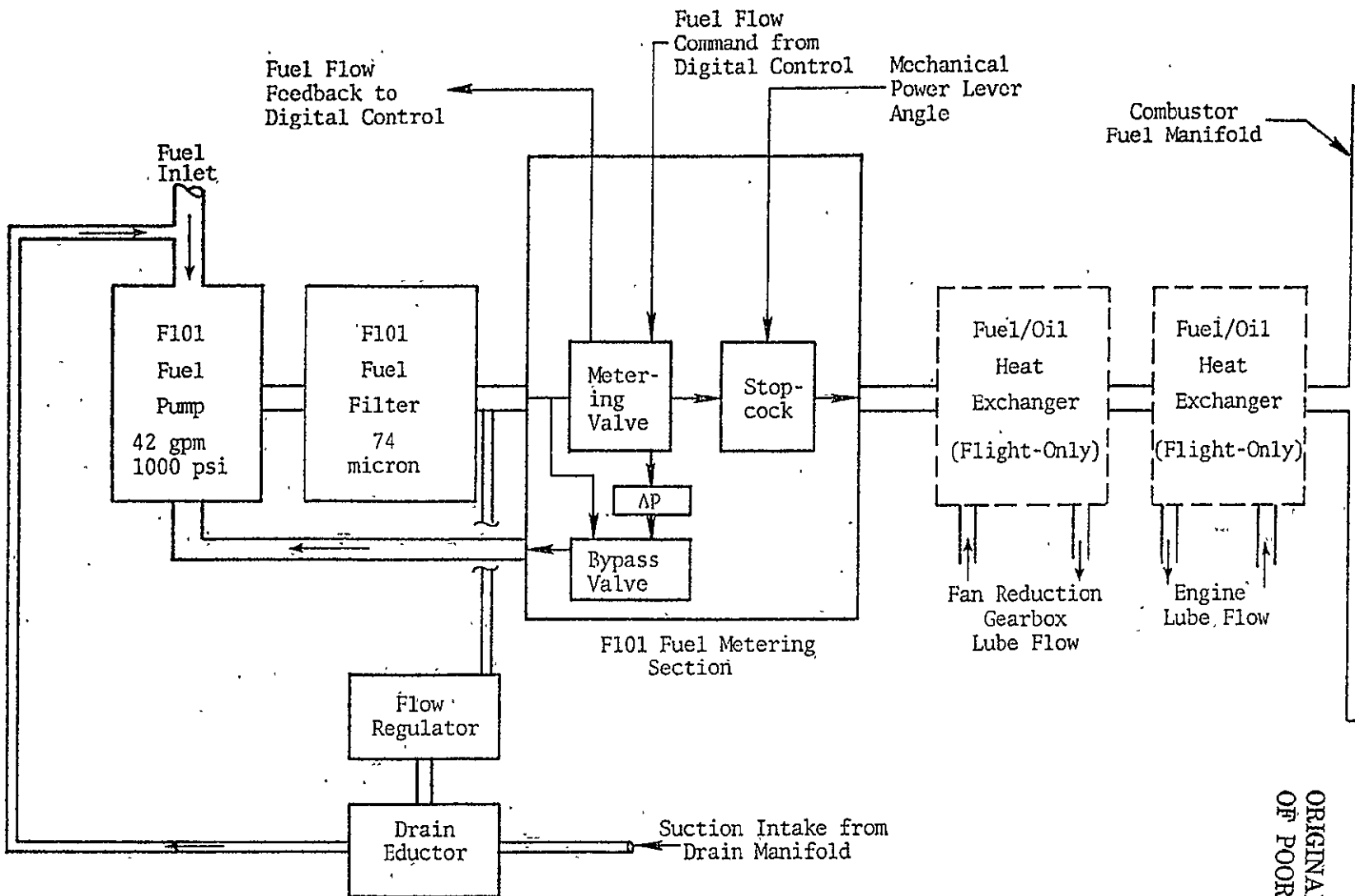


Figure 70. Fuel Delivery System.

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The fuel pump is a standard F101 main fuel pump, unmodified. It is a balanced vane design of fixed displacement and contains an integral centrifugal booster stage to charge the vane intakes. Sizing of the fuel delivery system is indicated by the fuel pump characteristics listed in Table XIII. A cross section view of the pump is shown on Figure 67 (Zone F-7).

The pump operates to provide the pumping performance ratings shown in Table XIII. (Pump installation was described in Section 7.4)

8.5 FUEL FILTER

The purpose of the fuel filter is to filter pump discharge flow to a 74 μm level to protect the fuel control metering and injection system against larger foreign particles.

The main fuel filter is a barrier, through-flow type of stainless steel wire mesh. It is mounted on the main fuel pump and has a clogged filter bypass valve, a service shutoff valve, and an impending bypass indication button. Design features are:

Rated Flow	50.4 gpm
Filtration (absolute)	74 μm
Impending Bypass Indication Pressure	22 psid
Bypass Valve Cracking Pressure	35 psid
Element Type	Disposable

Fuel enters the filter, flows through the element mesh, and is discharged from the center of the element. If the element is clogged, the bypass valve opens allowing unfiltered fuel to flow to the system. The impending bypass indicator button extends at a pressure level equivalent to approximately 80% of filter life. The service shutoff valve seals off both the inlet and the discharge fuel flowpaths through the filter to prevent fuel leakage when the filter bowl is removed to service the filter element.

Location of the fuel filter is shown on Figure 70.

8.6 FUEL-OIL HEAT EXCHANGER

The fuel-oil heat exchanger provides the means for transferring heat from the engine lube system, and from the fan reduction gearbox to the fuel. In addition to cooling the oil, the heat exchanger serves to heat the fuel under cold operating conditions in order to avoid the possibility of fuel system icing.

An off-engine-mounted slave oil cooler will be used for the experimental engines. The slave cooler uses water for cooling instead of fuel. The unit is a stainless shell-and-tube design, qualified and in production for the GE LM2500 engine and used on shipboard applications. The slave cooler has a heat transfer capability approximately three (3) times the estimated heat load of the QCSEE engine. The unit consists of 332 0.953-cm (0.375-in.) diameter tubes (each 0.610 m [2.0 ft] long) and 9 crossflow oil baffles. The cylindrical shell is 25.4-cm (10 in.) diameter and 0.610 m (2.0 ft) long. Drains are provided to avoid water freezing during winter operation.

Water is routed through the tubes and makes four passes. Oil flows over the tubes and makes 10 cross-counterflow passes. A waterflow of 100 gpm may be used at a pressure drop of 10 psid.

The slave oil cooler is located and mounted on the test stand superstructure above the engine.

The flight engine will use a fuel-oil heat exchanger located in the gearbox and accessories area of the engine. The heat exchanger will consist of two (2) cores with fuel flowing in series from one core to the other. Fan reduction gearbox oil operating at a lower temperature level than engine lube system oil will flow through the first core. Lube system oil will flow through the second core. At present, a nonbrazed (mechanical tube joint) aluminum shell-and-tube oil cooler is contemplated for a flight engine. Other designs will be considered on the basis of reliability, cost, size, and weight. Current weight estimate is 13.61 kg (30 lb) for the entire unit.

8.7 DRAIN EDUCTOR

The purpose of the drain eductor is to pump fuel component seal drain leakage back to the fuel pump intake and to prevent dumping leakage overboard.

The drain eductor consists of a production CF6-50 design used to pump aircraft drain can fuel back to the fuel pump inlet during engine coastdown after stopcocking the engine. The CF6-50 part is identified as P/N 9070M89P02. A cross section view of the drain eductor is shown in Figure 71.

The drain eductor is used with an inline jet supply flow regulator which maintains a constant jet supply flow. The flow regulator is separately housed and is a standard Fluid Regulators Corp. design identified as P/N Q1547-01.

Pump discharge fuel pressure extracted from the filter discharge is supplied to inline flow regulator Q1547-01. The regulator maintains 550 pph constant flow to the drain eductor jet supply under varying pump discharge pressure conditions ranging from 250 psig to 1000 psig. Constant motive flow and pressure in the jet maintains constant jet-pumping characteristics in the eductor.

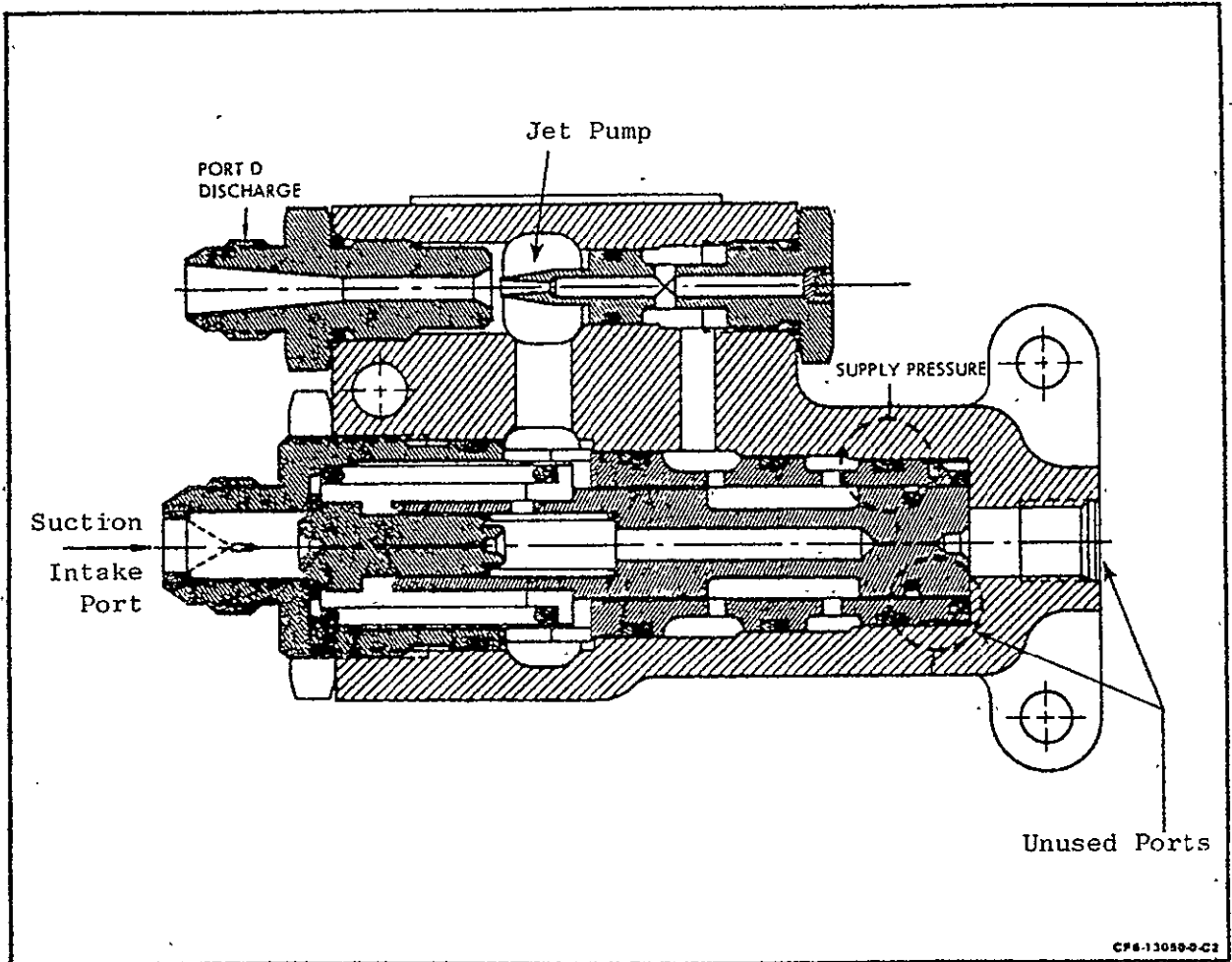


Figure 71. Drain Eductor Cross Section.

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The constant motive pressure is applied to the jet supply port shown in Figure 71. Fuel drain manifolds are connected to the suction intake port; drain manifold flow is pumped through the suction check valve and into the suction chamber of the jet pump. Jet flow and suction flow mix in the jet diffuser and are returned to fuel pump inlet pressure at pressure levels up to 50 psig. A partial vacuum is maintained in the suction chambers and the drain manifold. The selector valve piston shown in Figure 71 is not used but is held to the right at all times by spring force, permitting continuous passage of the jet supply flow during pump operation. Seal leakage air and fuel vapor are continuously returned to fuel pump intake.

The flow regulator and drain eductor components are bolted to the fan cowl in the gearbox and accessory compartment. Stator actuator drain lines thus have a rise in elevation in order to reach the eductor system's suction manifold.

For a flight design, the eductor would be simplified to eliminate unused valving and to incorporate integrally regulated jet flow. The eductor would be relocated below the lowest drain point elevation in the core engine compartment.

9.0 CORE COMPRESSOR STATOR CONTROL SYSTEM

9.1 PURPOSE

The F101 core compressor used in the QCSEE includes provisions for varying the angle of the inlet guide vanes and stator vanes in Stages 1 through 3 to accommodate the relatively wide speed range in which the compressor must perform. The core compressor stator control system positions and controls these variable vanes.

9.2 DESCRIPTION

The variable vanes are connected through a system of levers, rings, and links which are actuated by two fuel-operated linear structures (Figure 72) mounted to the compressor casing on opposite sides of the engine. The actuator motions are synchronized by means of the inherent rigidity of the linkage system.

Fuel flow for operation of the actuators is controlled by a 4-way, electrohydraulic servovalve mounted to the fuel control and operated by an electrical signal from the digital control. A schematic of the valve design is shown on Figure 73. The electrical signal is applied to parallel, redundant coils of the flat armature torque motor which applies torque to the jet pipe causing it to deflect. This deflection unbalances the pressure on the opposite ends of the spool, causing it to move until the jet pipe is returned to its center position by the feedback spring, the force of the spring just counteracting the torque generated by the electrical signal current. The position of the spool determines the porting between the high pressure supply from the fuel pump (P), the actuation ports (1 and 2), and the low pressure return (R).

High pressure fuel is supplied to the servovalve from a port on the fuel control and the servovalve low pressure return is connected to the fuel pump inlet.

Core stator position feedback is provided for the control loop by two electrical linear variable position transducers (LVDT) located on opposite sides of the compressor and driven by the actuator system as shown in Figure 74.

9.3 OPERATION

The core stators are basically controlled as a function of core corrected speed in accordance with a schedule programmed into the digital control (See Appendix C). The digital control program also includes a schedule reset function to aid in achieving rapid thrust transients under certain conditions as described in 4.5. The digital control compares scheduled stator position with actual stator position as indicated by the inputs from the stator feedback LVDT's and manipulates the signal to the stator servovalve as necessary to set the correct stator position.

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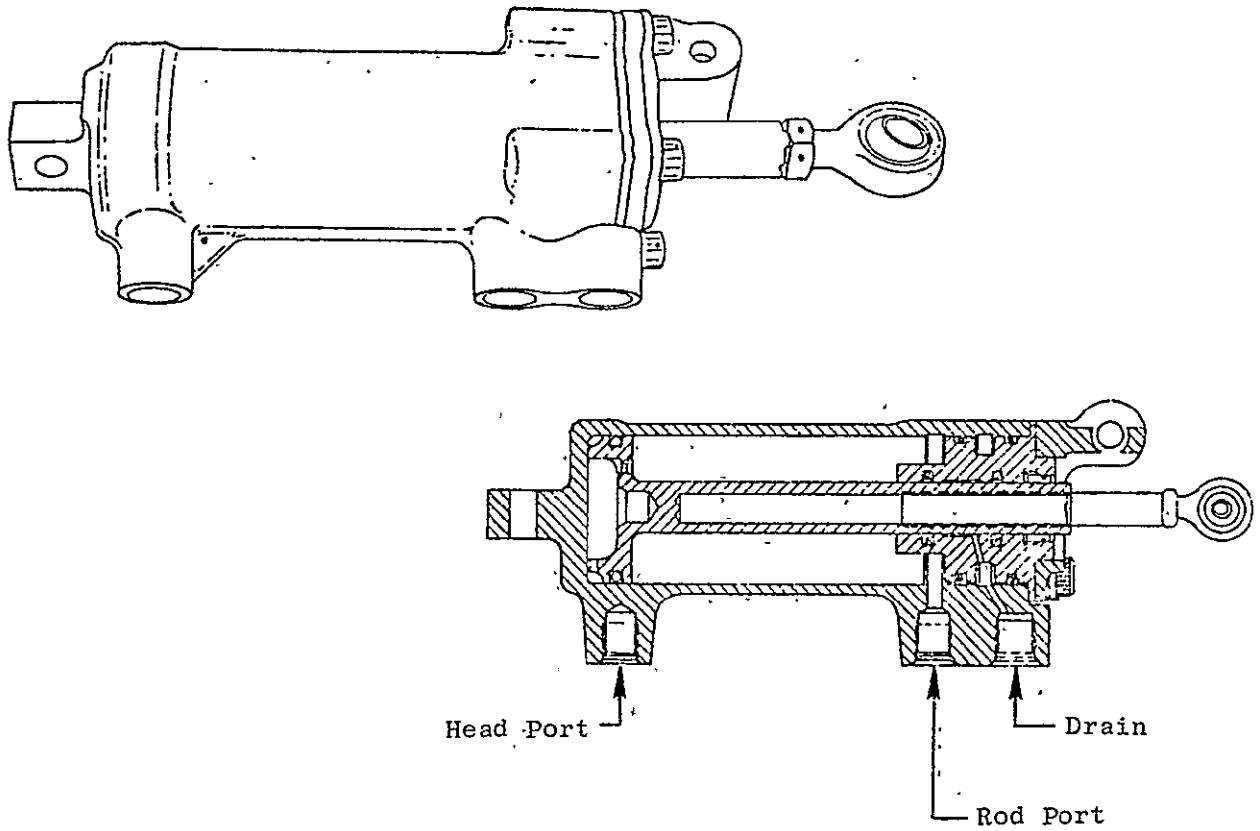


Figure 72. Core Stator Actuator.

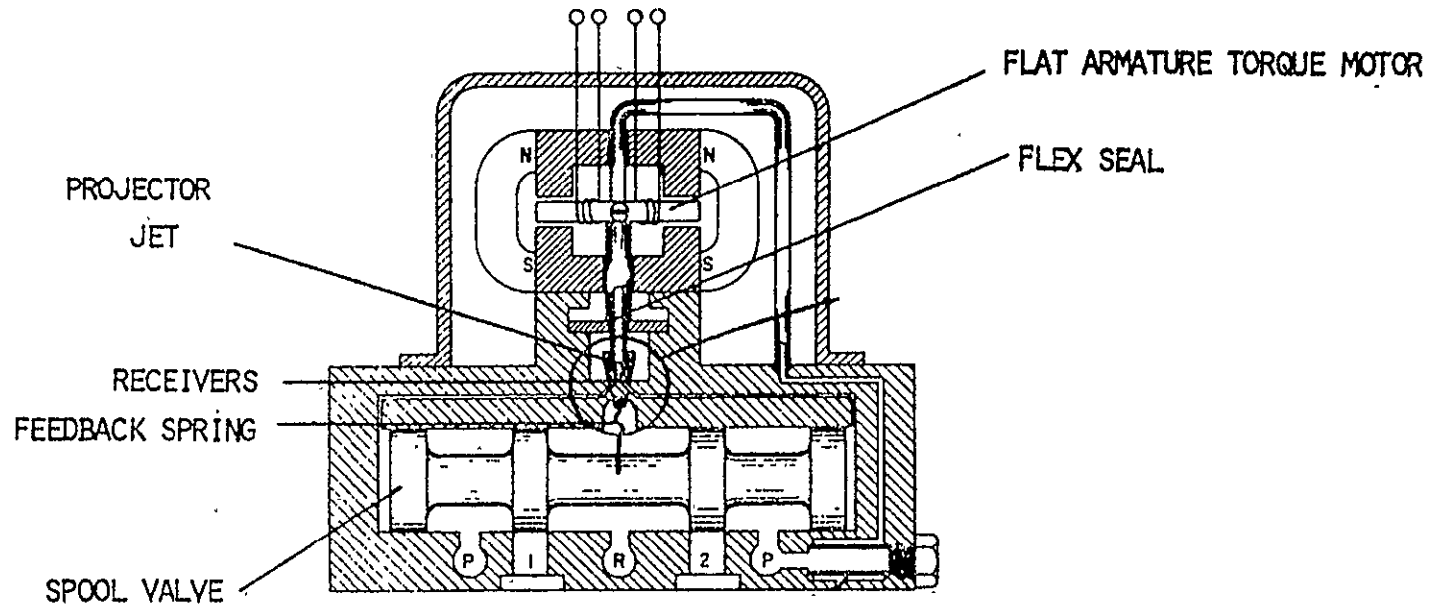


Figure 73. Electrohydraulic Servovalve.

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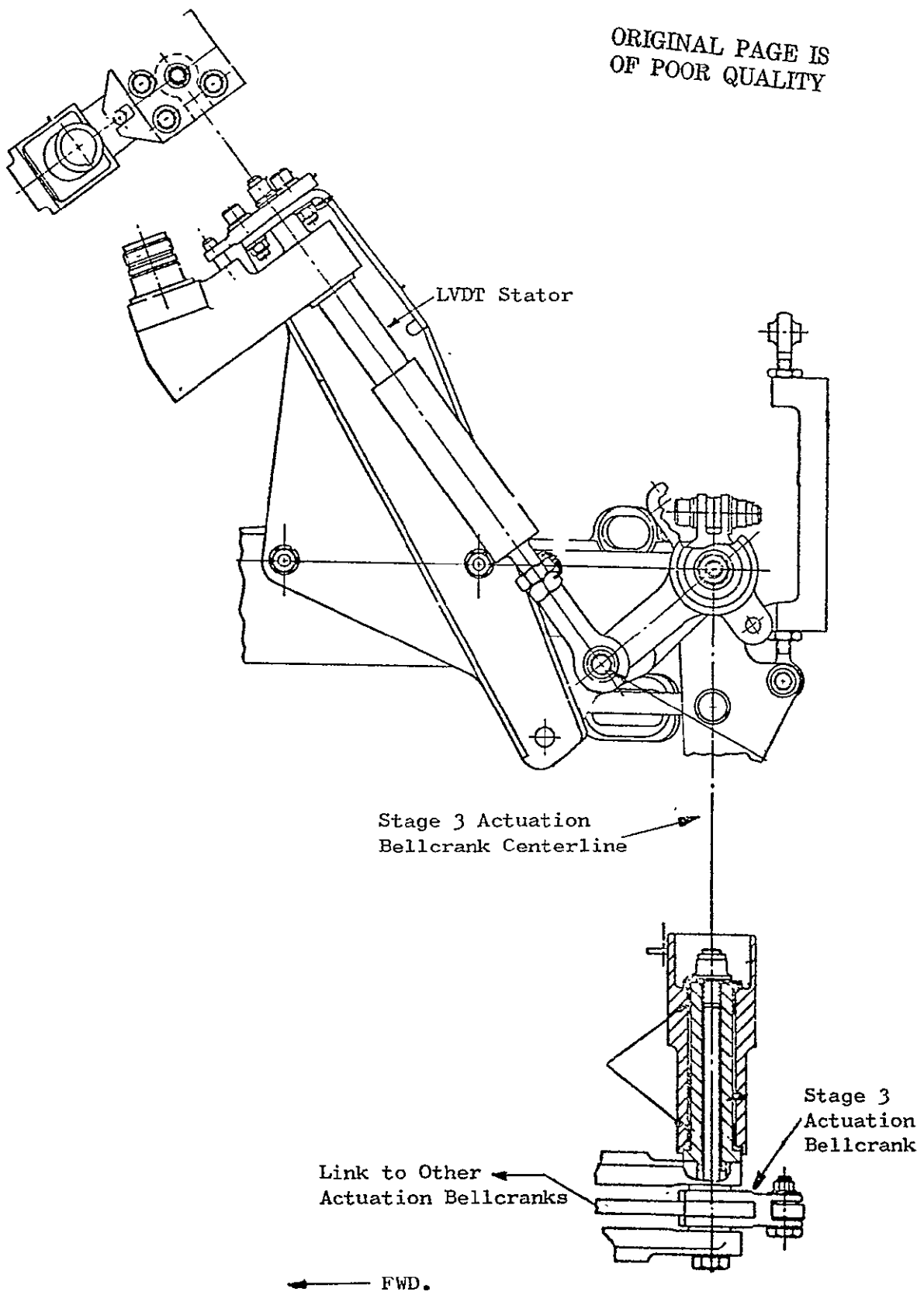


Figure 74. Core Stator Feedback LVDT.

9.4 VARIATION FOR FLIGHT DESIGN

For a flight design there would be little or no change in the core stator actuators. The control loop would probably be modified somewhat to incorporate simplified hydromechanical backup elements to provide some stator control in the event of a primary control malfunction.

For a second generation QCSEE, it is expected that digital electronic technology will have advanced and been operationally proven to be sufficiently reliable that no hydromechanical backup will be necessary.

10.0 SENSORS

The engine sensors are the devices which change the variable to be measured into a form that can be used as an input signal to the engine digital or hydromechanical control or as an input signal to an indicator gage. The sensors include the following:

- Low Pressure Turbine (LPT) Speed Sensor
- Fan Inlet Temperature Sensor
- Compressor Discharge Temperature Sensor
- Absolute Pressure Transducers
- Differential Pressure Transducers

10.1 LOW PRESSURE TURBINE (LPT) SPEED SENSOR

The LP shaft speed sensors produces two electrical signals that represent the rotation speed of the low pressure turbine shaft. One signal will be used for governing engine fan speed. The other signal will be used to limit the rate of speed change and maximum speed in the event of a loss of fan load, overspeed, or control failure. Each signal contains a signature which occurs once per revolution for dynamic balancing.

The speed sensor is very similar to that used on the F101 engine and is utilized as shown in Figure 75. The sensor consists of a curved metal tube containing lead wires with a magnetic pickup having a positioning flange on one end and an electrical connector (plus a mounting flange with a compression spring) on the other end. Design features are:

Rated speed (100%)	7996 rpm
Shaft acceleration	± 1200 rpm/sec
Environmental temperature	-40° F to 350° F (-40° C to 176.7° C)
Signal frequency	36 pulses/rev with a 1/rev signature
Signal amplitude (at 10% speed)	0.2 volts peak-to-peak minimum
Signal amplitude (at 100% speed)	10.0 volts peak-to-peak maximum
Balance signal (1/rev) amplitude ratio	2:1

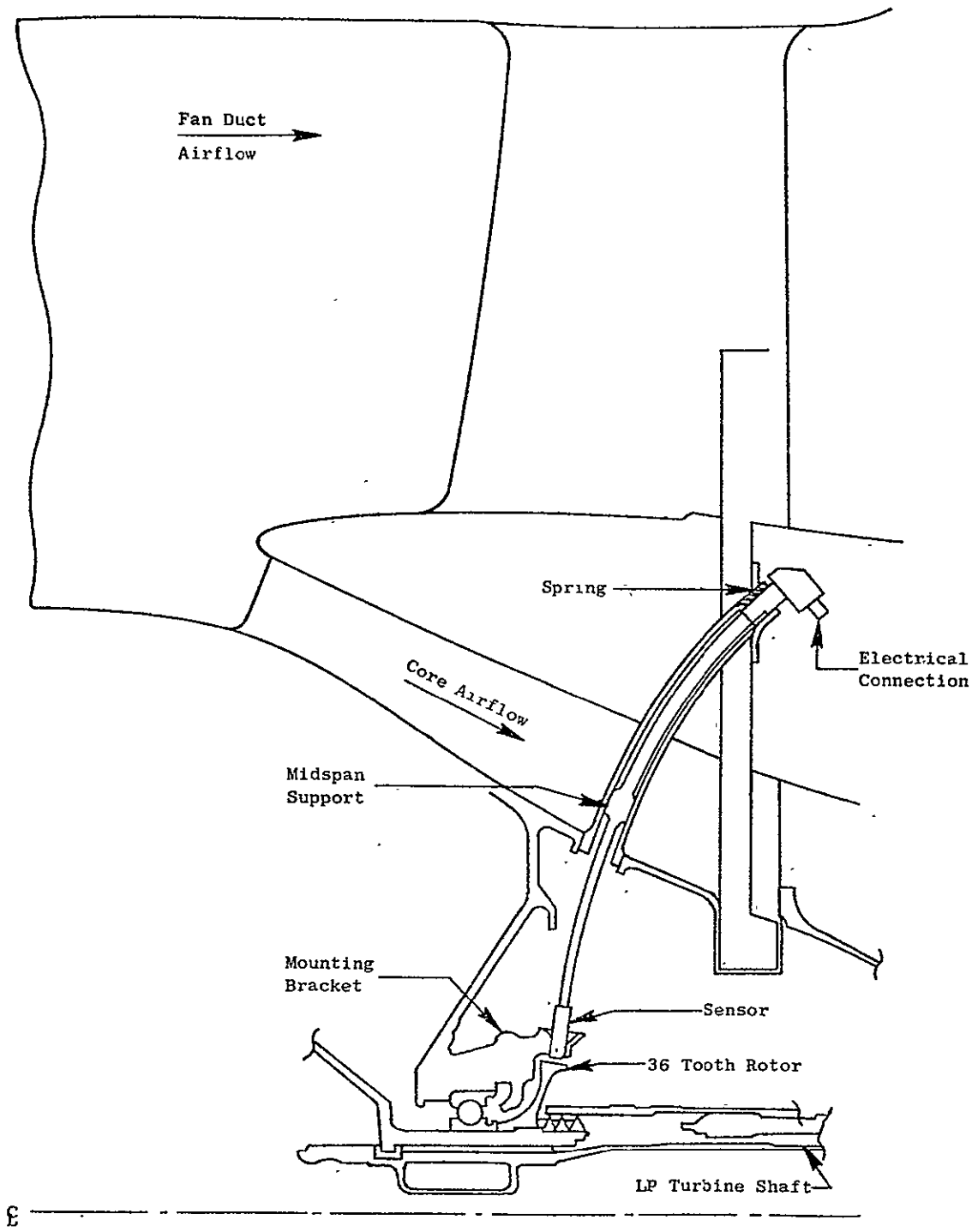
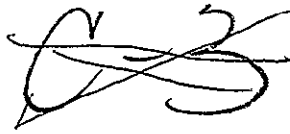


Figure 75. Low Pressure Turbine Speed Sensor.



The magnetic pickup consists basically of a permanent magnet behind a soft-iron pole piece containing a bobbin on which two coils have been wound. The magnetic flux linking the coil is high when a ferrous metal object (tooth) is placed in front of the pole piece and is low with no ferrous metal (slot) in front of the pole piece. The generated voltage is proportional to the rate of flux change in the pole piece, and the frequency of the a.c. signal is a product of the number of teeth and shaft speed in revolutions per second. The wave form of the signal is nearly sinusoidal depending upon the relative width of slots and teeth on the rotating disk and also the width of the pole piece relative to the slots and teeth. Signal output from the sensor is routed to a conditioner device in the digital control which produces a uniform voltage amplitude and wave form at varying speed so that ultimately the conditioned signal is interpreted in terms of frequency rather than voltage amplitude.

The sensor is installed (see Figure 75) in a fan frame strut by passing the pickup end through a tube in the strut until it is positioned in close proximity to a gear-like wheel located immediately aft of the LPT shaft front bearing. The spring-loaded mounting flange at the connector end is bolted to a pad on the aft side of the strut near the outside.

The flight design of the LPT speed sensor will be similar to that shown except for possible variations in external configuration.

10.2 FAN INLET TEMPERATURE (T12) SENSOR

The T12 sensor provides the engine control with an electrical signal representing the total temperature of the air entering the fan for use in scheduling and computing within the digital control.

The fan inlet temperature sensor in Figure 76 is identical to that used on the F101 engine. The sensor is a wire-wound resistance-type device mounted on and protruding through the inlet duct into the fan inlet airstream. The sensor consists of a sensing element and housing. The sensing element contains a platinum wire wound on a cylindrical platinum mandrel. The wires are insulated from each other and from the mandrel by a ceramic insulant. The element is hermetically sealed in a capped platinum sheath and the connections are potted. The housing is a slotted airfoil which controls the airflow so that the sensed temperature is that of the free stream. A series of small holes bleeds off the boundary layer and turns the stream, but not heavier particles, inward toward the sensing element. The boundary-layer air is exhausted out the top. Some of the diverted airstream flows through the first slot and carries the lighter liquid contaminants. The remaining portion of the diverted flow goes through the second slot and around the sensing element. Free-stream air, which flows around the sensing element, does not contact any portion of the sensor housing or airfoils.

The T12 sensor operates on the principle that the resistance of the platinum wire is a predictable function of temperature. A constant direct current of 12.5 mA is applied to the sensor coil and the voltage used as an indication of temperature.

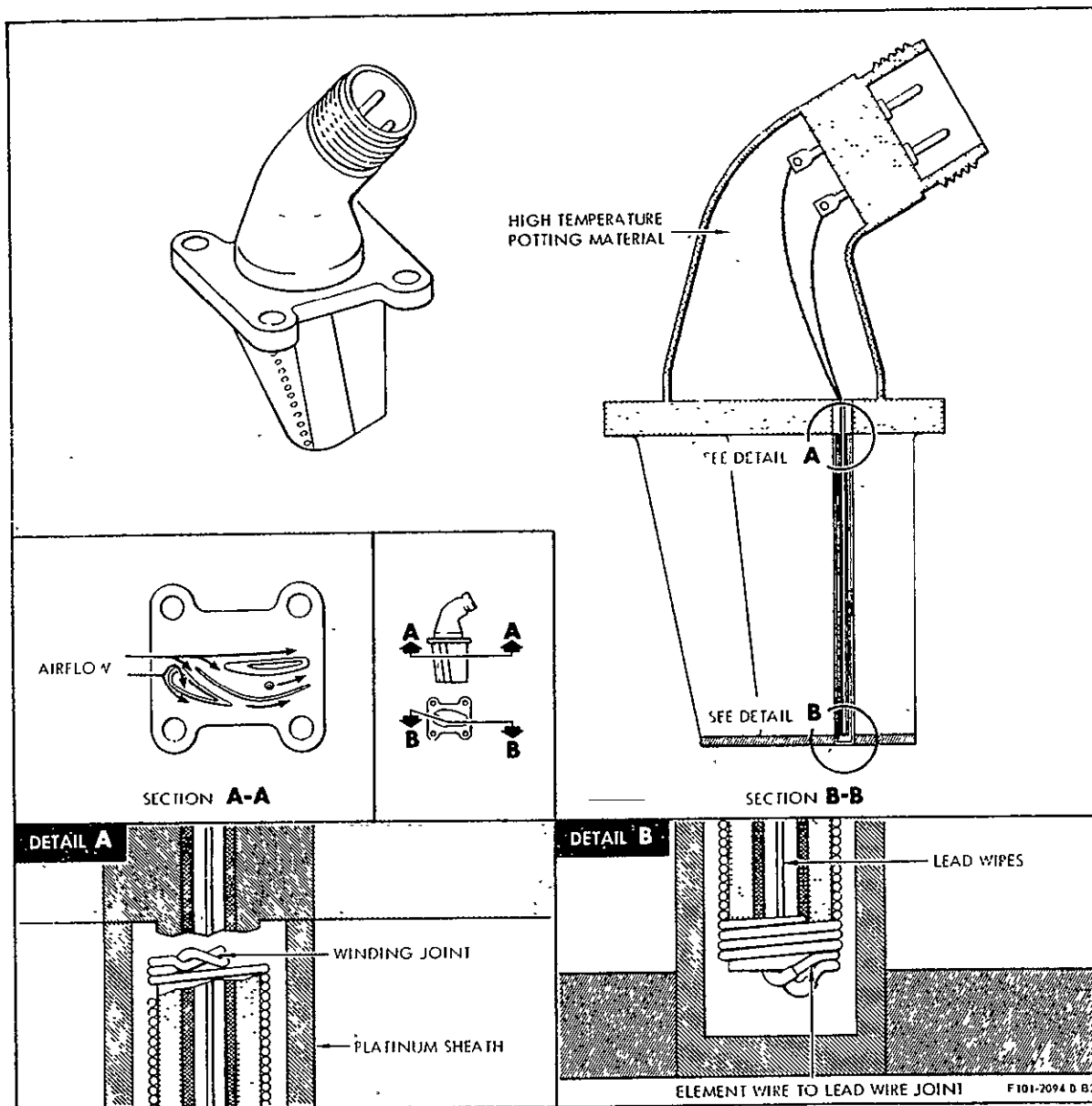


Figure 76. Fan Inlet Temperature (T12) Sensor.

Design Features

Temperature Range	-40° C to 7.1° C (-40° F to 160° F)
Resistance Range	168 to 256 ohms
Excitation	12.5 mA d.c. (constant)
Accuracy	±1.11° C (±2° F) maximum
Recovery Error	Less than 0.5% at Mach 0.4
Response Time (to 63.2% of final value)	Less than 5 seconds to 48.8 kg/sec/m ² (10 pps/ft ²) airflow

10.3 COMPRESSOR DISCHARGE TEMPERATURE SENSOR (T3)

Compressor discharge temperature is sensed by a thermocouple located in the core air flowpath at the entrance to the combustor. The thermocouple signal is used in the digital control for calculation and control of turbine inlet temperature.

The temperature sensor shown in Figure 77 is similar to that used on the F101 and CFM56 engines. The sensor is mounted on the outer combustor case utilizing an existing engine borescope plug. The sensor will protrude through the inner combustor case and into the combustor outer-flow passage. The probe construction will be ruggedized for reliability utilizing a stainless steel sheathed-lead sealed at the sensor and connector ends. The design of the temperature sensor tip will optimize time response and repeatability of the measurement.

The probe consists of an ungrounded chromel-alumel thermocouple, encapsulated in a swaged magnesium-oxide tip which senses the air temperature surrounding the probe tip. The output signal from the sensor is routed directly to the digital control.

10.4 ABSOLUTE AND DIFFERENTIAL PRESSURE TRANSDUCERS

Two absolute-pressure transducers and two differential-pressure transducers are included within the QCSEE engine-mounted digital control to convert air pressure inputs into electrical signals for use in the control. Pressures sensed are:

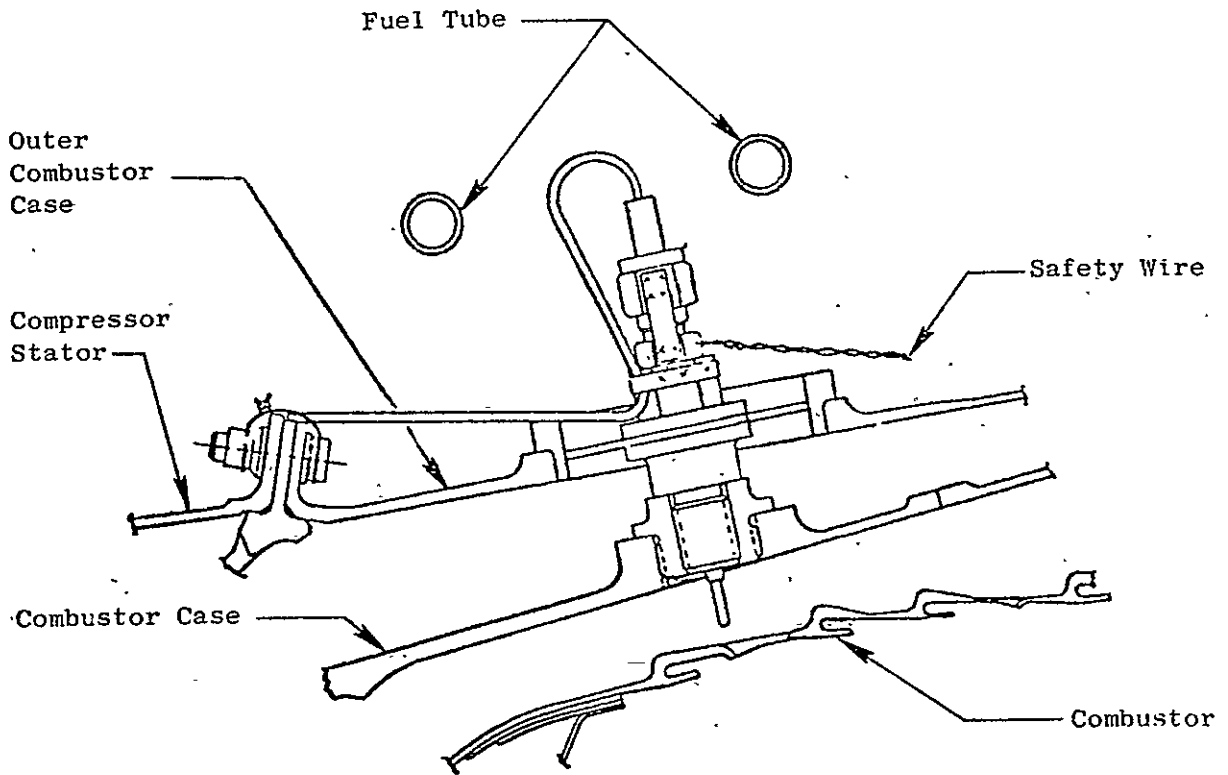


Figure 77. Compressor Discharge Temperature (T3) Sensor.

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Absolute

Compressor Discharge Static Pressure (PS3)

Free Stream Total Pressure (PTO)

Differential

PTO-PS11 (Inlet Throat Static Pressure)

P14-PTO (P14 is Fan Discharge Pressure)

It should be noted that the P14-PTO sensor was included as a potential thrust parameter. As noted in Section 4.0, this is not the thrust parameter to be used during initial experimental engine testing, but the transducer has been retained and may be used at a later time.

Location of the source for these sensed pressures (except P14) was discussed in Section 4.9. Operating ranges are 0 to 300 psia for PS3, 0 to 20 psia for PTO, and 0 to 12 psid for both differential transducers.

All of these sensors are thin-film, strain gage bridge transducers identical to those used in the F101 engine. A typical cross section is shown in Figure 78. The sensors receive their electrical excitation from the control and change the ΔP and static pressure signals to electrical signals. They are located inside the digital control chassis.

The strain member is a cantilever beam on which a ceramic film is deposited for electrical insulation. The thin metal film resistors forming a 4-element Wheatstone bridge are vacuum deposited on the ceramic insulator film. The beam is linked to a force-collector diaphragm which induces a strain on the beam proportional to applied pressure.

The sensors operate on the principle of a mechanical distortion producing a change in electrical resistance across a strain gage and, hence, a change in electrical current output from a bridge circuit. Referring to Figure 78, pressure is ported to the sensing diaphragm which deflects and drives a linkage pin against the sensing beam. The beam is shaped in such a way that it bends and causes "stretch" on the surface to which the strain gages are attached.

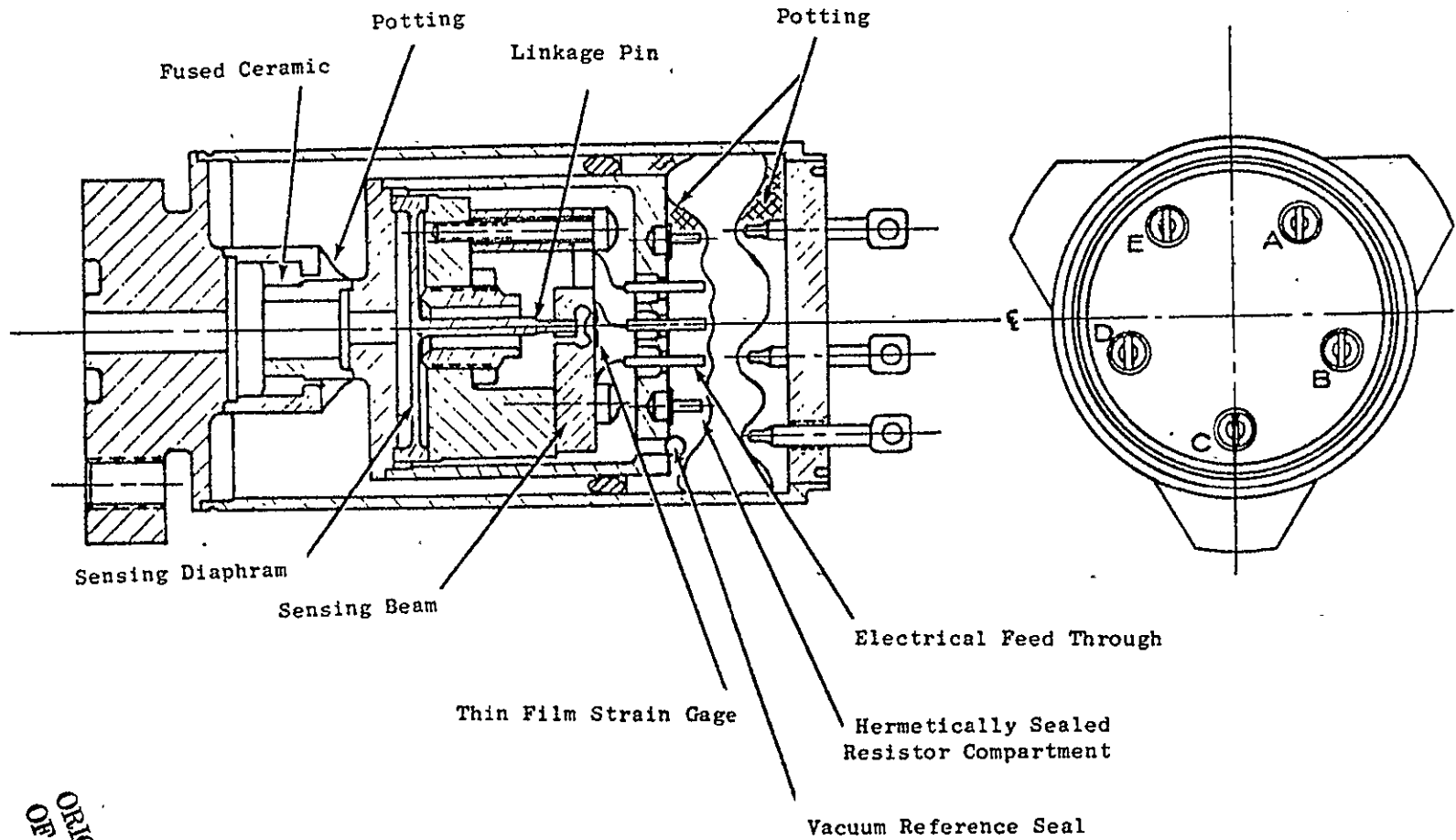


Figure 78. Pressure Transducer.

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11.0 MISCELLANEOUS

11.1 CONTROL ALTERNATOR

The QCSEE control system includes an engine-driven control alternator that provides primary power for operation of the digital control, power for an isolated emergency fan overspeed function in the digital control, and core speed indication both for the digital control and for remote indication.

The control alternator, which is identical to the one used on the F101 engine, is shown on Figure 79. It consists of a rotor containing 12 equally spaced permanent magnets with adjacent magnets having opposite polarity and a stator containing a laminated soft-iron core with 12 equally spaced poles wound with magnet wire. The coils are combined into four separate windings and utilized as shown on Figure 79. The voltage generated in each coil is proportional to the rate of flux change in the stator poles, and the frequency is proportional to the number of rotor pole pairs, both determined by speed of the rotor.

Outputs of the windings at 100% speed (24,903 rpm) are:

<u>Winding</u>	<u>Maximum Open Circuit Voltage (volts rms)</u>	<u>Maximum Short Circuit Current (amperes rms)</u>
A	310	3.5
B1 & B2	243	1.7
C	106	5.9
D	71	5.9

The alternator is mounted on the aft side of the accessory gearbox near the left end when looking forward. The rotor mounts to and is driven by a shaft protruding from and supported by bearings in the gearbox. The rotor hub threads (left-hand) onto the shaft until it seats and is positioned by a nonlocking taper. A left-hand thread locknut with a Vespel insert is used to secure the rotor. A pilot, with an O-ring seal, positions the stator radially. The stator is clamped to the gearbox by means of locknuts (and washers) threaded to three studs protruding from the gearbox pad.

11.2 ELECTRICAL INTERCONNECTIONS

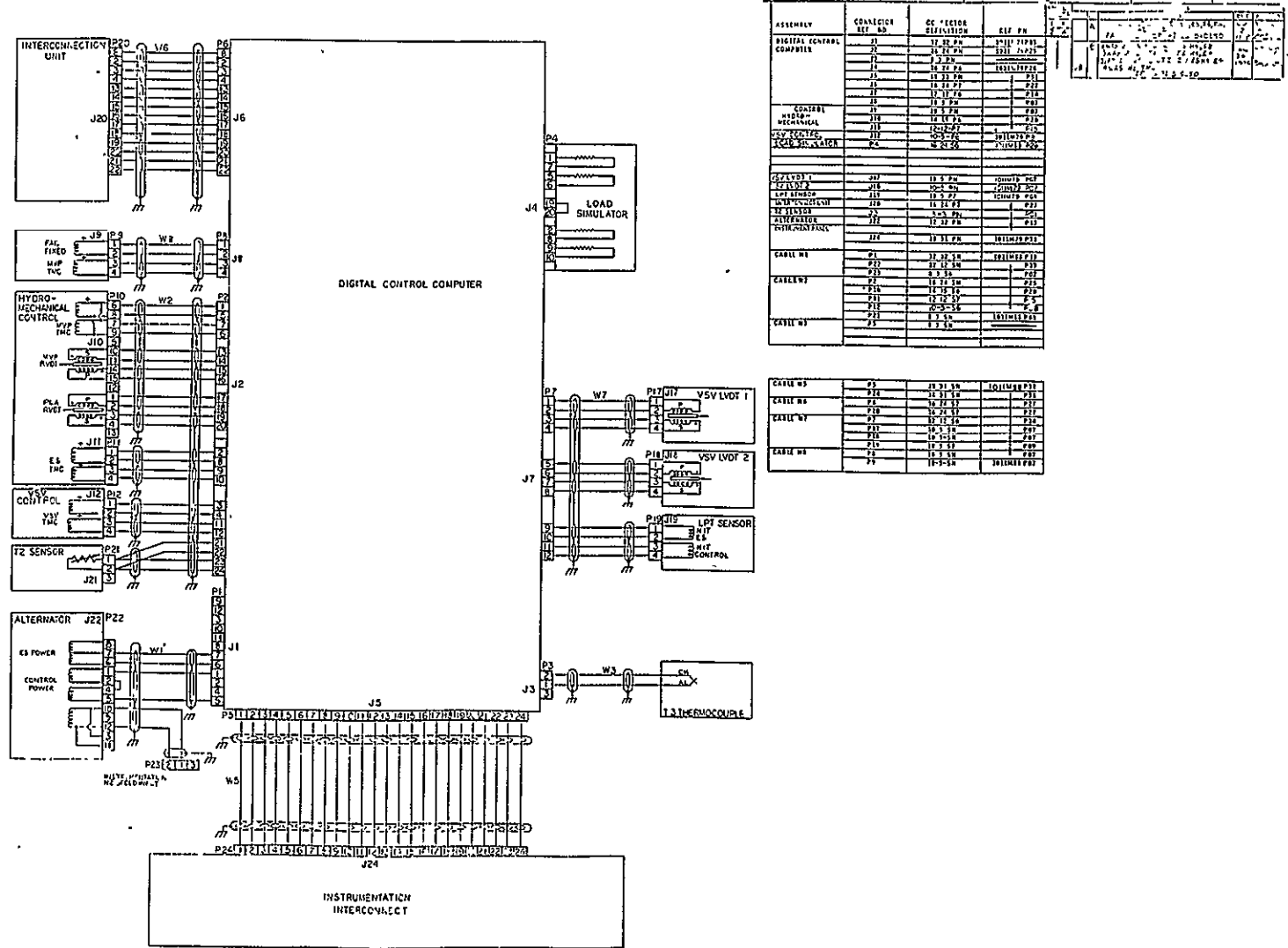
Electrical interconnections in the QCSEE control system are accomplished using connector and cable designs essentially equivalent to those used on the F101. Stainless steel connectors are used on all connectors on and around

the engine. Interconnecting cables are made up with wires combined in shielded, twisted pairs to minimize electromagnetic interference. Virtually all individual wires are of stranded AWG 20.

An electrical interconnection schematic is shown on Figure 80.

11.3 WEIGHT

Weight estimates have been made for all system components, both for the designs to be used on the experimental engine and for predicted flight engine designs. The weight estimates are tabulated in Table XIV.



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Figure 80. Electrical Interconnections.

Table XIV. Control System Weight.

	Experimental	Predicted Flight
	(lbs)	
Fuel Pump	16.5	14.5
Fuel Filter	2.7	3.4
Hydromechanical Control	41.0	20.0
Core Stator Actuators (2)	4.0	4.5
Drain Eductor	3.0	---
<u>Eductor Flow Regulator</u>	<u>3.0</u>	<u>3.0</u>
Fuel System Total	70.2	45.4
Digital Control and Mounting Hardware	51.6	26.0
Alternator	3.5	4.5
LPT Speed Sensor	1.1	1.1
T12 Sensor	0.5	0.5
<u>T3 Sensor</u>	<u>1.0</u>	<u>1.0</u>
Electrical System Total	57.7	33.1

APPENDIX A

NOMENCLATURE DEFINITION

A8	Exhaust Area
A41	High Pressure Turbine Inlet Area
A49	Low Pressure Turbine Inlet Area
βC	Core Stator Vane Angle
FD	Ram Drag
FG	Gross Thrust
FN	Net Thrust
HP	High Pressure
LP	Low Pressure
MO	Aircraft Mach Number
M11	Inlet Throat Mach Number (Same as XM11)
N1K	Same as PCNLR
N1T	Percent Fan Turbine rpm
NH	Core rpm
NL	Fan rpm
OTW	Over-The-Wing
PAMB	Ambient Pressure
PCBP	Compressor Bleed Pressure
PCNH	Percent Core rpm
PCNHR	Percent Corrected Core rpm ($PCNH/\sqrt{T25.518.7}$)
PCNL	Percent Fan rpm
PCNLR	Percent Corrected Fan rpm ($PCNL/\sqrt{T12/518.7}$) (Equivalent to N1K)
PLA	Power Lever, Angle
PS3	Compressor Discharge Static Pressure
PS3QOT	PS3/PTO
P8	Core Exhaust Nozzle Throat Total Pressure
PS8	Core Exhaust Nozzle Throat Static Pressure
PS11	Inlet Throat Static Pressure
PS14	Fan Discharge Static Pressure
PTO	Free Stream Total Pressure
P14	Fan Discharge Total Pressure
P14QOT	P14/PTO
P15	Bypass Duct Inlet Total Pressure
P49	Low Pressure Turbine Inlet Total Pressure
P49QOT	P49/PTO
SM12	Fan Stall Margin
TP1, TP2, etc.	Thrust Parameters as Defined in Section 4.2.1
TO	Ambient Temperature
T1	Nacelle Inlet Total Temperature
T2	Fan Inlet Total Temperature (Hub)
T3	Compressor Discharge Total Temperature
T8	Core Exhaust Total Temperature
T8QT2	Same as T8/T12
T12	Fan Inlet Total Temperature
T12R	Fan Inlet Reference Total Temperature (Figure 7)
T15	Bypass Duct Inlet Total Temperature

T25	Core Inlet Total Temperature
T41	High/Low Pressure Turbine Inlet Total Temperature
T41C	T41 Calculated from T3, WF, and PS3
T41CT2	Same as T41C/T2
T49	Low Pressure Turbine Inlet Temperature
T49QT2	Same as T49/T12
UTW	Under the Wing
VSV	Variable Stator Vane Position (Equivalent to βC)
WC	Cooling Bleed Airflow
WFM	Engine Fuel Flow
W25	Core Air Flow
XM11	Same as M11

APPENDIX B

CONTROL SYSTEM FAILURE ANALYSIS

Failure	Control System Effects	Engine Effects
A. <u>Electrical Power Supply Failure</u>		
1. Lose digital control power supply (alternator, lead or connector failure).	WF decreases to min. WF.	Decel to below Idle
2. Lose emergency overspeed circuit power supply (alternator, lead, or connector failure).	Lose fan overseed protection. Fault light will notify operator.	No immediate effect. Emergency fan overspeed protection lost, normal maximum. N1 limit retained.
3. Lose power to control room elements of digital control.	Lose commands to digital control. Fault will be detected through test word and control will revert to next to last set of commands.	Remains at prefault condition. Manual thrust reduction possible with backup N2 hydromechanical governor.
B. <u>Electrical Feedback Failures</u>		
1. Lose WF metering valve feedback signal.	Digital control senses maximum WF. This exceeds accel schedule and causes WF reduction to minimum WF.	Decel to below idle.
2. Lose VSV feedback signal.	Indicates VSV at mid-range position equivalent to approximately 75% corrected rpm, 30% thrust (SLS). VSV will go fully closed if operating below this rpm, fully open if operating above.	Potential core compressor stall at high power settings, thrust loss at low power settings.
3. Lose LPT rpm signal to digital control	Senses N1 loss causing WF increase until N2 sched., T41 limit or inlet Mach limit encountered (unless already on one of these). Low N1 override closes VSV. (Fail-safe feature).	Thrust loss due to closed VSV.
4. Lose LPT speed signal to emergency overspeed circuit.	Lose emergency overspeed protection. Loss of N1 readout notifies operator.	No immediate effect. Emergency overspeed protection lost, normal maximum N1 limit retained.

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Failure	Control System Effects	Engine Effects
C. <u>Electrical Input Failures</u>		
1. Command data link.	Lose commands to digital computer. Fault detected through test word. Computer will revert to next to last set of commands.	WF control remains at prefault condition. Manual rpm reduction and shutoff possible with hydro-mechanical control.
2. T12 sensor open circuit.	Sensed T12 goes to 160F, fan speed reduced 600 rpm or less depending on conditions, VSV close 18° or less.	Thrust reduction of up to 25%.
3. T12 sensor element short circuit.	Sensed T12 goes to -40° F, backup T12 input (adjusted to be just below actual T12) is selected for control functions.	Small VSV shift open, NI increase if actual T12 > 90° F.
4. T12 sensor circuit shorted to ground.	Sensed T12 shifts a small amount to -40° F depending on location of short. Same effect as C.3.	Same as C.3.
5. T3 thermocouple circuit open, shorted lead-to-lead, or shorted to ground.	T41C low resulting in loss of over-temperature protection	Turbine overtemperature if operating on T41C limit. If not on limit no immediate effect but overtemperature protection lost. Low T41 indication alerts operator.
6. Fuel temperature signal lost.	Reduction in WF in starting range.	Reduction in starting WF, possible hung start if actual fuel temperature is low.
7. Throttle RVDT failure.	No effect. Currently used only for indication.	No effect.
D. <u>Pressure Sensing Failures</u>		
1. PTO sensing line leak.	No effect for sea level operation. At altitude, a false low inlet $\Delta P/P$ is sensed which in effect raises the $\Delta P/P$ limit.	No effect at sea level. At altitude flight conditions with high power setting, engine could accel to NI or T41C limit and inlet might choke.
2. PTO sensor open or short.	Sensed PTO at max. or min depending on location of fault. <u>Failure to max</u> - a false low inlet $\Delta P/P$ is sensed causing WF to decrease to min. WF.	Decel to below idle.

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Failure	Control System Effects	Engine Effects
<p>D. <u>Pressure Sensing Failures</u></p> <p>3. PS11 sensing line leak.</p> <p>4. PTO-PS11 sensor open or short circuit</p> <p>5. PS3 sensing line leak.</p> <p>6. PS3 sensor open or short</p>	<p><u>Failure to min</u> - a false low inlet $\Delta P/P$ is sensed resulting in a continuous $\Delta P/P$ error in a direction to increase WF.</p> <p>Sensed PS11 shifts upward giving a false, low indication of inlet $\Delta P/P$ and, in effect, raising the $\Delta P/P$ limit.</p> <p>Sensed inlet $\Delta P/P$ shifts to near max. or near min. depending on location of fault. Results same as D.2 above.</p> <p>Accel fuel schedule reduced and T41C sensing error in upward direction introduced.</p> <p>Sensed PS3 shifts to near max. or min extreme depending on location of fault.</p> <p><u>Failure to max.</u> - Accel fuel schedule raised and T41C in error in low direction.</p> <p><u>Failure to min.</u> - Accel fuel schedule reduced and sensed T41C in error in high direction.</p>	<p>Same as D.1 above.</p> <p>Same as D.1 above.</p> <p>Same as D.2 above.</p> <p>Small leak, no effect. Large leak will cause thrust reduction.</p> <p>Stall or overtemperature may occur on throttle burst. Steady state overtemperature if operating on T41C limit (engine should seldom be on this limit).</p> <p>Engine decel - probably to idle or below.</p>
<p>E. <u>Digital Control Failures</u></p> <p>1. WF output circuit to zero change condition.</p>	<p>Fail-fixed servovalve hydraulically locks fuel metering valve at position existing at time of failure.</p>	<p>Engine WF remains at pre-fault level, can be reduced in response to power level angle (PLA) with the backup governor in the hydromechanical control.</p>

Failure	Control System Effects	Engine Effects
E. <u>Digital Control Failures</u> (Cont'd)		
2. WF output circuit to max. increase.	Same as E.1 above.	Same as E.1 above.
3. WF output circuit to max. decrease.	Same as E.1 above.	Same as E.1 above.
4. VSV output circuit to zero output	VSV go to actuator stop in closed direction.	Thrust loss.
5. VSV output circuit to max. open.	VSV go to actuator stop in open direction.	Compressor stall.
6. VSV output circuit to max. closed.	Same as E.4 above.	Same as E.4 above.
7. Analog-to-digital conversion failure.	Detected by self-test feature. WF output goes to zero change condition. VSV output update stops and output drifts toward closed.	Initially WF remains at pre-fault level, VSV slowly closes resulting in N2 increase to backup governor setting. Decel can be accomplished with backup governor.
8. Digital-to-analog conversion failure.	Same as E.7 above.	Same as E.7 above.
9. Central Processor failure.	Same as E.7 above.	Same as E.7 above.
10. Digital computer clock	No effect. Operation continues on redundant clock, fault light notifies operator.	No effect.
F. <u>Hydromechanical Control System Failures</u>		
1. Hydromechanical fuel control metering valve fails open.	WF increases, increasing rotor rpm until operator or emergency overspeed function cuts off fuel flow.	Accel to overspeed limit and then to shutdown.
2. Hydromechanical control fuel bypass valve goes closed.	Fuel control loop closes metering valve to maintain schedules and limits. Excess fuel is bypassed through relief valve causing fuel temperature rise.	Possible WF instability, shutdown required to prevent excessive fuel heating.

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Failure	Control System Effects	Engine Effects
F. <u>Hydromechanical Control System Failures (Cont'd)</u>		
3. WF trim servovalve coil open circuit	Second coil continues to function. Possible slight change in servovalve gain. If second coil fails, metering valve becomes hydraulically locked at predefault position.	Probably no effect if one coil fails. If both fail, WF remains at predefault level, can be reduced by backup N2 governor in response to PLA.
4. WF trim servovalve feedback spring failure.	Servovalve proportional characteristic lost, WF unstable unless being controlled by backup governor.	WF unstable is in electrical control mode. Can be corrected by PLA retard to backup N2.
5. WF trim servovalve spool stuck.	Servovalve won't respond to input changes, remains at condition existing when spool stuck.	<p>Depends on predefault conditions as follows:</p> <p><u>Steady State</u> - WF remaining at pre-fault level. Can be reduced by backup governor in response to PLA.</p> <p><u>WF Increase</u> - Increase continues until backup governor interferes. PLA control with backup governor still available.</p> <p><u>WF Decrease</u> - Decrease continues to min. WF engine decels to below idle.</p>
6. WF trim servovalve jet plugged.	Servovalve tends to stay at condition existing when plugging occurred.	Same as F.5 above.
7. Emergency overspeed servovalve coil open circuit.	Second coil provides continued operation. If both coils fail, the overspeed function is lost and a fault light alerts the operator.	No effect if only one coil fails. If both fail, there is no immediate effect except that emergency overspeed protection is lost. Normal N1 limit is retained.
8. VSV servovalve coil fails.	No effect. Operation continues on redundant coil. Redundancy lost.	No effect.
9. VSV servovalve feedback spring fails.	Servovalve proportional characteristic lost, VSV unstable.	VSV unstable, possibly large enough to necessitate shutdown.

Failure	Control System Effects	Engine Effects
<p>F. <u>Hydromechanical Control System Failures (Cont'd)</u></p> <p>10. VSV servovalve spool stuck.</p> <p>11. VSV servovalve jet plugged.</p>	<p>Servovalve won't respond to input changes, remains at condition existing when spool stuck.</p> <p>Servovalve tends to stay at prefault conditions.</p>	<p>Depends on prefault conditions as follows:</p> <p><u>Steady State</u> - VSV remain at prefault position. If at high power setting, compressor stall likely when power setting reduced.</p> <p><u>VSV Opening</u> - Opening continues. Compressor stall likely.</p> <p><u>VSV Closing</u> - Closing continues, thrust is reduced.</p> <p>Same as F.10.</p>

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APPENDIX C

DIGITAL CONTROL PROCESSOR
SOFTWARE

1. Instruction Repertoire

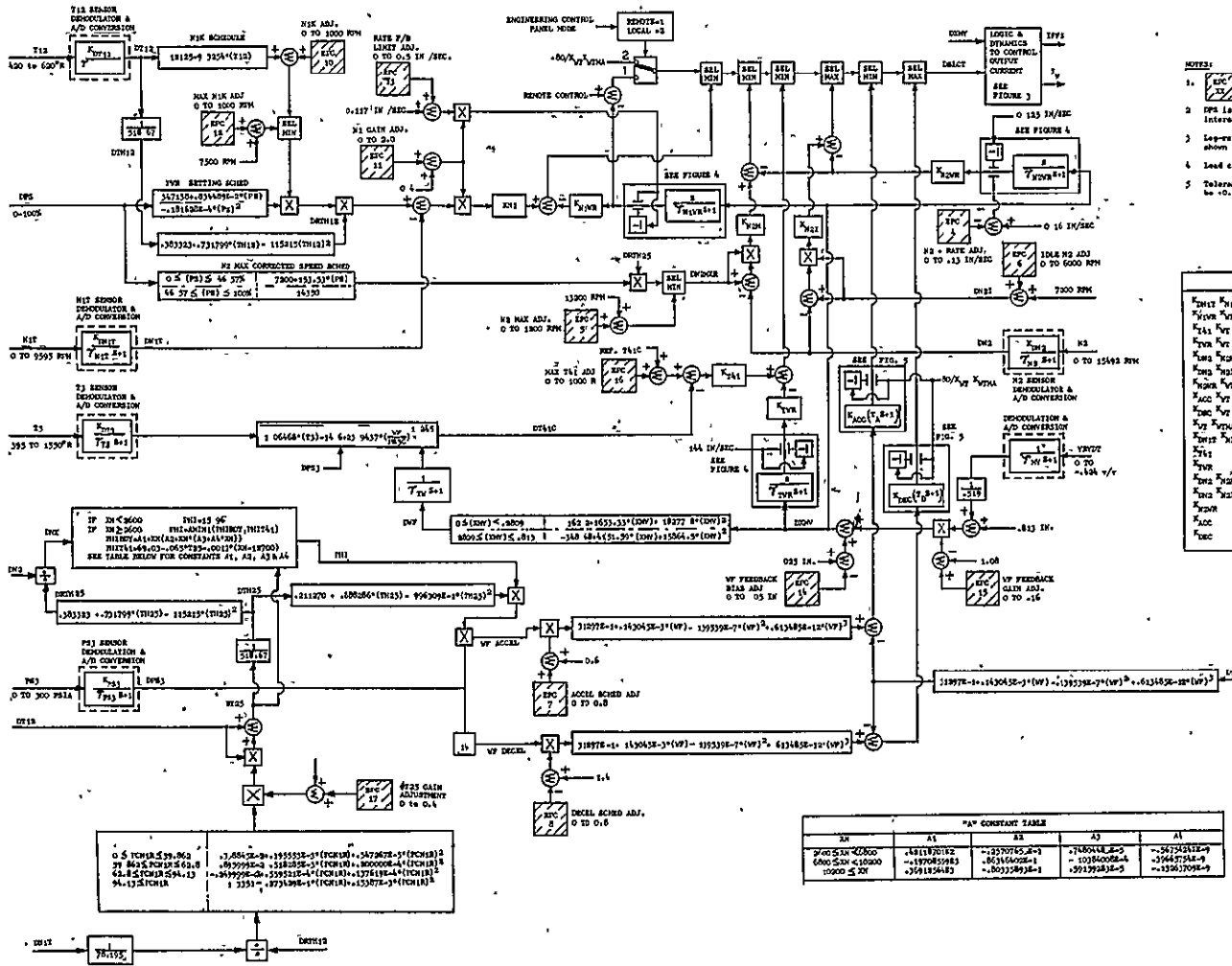
<u>Mnemonic</u>	<u>Execution Time (Microseconds)</u>	<u>Operation</u>
OUT 0	1	No - operation
OUT 1	1	Load DA converter
OUT 2	1	Sample Output Sample and Hold No. 1
OUT 3	1	Sample Output Sample and Hold No. 2
OUT 4	1	Sample Output Sample and Hold No. 3
OUT 5	1	Sample Output Sample and Hold No. 4
OUT 6	1	Sample Output Sample and Hold No. 5
OUT 13	1	Transmit accumulator off-engine equipment.
OUT 14	1	Initiate AD conversion
OUT 15	1	Reset program counter input counter
LDA XXX	1	Load accumulator with contents of scratch pad memory address XXX (XXX is 0 to 255).
LAI XXXX	12	Load accumulator with the number XXXX (0 to 4095).
LMI XXXX	12	Load MQ register with the number XXXX (0 to 4095).
ADD XXX	1	Add contents of scratch pad memory address XXX (0 to 255) to contents of accumulator.
ADD C. XXX	1	Add, with carry, contents of memory address XXX (0 to 255) to contents of accumulator.
SUB XXX	1	Subtract contents of scratch pad memory address XXX (0 to 255) from contents of accumulator.
SUBC XXX	1	Subtract, with borrow, contents of scratch pad memory address XXX (0 to 255) from contents of accumulator.
STO XXX	1	Store contents of accumulator in scratch pad memory address XXX (0 to 255).
BRMA XXXX	1	Branch on negative result of last subtraction to program memory address XXXX (0 to 4095).
BRMR XXXX	1	Branch on negative result of last subtraction to program memory address which is present address plus XXXX (XXXX must result in an address within the memory range-branch relative).

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<u>Mnemonic</u>	<u>Execution Time (Microseconds)</u>	<u>Operation</u>
INP 0	12	Transfer AD register to accumulator.
INP 1	12	Transfer command link register to accumulator.
MPYM XXX	12	Multiply scratch pad memory address register. Result is double precision with the most significant portion in accumulator and least significant portion in MQ register. Result is unsigned, and multiplication is fractional.
MPY XXX	12	Same as MPYM except multiplication in memory is signed as is result (two's complement).
RSH XXXX	1	Shift accumulator and MQ registers arithmetically right one place.
RSHM XXX	1	Shift accumulator and MQ registers right logically one place.
ROT XXX	12	Interchange the contents of the accumulator and the MQ registers.
DIV XXX	12	Divide the contents of the combined accumulator and MQ registers by the signed divisor in scratch pad memory address XXX (0 to 255). Quotient is in MQ register and is signed (one's complement). Division is not fractional.
JUPA	1	Same as BRMA except transfer is unconditional.
JMPR	1	Same as BRMR except transfer is unconditional.

2. BLOCK DIAGRAM

The digital control processor is designed to perform the control functions shown in block diagram form on Figures 81 through 86.



DIGITAL GAIN	
K_{P1}	0.1825 MA/RPM
K_{P2}	164.5 MA/2000
K_{P3}	5.954×10^{-3} MA/R
K_{T1}	33.85 MA/10/SEC
K_{T2}	2.967210^{-3} MA/2000RPM
K_{T3}	1.618210^{-3} MA/2000RPM
K_{ACC}	164.5 MA/20/SEC
K_{TDC}	403.7 MA/2M
K_{TDC}	403.7 MA/2M
K_{TDC}	7.564
K_{TDC}	1.618×10^{-3}
K_{TDC}	4.9452×10^{-3}
K_{TDC}	4.3412
K_{TDC}	2.9121510^{-3} MA/2000RPM
K_{TDC}	2.4134210^{-3} MA/2000RPM
K_{TDC}	21.709
K_{TDC}	33.62
K_{TDC}	33.62

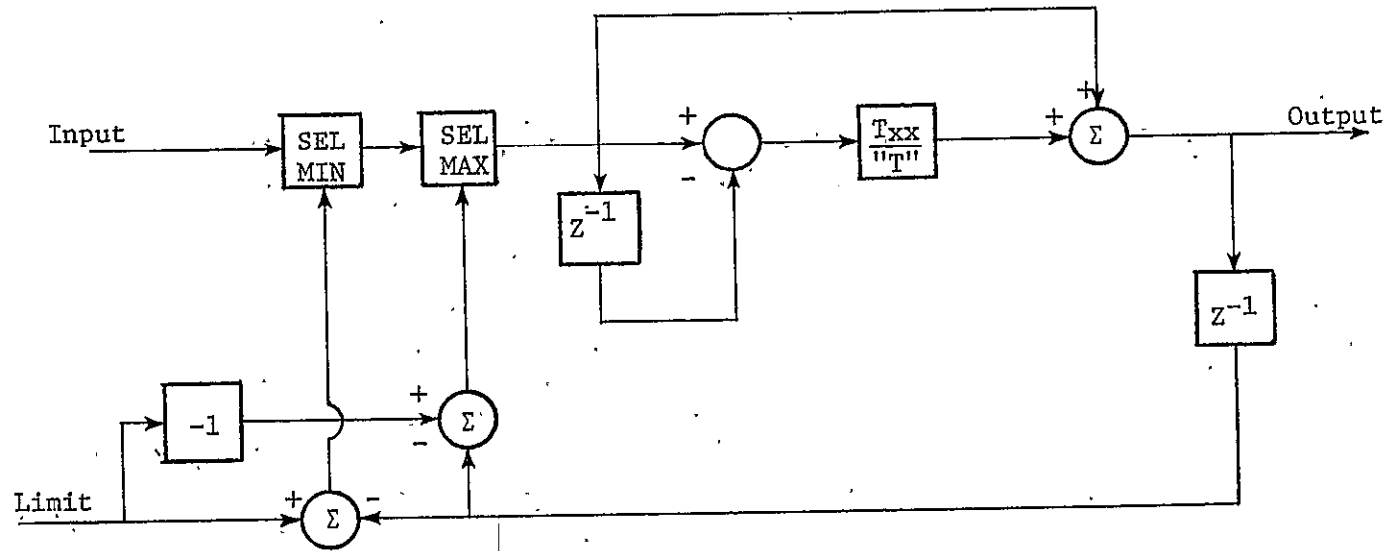
TIME CONSTANTS	
FREQUENCY RANGE	VALUE, SEC.
T11	$\leq 6^{\circ}$
T20R	0.5
T20R	0.5
T21T	≤ 0.01
T24	≤ 0.01
T23	$10^{-3} \times T_{20R}^{**}$
T24	0.05
T25	≤ 0.01
T26	0.05
T27	0.10
T28	0.05
T29	≤ 0.05

* $\theta = 10$ PPM/PS AIR FLOW DENSITY
 ** $T_{20R} = 0.05$
 *** $T_{20R} = 0.05$

A CONSTANT TABLE			
SN	A1	A2	A3
2400-2410	4.911870182	-0.2207452-1	-1.2480418-0
6000-6010	-1.1770451983	-0.82164028-1	-0.10180008-4
10000-1010	-0.3911824483	-0.403128492-1	-0.22130136-3

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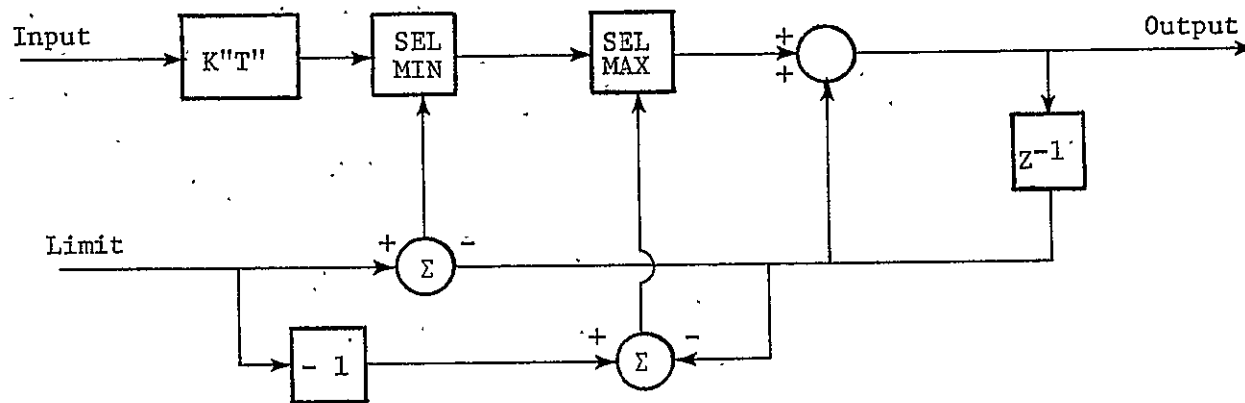
Figure 81. QCSEE OTW Fuel Flow Control Block Diagram.



Notes

1. Z^{-1} Value at Last Iteration
2. "T" Digital Control Sampling Rate
3. T_{xx} Required Time Lead

Figure 83. Lead Circuit Mechanization.

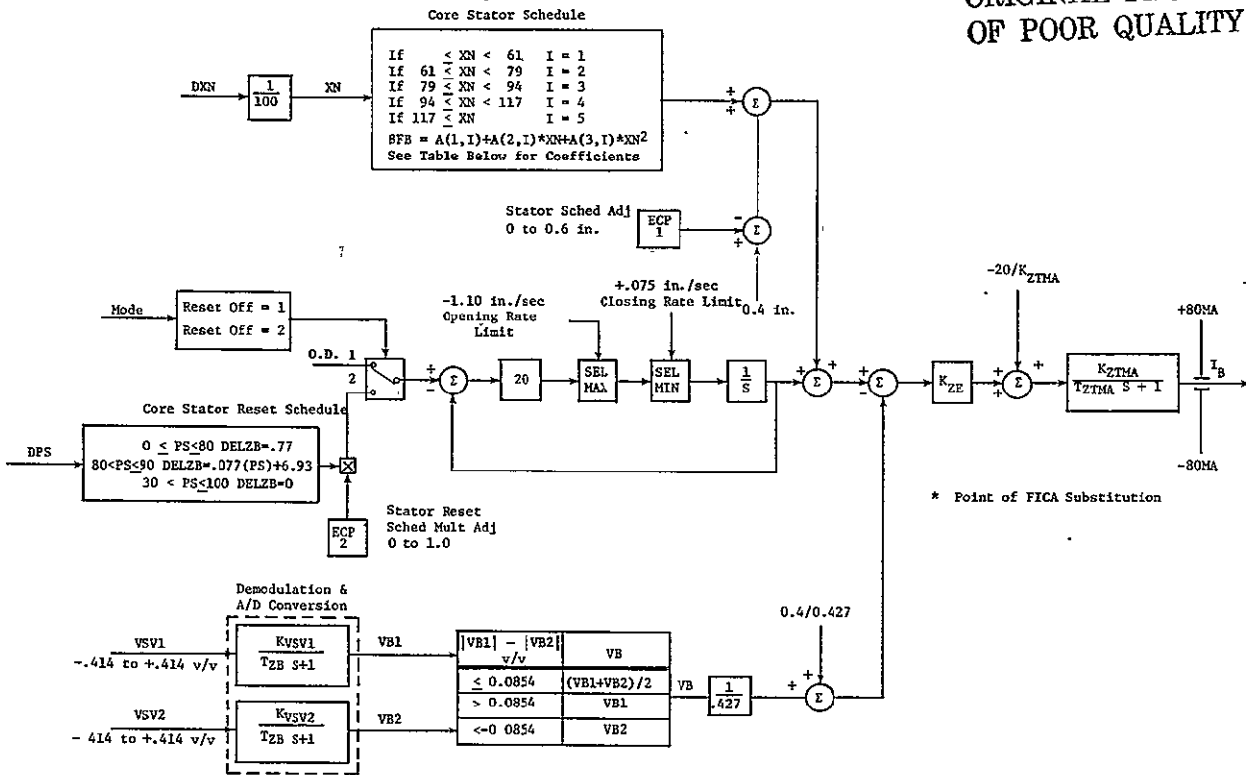


Notes

1. Z^{-1} Value at Last Iteration
2. "T" Digital Control Sampling Rate

Figure 85. Integrating Circuit Mechanization.

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Notes

1. **ECP XX** Denotes Potentiometers on Engineering Control Panel, Figure 65.
2. DPS is Digital Power Setting from Interconnect Unit.
3. Integrating Circuit Mechanized as Shown in Figure 85.
4. Tolerance on all Bias and Limit Values Shall be ± 0.1 Percent of the Specified Full Scale Range.

Coefficient Table			
A(1,I)	A(2,I)	A(3,I)	I
2.2795249	-0.013151068	0.71650476E-4	1
0.87748352	0.032617459	-0.30322192E-3	2
8.3086021	-0.14282437	0.72784862E-3	3
-5.7799969	0.16498718	-0.95213391E-3	4
16.450925	-0.22620007	0.76669457E-3	5

Time Constants	
Frequency Range 0.01 to 10.0 Hz	
Symbol	Value, sec
T_{ZTMA}	≤ 0.01
T_{ZE}	≤ 0.01

Digital Gains	
K_{ZE} K_{ZTMA}	453 ma/in.

Figure 86. QCSEE OTW Compressor Stator Control Block Diagram.

3. INPUT ORDER LIST

Input Number	Input Name	Ram Storage Address	Scaling
<u>Analog</u>			
1	A/D test word	Temperature	5 volts
2	PLA	74	204+ (0.14115*DEG) b/DEG
3	N2	42	3.7832 RPM/bit
4	N1T	45	4.3431 RPM/bit
5	T12	46	(bits* 0.04884) -40 = ° F
6	T3	41	(bits* 0.2823)-65 = ° F
7	MVP	43	(bits* -204)* 0.00022068 = Inches
8	PTO	48	0.00464 psia/bit
9	PS3	44	0.07326 psia/bit
10	PTO-PS11	47	0.00293 psid/bit
11	P14-PTO-Not Used		
12	Not Used		
13	BC1	75	((bits-204)/4449.27536)- 0.404v/v
14	BC2	76	Same as Input 13
15	O/S TM Sig.	77	
16	Hyd. Pump Pressure	78	Undefined
17	WF Temperature	79	13.65 bit/° F
18	WF Man. Pressure	80	5.12 bit/psia
19	EGT	81	2.05 bits/° F
20	WF	82	0.410 bits/PPH
21	Oil Inlet Pressure	83	27.30 bits/psig
22	Scavenge Oil Pressure	84	27.30 bits/psig
23	Lub. Inlet Temp.	85	16.38 bits/° F
24	Oil Disch. Temp.	86	11.70 bits/° F
25	T25	87	20.475 bits/° F
26	P5	88	163.80 b/psia
27	G/B Inner Race Temp.	89	13.64 b/° F
28	Horizontal Vib.	71	81.90 b/mil
29	Vertical Vib.	70	81.90 b/mil
30	VSV Position	90	(4095/(VSV° +5)) b/°VSV
31	Clock Fail Signal	91	E > 2.4v = Fail

Digital Mux Inputs

1	Test Word (1365)	Temperature	None
2	Remote Mode Word	187/210/233	See Spec.
3	Remote Power Demand	188/211/234	40.95 b/%Power
4	Not Used		
5	Not Used		
6	Local Mode Word	189/212/235	See Spec.
7	VSV Schedule Adjust.	190/213/235	6825 b/inch
8	VSV Reset Adjust.	191/214/237	0 to 1.0 Multiplier
9	FFSV DB Adjust.	192/215/238	287.368 b/m
10	Spare		

3. INPUT ORDER LIST (Cont'd)

Input Number	Input Name	Ram Storage Address	Scaling
-----------------	---------------	---------------------------	---------

Digital Mux Inputs (Cont'd)

11	N2 Max. Adjustment	194/217/240	3.413 b/RPM
12	N2 Idle Adjustment	195/218/241	0.683 b/RPM
13	Accel. Schedule Adj.	196/219/242	0 to 0.8
14	Decel. Schedule Adj.	197/220/243	0 to 0.8
15	FICA1 Adjustment	198/221/244	0.819 b/in. ² A8
16	N1K Schedule Adjustment	199/222/245	4.095 b/RPM
17	N1K Gain Adjustment	200/223/246	0 to 2.0
18	N1K Max. Adjustment	201/224/247	4.095 b/RPM
19	MVP F/B Rate Limit Adj.	202/225/248	31500 B/inch/sec.
20	MVP Bias Adjustment	203/226/249	8/900 b/inch
21	MVP Gain Adjustment	204/227/250	0 to 0.16
22	T41C Ref. Adjustment	205/228/251	4.095 b/° R
23	Power Demand	206/229/252	40.95 b/%
24	FICA 3	207/230/253	Not Used
25	FICA 4	208/231/254	Not Used
26	FICA 2	209/232/255	Not Used

4. QCSEE OTW RAM MEMORY MAP

0	Zero	34	Δ PS11/PTO 0-2047=0-4.0 PRU
1	One	35	1023
2	2048	36	DT25
3	Temporary Storage	37	$\sqrt{\theta 25}$
4	Temporary Storage	38	P14-PTO
5	Temporary Storage	39	$\sqrt{\theta 12}$
6	Temporary Storage	40	VRVDT (MVP F8 Raw)
7	Temporary Storage	41	T3
8	Temporary Storage	42	N2
9	Temporary Storage	43	DXMV
10	Temporary Storage	44	PS3
11	Temporary Storage	45	N1T
12	Temporary Storage	46	T ₁₂
13	Temporary Storage	47	PTO-PS11
14	Temporary Storage	48	PTO
15	Temporary Storage	49	DT25
16	Temporary Storage	50	DRTH25
17	Temporary Storage	51	Remote Direct Velocity Demand
18	Temporary Storage	52	DXMV-DXMV. Z ⁻¹
19	Temporary Storage	53	T _{N1WR} EoZ ⁻¹ MSB
20	Remote Mode = 1	54	T _{N1WR} EoZ ⁻¹ LSB
21	VSV Reset ON = 1	55	T _{N1WR} EiZ ⁻¹
22	FICA 1 ON = 1	56	Subroutine Return CTR No. 1
23	FICA 2 ON = 1 Karman	57	Subroutine Return CTR No. 2
24	FFSV - ϕ , Other = 1	58	Subroutine Return CTR No. 3
25	βC	59	T _{N2WR} EoZ ⁻¹ MSB
26	TER E _{OUT} Z ⁻¹ MSB	60	T _{N2WR} EoZ ⁻¹ LSB
27	TER E _{OUT} Z ⁻¹ LSB	61	Test Word Result 1 = OK, $\phi = \overline{OK}$
28	DWF 0-4095, 0-13910	62	Decel EiZ ⁻¹
29	T _{TWR} EoZ ⁻¹ MSB	63	Accel EiZ ⁻¹
30	T _{TWR} EoZ ⁻¹ LSB	64	"Eng. Panel Readout"
31	T41C	65	K _{DC} EoZ ⁻¹ MSB
32	EoZ ⁻¹ T _{TW} MSB	66	K _{DC} EoZ ⁻¹ LSB
33	EoZ ⁻¹ T _{TW} LSB	67	Fault Word

4. QCSEE OTW RAM MEMORY MAP (Cont'd)

68	A/D-D/A Fault Counter	103	FICA SPS3
69	A/D-D/A Test Results 1=OK	104	FICA T56
70	Vertical Vib.	105	FICA VT56
71	Horizontal Vib.	106	FICA P15
72	Vib. Counter	107	FICA SP15
73	WF MCI Word	108	FICA VPS3
74	PLA	109	FICA ST56
75	β C1 Feedback	110	FICA VP15
76	β C2 Feedback	111	FICA SQRT Subroutine CTR
77	O/S TM Signal	112	FICA Temporary
78	Hyd. Pump Outlet Pressure	113	FICA P42
79	WF Temperature	114	FICA XNL
80	WF Manifold Pressure	115	FICA T56X
81	EGT - T56	116	FICA Temporary
82	WF	117	FICA XNH
83	Oil Inlet Pressure	118	FICA DZWF = X1W
84	Scavenge Oil Pressure	119	FICA DZBETA = X1B
85	Lub. Inlet Temperature	120	FICA T3S
86	Oil Discharge Temperature	121	FICA DT3S
87	T25	122	FICA T56S
88	P5	123	FICA DT56S
89	G/B Temperature	124	FICA EIPS3
90	VSV Position	125	FICA EIP56
91	Clock Fail	126	FICA EIPS56
92	DXN N2/ $\sqrt{025}$ 0 - 2047	127	FICA SPS3 (LSB)
93	DZBRST MSB Z ⁻¹	128	FICA ST546 (LSB)
94	DZBRST LSB Z ⁻¹	129	FICA SP15 (LSB)
95	4095	130	FICA LSYNC
96	WFTMC	131	FICA NSYNC
97	VSV TMC	132	FICA XNHC
98	FICA WF in PPH	133	FICA EXNL
99	FICA T1	134	FICA EPS3
100	FICA ZWF in Inches	135	FICA EXNH
101	FICA P1	136	FICA ET56
102	FICA PS3	137	FICA EXWF

4. QCSEE OTW RAM MEMORY MAP (Cont'd)

138	FICA XNL (LSB)	173
139	FICA ET3	174 1024
140	FICA Integ. Subroutine CTR	175 256
141	FICA XNH (LSB)	176 128
142	FICA ZWF (LSB)	177 32
143	FICA EXBETA	178 16
144	FICA ZBETA	179 4
145	FICA ZBETA (LSB)	180 Temporary
146	FICA M Error	181 Temporary
147	FICA T3S (LSB)	182 Temporary
148	FICA T56S (LSB)	183 Temporary
149	FICA XLNC	184 Temporary
150	FICA XNL OTW	185 Temporary
151	FICA XNH OTW	186 Total MCI Word
152	FICA T3S OTW	187 Remote Mode Word
153	FICA ZWF OTW	188 Remote Power Demand
154	FICA PS3 OTW	189 Local Model Word
155	FICA ZBETA OTW	190 VSV Schedule
156	FICA T56 OTW and T56S	191 VSV Reset
157	FICA SW 3	192 FFSV Deadband
158	QL = DXNL	193 N2-MVP FB Rate Limit
159	QH = DXNH	194 N2 Max.
160	ABS Subroutine CTR	195 N2 Idle
161	ABS EXNL	196 Accel Schedule
162	ABS EXNH	197 Decel Schedule
163	ABS ET3	198 FICA 1
164	ABS ET56	199 N1K Schedule
165	ABS EZWF	200 N1K Gain
166	ABS EZBETA	201 N1K Max.
167	ABS EPS3	202 MVP Feedback Rate Limit
168		203 MVP Feedback Bias
169		204 MVP Feedback Gain
170		205 T41C Ref.
171		206 Power Demand
172		207 FICA 3

4. QCSEE OTW RAM MEMORY MAP (Concluded)

208	FICA 4	243	Decel Schedule Z^{-2}
209	FICA 2	244	FICA 1 Z^{-2}
210		245	N1K Schedule Z^{-2}
211		246	N1K Gain Z^{-2}
212		247	N1K Max Z^{-2}
213		248	MVP Feedback Rate Z^{-2}
214		249	MVP Bias Z^{-2}
215		250	MVP Gain Z^{-2}
216		251	T41C Ref. Z^{-2}
217		252	DPS Power Demand Z^{-2}
218		253	FICA 3 Z^{-2}
219		254	FICA 4 Z^{-2}
220		255	FICA 2 Z^{-2}
221			
222			
223			
224			
225			
226			
227			
228			
229			
230			
231			
232			
233	Remote Mode Word Z^{-2}		
234	Remote Power Demand Z^{-2}		
235	Local Mode Word Z^{-2}		
236	VSV Schedule Z^{-2}		
237	VSV Reset Z^{-2}		
238	FFSV DB Adj. Z^{-2}		
239	WF N2 Rate Limit Z^{-2}		
240	N2 Max. Z^{-2}		
241	N2 Idle Z^{-2}		
242	Accel Schedule Z^{-2}		

5.0 PROGRAM MEMORY LISTING

1	LAI	1
2	SIO	1
3	LAI	2048
4	SIO	2
5	SUB	1
6	OUT	1
7	BRM	2
8	SIO	3
9	LAI	0
10	OUT	0
11	SIO	0
12	LAI	4096
13	SIO	5
14	SIO	95
15	SIO	96
16	SIO	140
17	SIO	33
18	SIO	111
19	SIO	100
20	INP	1
21	SIO	3
22	OUT	14
23	LAI	803
24	ADD	3
25	SUB	0
26	BRM	4
27	OUT	0
28	OUT	0
29	JMP	5
30	LAI	2130
31	ADD	3
32	SUB	0
33	BRM	3
34	LJA	0
35	JMP	2
36	LDA	1
37	SIO	61
38	INP	0
39	BRM	2
40	OUT	14
41	SIO	0
42	INP	1
43	SIO	167
44	BRM	5
45	LDA	2
46	BRM	2
47	OUT	2
48	JMP	5
49	OUT	0
50	OUT	0
51	OUT	0
52	LDA	0
53	ADD	0
54	SIO	10

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55	LAI	972
56	SIO	4
57	INP	0
58	SIO	74
59	INP	1
60	SIO	188
61	OUT	14
62	LDA	0
63	SUB	4
64	BRM	7
65	LAI	3021
66	ADD	0
67	SUB	0
68	LDA	0
69	BRM	0
70	JMP	0
71	OUT	0
72	OUT	0
73	OUT	0
74	JMP	5
75	LDA	1
76	SIO	5
77	ADD	68
78	BRM	2
79	SIO	67
80	LDA	5
81	SIO	68
82	LDA	0
83	SUB	67
84	LDA	0
85	BRM	2
86	LAI	256
87	ADD	67
88	SIO	67
89	INP	0
90	OUT	14
91	SIO	42
92	INP	1
93	LDA	235
94	SUB	0
95	BRM	2
96	JMP	2
97	LDA	233
98	SIO	235
99	LAI	0
100	LSH	2
101	SIO	20
102	LSH	2
103	LSH	2
104	LSH	2
105	LSH	2
106	LSH	2
107	LSH	2
108	LDA	0
109	LSH	2

Check
A/D & D/A
Test
Word

Decode
Mode
Word

(cont. to 119)

110	SIO	21
111	LDA	0
112	LSH	2
113	SIO	157
114	LDA	0
115	LSH	2
116	SIO	23
117	LDA	0
118	LSH	2
119	SIO	22
120	LDA	0
121	LSH	2
122	SIO	24
123	INP	0
124	OUT	14
125	SIO	45
126	INP	1
127	LJA	48
128	BRM	2
129	SIO	7
130	LAI	647
131	MPY	47
132	SIO	8
133	ADD	8
134	ADD	1
135	SIO	10
136	SUB	7
137	LDA	10
138	ADD	1
139	BRM	2
140	JMP	2
141	LDA	7
142	SIO	7
143	LDA	8
144	DIY	7
145	ROT	0
146	SIO	34
147	INP	0
148	OUT	14
149	SIO	46
150	INP	1
151	SIO	189
152	ROT	0
153	ROT	0
154	INP	0
155	OUT	14
156	SIO	41
157	INP	1
158	SIO	190
159	ROT	0
160	ROT	0
161	INP	0
162	OUT	14
163	SIO	40
164	INP	1

Compute
PST1/PTO

165	SIO	191
166	LAI	126
167	SIO	3
168	LDA	40
169	SUB	0
170	BRM	5
171	SUB	3
172	LDA	40
173	BRM	6
174	JMP	6
175	OUT	0
176	OUT	0
177	OUT	0
178	JMP	-4
179	LDA	3
180	SIO	3
181	LMI	2212
182	MPY	3
183	SIO	3
184	LAI	3488
185	SIO	4
186	LMI	606
187	MPY	250
188	ADD	4
189	LAI	0
190	MPY	3
191	SIO	5
192	INP	0
193	OUT	14
194	SIO	46
195	INP	1
196	SIO	192
197	LMI	114
198	MPY	249
199	SIO	4
200	LAI	57
201	SUB	4
202	ADD	3
203	SIO	3
204	LDA	2
205	SUB	1
206	SIO	4
207	SUB	3
208	LDA	3
209	BRM	2
210	JMP	2
211	LDA	4
212	SIO	185
213	SIO	43
214	INP	0
215	OUT	14
216	SIO	44
217	INP	1
218	SIO	173

HF
Feedback
Gain & bias
Adjustment

(Cont'd.
on next page)

217	LAI	2112
220	SIO	4
221	LMI	1323
222	MPYM	46
223	ADD	4
224	SIO	152
225	INP	0
226	OU1	14
227	SIO	47
228	INP	1
229	SIO	194
230	LAI	1323
231	SIO	0
232	LMI	1232
233	MPYM	132
234	SIO	0
235	INP	0
236	OU1	14
237	SIO	38
238	INP	1
239	SIO	195
240	LAI	1233
241	SUB	0
242	ADD	0
243	SIO	0
244	LMI	210
245	MPYM	240
246	ADD	0
247	SIO	0
248	INP	0
249	OU1	14
250	INP	1
251	SIO	196
252	LAI	1000
253	SIO	0
254	LMI	210
255	MPYM	247
256	ADD	0
257	SIO	0
258	SUB	0
259	LMI	0
260	SHHM	2
261	MPYM	2
262	LMI	0
263	SIO	0
264	INP	0
265	OU1	14
266	SIO	15
267	INP	1
268	SIO	197
269	LMI	100
270	MPYM	252
271	SIO	0
272	INP	0
273	OU1	14
274	SIO	10

Generate
Max. NIK
Schedule

275	INP	1
276	SIO	198
277	LAI	3410
278	SUB	0
279	LAI	0
280	MPYM	252
281	SIO	0
282	INP	0
283	OU1	14
284	SIO	77
285	INP	1
286	SIO	199
287	LAI	1422
288	ADD	0
289	LAI	0
290	MPY	0
291	SIO	0
292	INP	0
293	OU1	14
294	SIO	78
295	INP	1
296	SIO	200
297	LAI	1042
298	SIO	1
299	LMI	2454
300	MPYM	46
301	SHHM	2
302	SHHM	2
303	SHHM	2
304	SIO	0
305	INP	0
306	OU1	14
307	SIO	79
308	INP	1
309	SIO	201
310	LAI	3471
311	SUB	0
312	LAI	0
313	MPYM	46
314	SHHM	2
315	SHHM	2
316	SHHM	2
317	ADD	1
318	SIO	39
319	LAI	0
320	MPYM	0
321	LSH	2
322	SIO	184
323	INP	0
324	OU1	14
325	SIO	80
326	INP	1
327	SIO	202
328	LMI	779
329	MPYM	46

Compute
NIK
Demand,

Compute
DRWH12

(Cont'd. to
1854)

330	SIO	101
331	INP	0
332	OU1	14
333	SIO	81
334	LAI	208
335	SIO	4
336	LAI	129
337	MPYM	46
338	ADD	4
339	SIO	99
340	LAI	1322
341	SUB	132
342	LDA	0
343	SHHM	0
344	OU1	0
345	JMPR	0
346	OUT	0
347	JMPR	0
348	SUB	22
349	SHHM	-3
350	SIO	130
351	SIO	131
352	LMI	1906
353	MPYM	46
354	SIO	150
355	LMI	1586
356	MPYM	42
357	SIO	151
358	LMI	1536
359	MPYM	44
360	SIO	154
361	LMI	739
362	MPYM	41
363	SIO	3
364	LAI	253
365	ADD	3
366	SIO	152
367	LAI	3994
368	ADD	43
369	SIO	3
370	LAI	3703
371	MPY	3
372	SIO	153
373	LAI	3944
374	ADD	25
375	SIO	3
376	LMI	3607
377	MPYM	3
378	SIO	155
379	LMI	1280
380	MPYM	81
381	SIO	3
382	LAI	294
383	ADD	3
384	SIO	156

FICA



385	LDA	0
386	SUB	131
387	SHHM	443
388	LDA	150
389	SIO	114
390	LDA	151
391	SIO	117
392	LDA	154
393	SIO	152
394	LDA	152
395	SIO	120
396	LDA	153
397	SIO	100
398	LDA	155
399	SIO	144
400	LDA	156
401	SIO	122
402	LDA	99
403	SIO	0
404	LAI	149
405	SIO	3
406	JMPP	3903
407	LMI	905
408	MPYM	114
409	DIV	0
410	ROI	0
411	SIO	149
412	LMI	2233
413	MPY	149
414	SUB	3
415	LAI	0
416	MPY	149
417	LSH	2
418	SIO	3
419	LAI	24
420	ADD	3
421	LAI	0
422	MPY	151
423	LSH	2
424	ADD	101
425	SIO	106
426	LDA	150
427	SIO	104
428	LDA	0
429	SIO	103
430	SIO	109
431	SIO	107
432	SIO	103
433	SIO	105
434	SIO	110
435	LAI	1
436	OU1	0
437	OU1	0
438	SIO	1
439	LAI	304

FICA



(Cont'd. on
next page)

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430 SUB	1
441 DRMP	062
442 J.M.P.	2
443 LDA	1
444 ADD	111
445 SIO	111
446 LMI	1132
447 MPT	137
448 ADD	130
449 SIO	3
450 LMI	1371
451 MPT	3
452 ADD	134
453 SIO	3
454 LMI	3470
455 MPT	3
456 ADD	135
457 SIO	3
458 LMI	140
459 MPT	3
460 ADD	133
461 SIO	3
462 LMI	3570
463 MPT	3
464 ADD	114
465 SIO	114
466 LMI	50
467 MPT	158
468 SIO	5
469 R01	0
470 SIO	6
471 LDA	114
472 SIO	7
473 LDA	130
474 SIO	3
475 J.M.P.	4019
476 LDA	7
477 SIO	114
478 LDA	3
479 SIO	135
480 LMI	303
481 MPT	137
482 ADD	134
483 SIO	3
484 LMI	3125
485 MPT	3
486 SIO	3
487 LDA	133
488 SUB	3
489 SIO	3
490 LMI	559
491 MPT	3
492 SIO	3
493 LDA	134
494 SIO	3

FICA

495 SIO	3
496 LMI	502
497 MPT	3
498 ADD	135
499 SIO	3
500 LMI	3358
501 MPT	3
502 ADD	117
503 SIO	117
504 LMI	53
505 MPT	159
506 SIO	5
507 R01	0
508 SIO	0
509 LDA	117
510 SIO	7
511 LDA	141
512 SIO	8
513 JMPP	4019
514 LDA	7
515 SIO	117
516 LDA	5
517 SIO	141
518 LMI	2732
519 MPT	130
520 ADD	139
521 SIO	3
522 LMI	2365
523 MPT	3
524 SIO	3
525 LDA	133
526 SUB	3
527 SIO	3
528 LMI	3294
529 MPT	3
530 ADD	137
531 SIO	3
532 LMI	1076
533 MPT	3
534 ADD	135
535 SIO	3
536 LMI	3084
537 MPT	3
538 ADD	134
539 ADD	134
540 SIO	3
541 LMI	3231
542 MPT	3
543 ADD	100
544 SIO	100
545 LMI	9700

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546 MPT	118
547 SIO	5
548 R01	0
549 SIO	6
550 LDA	100
551 SIO	7
552 LDA	142
553 SIO	8
554 JMPP	4019
555 LDA	7
556 SIO	100
557 LDA	8
558 SIO	142
559 LMI	528
560 MPT	135
561 SIO	3
562 LDA	134
563 SUB	3
564 SIO	3
565 LMI	310
566 MPT	3
567 SIO	3
568 LDA	143
569 SUB	3
570 SIO	3
571 LMI	570
572 MPT	3
573 ADD	144
574 SIO	144
575 LMI	128
576 MPT	119
577 SIO	5
578 R01	0
579 SIO	6
580 LDA	144
581 SIO	7
582 LDA	145
583 SIO	6
584 JMPP	4019
585 LDA	7
586 SIO	144
587 LDA	8
588 SIO	145
589 LDA	146
590 LMI	0
591 LSH	-2
592 LSH	2
593 LSH	2
594 LDA	0
595 LSH	2
596 SIO	10
597 LDA	0
598 LSH	2
599 SIO	103
600 LMI	1241

FICA

601 MPT	134
602 ADD	130
603 SIO	3
604 LMI	2000
605 MPT	3
606 ADD	135
607 SIO	3
608 LMI	2026
609 MPT	3
610 ADD	133
611 SIO	3
612 LMI	816
613 MPT	3
614 ADD	139
615 SIO	3
616 LMI	3452
617 MPT	3
618 ADD	120
619 SIO	3
620 LDA	5
621 SUB	10
622 LDA	3
623 DRMP	2
624 JMPP	2
625 LDA	120
626 SIO	120
627 LMI	147
628 MPT	121
629 SIO	5
630 R01	0
631 SIO	6
632 LDA	120
633 SIO	7
634 LDA	147
635 SIO	5
636 JMPP	4019
637 LDA	7
638 SIO	120
639 LDA	8
640 SIO	147
641 LMI	1040
642 MPT	134
643 ADD	135
644 SIO	3
645 LMI	1369
646 MPT	3
647 ADD	139
648 SIO	3
649 LMI	2932
650 MPT	3
651 ADD	133
652 SIO	3
653 LMI	948
654 MPT	3
655 ADD	130

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(Cont'd. on next page)

030 SIO	3
031 LAI - 2348	
032 MPY	3
033 A U	122
034 SIO	3
035 LJA	0
036 SIO	183
037 LJA	3
038 SIO	2
039 JAPP	2
040 LJA	122
041 SIO	122
042 LAI	224
043 MPY	123
044 SIO	0
045 SIO	0
046 LJA	122
047 SIO	1
048 LJA	140
049 SIO	8
050 JAPP	4014
051 LJA	7
052 SIO	122
053 LJA	8
054 SIO	148
055 LAI	132
056 A U	100
057 SIO	7
058 L I	3046
059 MPY	1
060 LAI	0
061 MPY	1
062 LSH	2
063 LSH	2
064 SIO	78
065 LJA	44
066 SIO	0
067 JAPP	3983
068 LJA	102
069 A U	103
070 A U	106
071 SIO	102
072 LJA	104
073 A U	105
074 A U	105
075 SIO	104
076 LJA	106
077 A U	107
078 A U	110
079 SIO	100
080 LAI	2163
081 MPY	102
082 LSH	2
083 SIO	3

FICA

111 LAI	1024
112 MPY	106
113 DIV	101
114 ROI	0
115 SIO	6
116 LAI	905
117 MPY	114
118 DIV	5
119 ROI	0
120 SIO	4
121 LAI	3628
122 MPY	0
123 SIO	7
124 LAI	2152
125 MPY	4
126 LSH	2
127 SUB	7
128 SIO	7
129 LAI	820
130 ADD	1
131 SIO	12
132 LAI	0
133 MPY	101
134 RSHM	2
135 RSHM	2
136 DIV	5
137 ROI	0
138 SIO	1
139 LAI	3620
140 MPY	7
141 LSH	2
142 LSH	2
143 LSH	2
144 SIO	4
145 LMI	272
146 MPY	4
147 SIO	7
148 LAI	1716
149 MPY	0
150 LSH	2
151 SUB	1
152 SIO	1
153 LAI	1145
154 ADD	1
155 LAI	0
156 MPY	44
157 LSH	2
158 SIO	0
159 LAI	1311
160 MPY	44
161 SIO	1
162 LAI	2104
163 MPY	0
164 LSH	2
165 SUB	1

FICA

166 SIO	5
167 SIO	183
168 JAPP	3983
169 LAI	1034
170 MPY	117
171 DIV	5
172 ROI	0
173 SIO	132
174 LAI	187
175 SUB	132
176 DRHM	4
177 LAI	1
178 SIO	1
179 LAI	24
180 SUB	1
181 DRHM	2
182 JAPP	-2
183 LDA	100
184 JAPP	10
185 LMI	833
186 MPY	4
187 SIO	1
188 LAI	588
189 SUB	7
190 LAI	0
191 MPY	4
192 LSH	2
193 SIO	1
194 LAI	885
195 ADD	1
196 LAI	0
197 MPY	106
198 LSH	2
199 LSH	2
200 SIO	4
201 LAI	1609
202 SIO	1
203 LAI	540
204 SIO	10
205 SUB	132
206 LDA	10
207 DRHM	4
208 OUI	0
209 OUI	0
210 JAPP	4
211 LDA	1
212 SUB	132
213 LDA	132
214 DRHM	2
215 JAPP	2
216 LDA	1
217 SIO	14
218 LAI	1014
219 SIO	17
220 LAI	245

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021 SIO	10
022 LAI	184
023 SIO	15
024 LAI	1201
025 SIO	1
026 LDA	14
027 SUB	7
028 SIO	7
029 DRHM	804
030 SUB	10
031 SIO	10
032 DRHM	846
033 LAI	3491
034 MPY	10
035 LSH	2
036 LSH	2
037 SIO	1
038 LAI	3064
039 SUB	1
040 LAI	0
041 MPY	10
042 LSH	2
043 LSH	2
044 SIO	7
045 LAI	344
046 SUB	1
047 JAPP	362
048 LMI	2478
049 MPY	1
050 LSH	2
051 LSH	2
052 LSH	2
053 SIO	10
054 LAI	440
055 SIO	10
056 LAI	0
057 MPY	1
058 LSH	2
059 LSH	2
060 SIO	10
061 LAI	1078
062 SUB	10
063 JAPP	413
064 LJA	14
065 SUB	17
066 SIO	10
067 DRHM	883
068 LAI	3071
069 MPY	10
070 LSH	2
071 LSH	2
072 LSH	2
073 SIO	1
074 LAI	3534
075 SUB	1

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070 LAI 0
 077 MPYM 10
 078 LSH 2
 079 SIO 7
 080 LAI 1284
 081 SUB 7
 082 JMP 913
 083 LDA 14
 084 SUB 10
 085 SIO 7
 086 JMP 902
 087 LAI 3107
 088 MPYM 7
 089 LAI 2
 090 LAI 2
 091 LSH 2
 092 SIO 10
 093 LAI 1143
 094 A J 10
 095 LAI 0
 096 MPYM 7
 097 SIO 10
 098 LAI 1429
 099 SUB 10
 100 SIO 7
 101 JMP 910
 102 LAI 2984
 103 MPYM 14
 104 LSH 2
 105 SIO 7
 106 LAI 3430
 107 SUB 7
 108 LAI 0
 109 MPYM 14
 110 SIO 7
 111 LAI 1079
 112 SUB 7
 113 SIO 0
 114 JMP 900
 115 LAI 2144
 116 MPYM 7
 117 SIO 14
 118 LAI 127
 119 SIO 10
 120 LAI 3002
 121 SUB 14
 122 LAI 0
 123 MPYM 7
 124 LSH 2
 125 SUB 10
 126 SIO 10
 127 LAI 2144
 128 MPYM 144
 129 SIO 7
 130 LAI 3002

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931 SUB 7
 932 LAI 0
 933 MPYM 144
 934 LSH 2
 935 SIO 7
 936 LAI 3969
 937 ADD 7
 938 SUB 16
 939 SIO 16
 940 LMI 819
 941 MPYM 3
 942 SIO 10
 943 ADD 10
 944 ADD 1
 945 SIO 14
 946 SUB 4
 947 LDA 14
 948 BRAR 2
 949 JMPR 2
 950 LDA 4
 951 SIO 14
 952 LDA 10
 953 DIV 14
 954 ROI 0
 955 SIO 3
 956 LAI 1069
 957 SIO 14
 958 LAI 010
 959 SIO 17
 960 LMI 467
 961 MPYM 3
 962 SIO 10
 963 LDA 132
 964 SUB 10
 965 SUB 14
 966 LAI 0
 967 MPYM 4
 968 DIV 0
 969 LDA 0
 970 ROI 0
 971 RSHM 2
 972 DIV 17
 973 ROI 0
 974 SIO 4
 975 LMI 1860
 976 MPYM 132
 977 LAI 0
 978 MPYM 132
 979 LSH 2
 980 SUB 132
 981 SIO 17
 982 LAI 4017
 983 SUB 16
 984 SIO 10
 985 LDA 0

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986 SUB 10
 987 BRAR 4
 988 JMPR 4
 989 OJI 0
 990 JMPR 34
 991 LDA 10
 992 LAI 0
 993 MPYM 10
 994 LSH 2
 995 SIO 10
 996 LAI 863
 997 BRAR 3
 998 SUB 10
 999 JMPR 3
 1000 ADD 10
 1001 OJI 0
 1002 SIO 10
 1003 LMI 3079
 1004 MPYM 132
 1005 SIO 7
 1006 LAI 280
 1007 ADD 7
 1008 LAI 0
 1009 MPYM 10
 1010 LSH 2
 1011 SIO 10
 1012 LDA 0
 1013 SUB 10
 1014 BRAR 2
 1015 JMPR 2
 1016 LDA 10
 1017 LAI 0
 1018 MPYM 10
 1019 LSH 2
 1020 SIO 10
 1021 BRAR -32
 1022 LDA 0
 1023 SUB 10
 1024 SIO 10
 1025 LAI 1010
 1026 SIO 7
 1027 LAI 2187
 1028 MPYM 18
 1029 SIO 10
 1030 LAI 3801
 1031 MPYM 17
 1032 ADD 10
 1033 ADD 7
 1034 SIO 10
 1035 LDA 0
 1036 SUB 10
 1037 BRAR 4
 1038 JMPR 4
 1039 OJI 0
 1040 JMPR 16

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1041 LDA 10
 1042 LAI 0
 1043 MPYM 10
 1044 LSH 2
 1045 LSH 2
 1046 LSH 2
 1047 SIO 7
 1048 LSH 2
 1049 LSH 2
 1050 ADD 7
 1051 SIO 7
 1052 LDA 0
 1053 BRAR -14
 1054 SUB 7
 1055 SIO 7
 1056 LDA 4
 1057 LAI 0
 1058 MPYM 7
 1059 LSH 2
 1060 SIO 7
 1061 LDA 4
 1062 SUB 7
 1063 SIO 4
 1064 LMI 3929
 1065 MPYM 4
 1066 SIO 10
 1067 LMI 223
 1068 MPYM 132
 1069 SIO 17
 1070 LAI 1180
 1071 SUB 17
 1072 SIO 17
 1073 LMI 2402
 1074 MPYM 3
 1075 ADD 17
 1076 LAI 0
 1077 MPYM 103
 1078 SIO 17
 1079 LSH 2
 1080 LSH 2
 1081 ADD 17
 1082 SIO 17
 1083 LMI 009
 1084 MPYM 98
 1085 DIV 16
 1086 ROI 0
 1087 SIO 3
 1088 LMI 2087
 1089 MPYM 3
 1090 SIO 7
 1091 LDA 2
 1092 SUB 7
 1093 LAI 0
 1094 MPYM 3
 1095 LSH 2

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1078	LAI	2
1079	SIO	7
1080	LAI	53
1081	MPY	7
1082	ADD	7
1083	SIO	7
1084	LAI	20
1085	LAI	7
1086	SIO	7
1087	LAI	3277
1088	MPY	17
1089	ADD	7
1090	SIO	13
1091	SIO	5
1092	LAI	div
1093	SIO	3
1094	LAI	0
1095	MPY	10
1096	LAI	10
1097	SIO	18
1098	JMPR	3983
1099	LAI	3994
1100	MPY	5
1101	LAI	0
1102	MPY	15
1103	LAI	2
1104	SIO	14
1105	LAI	435
1106	SIO	14
1107	LAI	410
1108	MPY	4
1109	SIO	7
1110	LAI	9
1111	SIO	7
1112	SIO	10
1113	LAI	0
1114	MPY	10
1115	ADD	2
1116	SIO	100
1117	LAI	0
1118	LAI	0
1119	MPY	14
1120	LAI	0
1121	SIO	0
1122	SIO	14
1123	LAI	134
1124	ADD	14
1125	LAI	0
1126	MPY	5
1127	LAI	0
1128	LSH	2
1129	SIO	14
1130	ADD	105
1131	SIO	14

FICA

1151	SIO	5
1152	LAI	243
1153	SIO	14
1154	LAI	114
1155	MPY	98
1156	ADD	4
1157	SIO	15
1158	LAI	0
1159	MPY	14
1160	DIV	5
1161	LDA	0
1162	MPY	15
1163	LAI	0
1164	MPY	104
1165	ADD	5
1166	SIO	14
1167	LAI	814
1168	MPY	14
1169	DIV	14
1170	ROI	0
1171	SIO	112
1172	LAI	895
1173	SUB	112
1174	BRMR	17
1175	LAI	737
1176	SIO	181
1177	LAI	247
1178	ADD	112
1179	LAI	0
1180	MPY	112
1181	LSH	2
1182	SIO	7
1183	LAI	350
1184	ADD	7
1185	LAI	0
1186	MPY	14
1187	DIV	151
1188	ROI	0
1189	ROI	0
1190	JMPR	17
1191	LAI	100
1192	MPY	112
1193	SIO	7
1194	LAI	1340
1195	ADD	7
1196	LAI	0
1197	MPY	112
1198	LSH	2
1199	SIO	7
1200	LAI	9
1201	ADD	7
1202	LAI	0
1203	MPY	14
1204	LSH	2
1205	LSH	2

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1206	LSH	2
1207	SIO	113
1208	LAI	163
1209	MPY	113
1210	DIV	19
1211	ROI	0
1212	SIO	7
1213	LAI	1674
1214	ADD	7
1215	LAI	0
1216	MPY	13
1217	LSH	2
1218	SIO	112
1219	LAI	141
1220	MPY	14
1221	DIV	113
1222	ROI	0
1223	SHR	2
1224	SIO	7
1225	LAI	504
1226	SUB	7
1227	LAI	0
1228	MPY	14
1229	DIV	113
1230	ROI	0
1231	SIO	7
1232	LAI	1257
1233	ADD	7
1234	LAI	0
1235	MPY	112
1236	LSH	2
1237	SIO	115
1238	LAI	11
1239	MPY	48
1240	ADD	4
1241	SIO	116
1242	LAI	404
1243	MPY	104
1244	SIO	7
1245	LAI	4
1246	ADD	7
1247	LAI	0
1248	MPY	15
1249	SIO	7
1250	LAI	3906
1251	MPY	8
1252	LAI	0
1253	MPY	10
1254	ADD	7
1255	DIV	116
1256	ROI	0
1257	SIO	8
1258	LDA	244
1259	RSHM	2
1260	SIO	7

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1261	LAI	44
1262	MPY	116
1263	DIV	151
1264	LAI	0
1265	MPY	116
1266	DIV	7
1267	LDA	0
1268	MPY	8
1269	DIV	7
1270	ROI	0
1271	SIO	7
1272	LDA	151
1273	ALS	7
1274	SIO	10
1275	LAI	668
1276	MPY	116
1277	LAI	0
1278	MPY	0
1279	DIV	151
1280	LDA	0
1281	MPY	110
1282	SIO	7
1283	LBA	10
1284	SUB	7
1285	SIO	8
1286	LSH	12
1287	LAI	0
1288	MPY	12
1289	LSH	2
1290	SIO	12
1291	LAI	61
1292	SIO	7
1293	LAI	2840
1294	MPY	12
1295	LSH	2
1296	SUB	7
1297	LAI	0
1298	MPY	12
1299	LSH	2
1300	SIO	7
1301	LAI	102
1302	ADD	7
1303	SIO	110
1304	LAI	1021
1305	SIO	7
1306	LAI	252
1307	SIO	100
1308	LAI	614
1309	SIO	151
1310	LDA	6
1311	SUB	7
1312	LAI	0
1313	MPY	4
1314	DIV	151
1315	LDA	0

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1310	MPY	yy
1311	DIV	100
1312	ROI	0
1313	ROI	0
1314	ROI	6
1315	LDA	17
1316	SUB	103
1317	LAI	y
1318	MPY	4
1319	LDA	2
1320	LDA	2
1321	SUB	7
1322	LAI	2263
1323	MPY	1
1324	LDA	2
1325	LDA	2
1326	SUB	y
1327	LAI	y25
1328	MPY	1y
1329	LDA	113
1330	ROI	0
1331	SUB	7
1332	LAI	0J2
1333	LAI	7
1334	LAI	525
1335	MPY	13
1336	ROI	1
1337	SUB	4
1338	LAI	30y
1339	MPY	3
1340	SUB	1
1341	LAI	1043
1342	ADD	7
1343	LAI	0
1344	MPY	4
1345	LDA	2
1346	LAI	0
1347	MPY	13
1348	LDA	2
1349	LAI	0
1350	MPY	10
1351	LDA	2
1352	SUB	4
1353	LAI	3041
1354	MPY	4
1355	LDA	2
1356	SUB	4
1357	LAI	260
1358	MPY	113
1359	DIV	14
1360	ROI	y
1361	SUB	7
1362	LAI	130y
1363	SUB	1
1370	LAI	0

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1371	MPY	113
1372	DIV	14
1373	ROI	0
1374	SUB	7
1375	LAI	3586
1376	ADD	1
1377	SUB	183
1378	LMI	369
1379	MPY	3
1380	SUB	7
1381	LAI	1843
1382	ADD	1
1383	LAI	0
1384	MPY	183
1385	LSH	2
1386	LAI	0
1387	MPY	16
1388	LSH	2
1389	LAI	0
1390	MPY	112
1391	LSH	2
1392	LSH	2
1393	SUB	183
1394	LMI	2913
1395	MPY	183
1396	LSH	2
1397	SUB	183
1398	LMI	4055
1399	MPY	183
1400	SUB	6
1401	SUB	1
1402	LDA	0
1403	SUB	1
1404	BRMR	2
1405	JMPR	2
1406	LDA	7
1407	SUB	7
1408	LMI	2047
1409	MPY	7
1410	DIV	114
1411	ROI	0
1412	SUB	1
1413	LDA	0
1414	BRMR	3
1415	SUB	1
1416	JMPR	3
1417	LDA	1
1418	OUT	0
1419	SUB	183
1420	LMI	207
1421	MPY	183
1422	ADD	183
1423	SUB	183
1424	LDA	4
1425	SUB	y

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1426	SUB	1
1427	LDA	0
1428	SUB	7
1429	BRMR	2
1430	JMPR	2
1431	LDA	1
1432	SUB	7
1433	LMI	1345
1434	MPY	7
1435	DIV	117
1436	ROI	0
1437	SUB	7
1438	LDA	0
1439	BRMR	3
1440	SUB	7
1441	JMPR	3
1442	LDA	7
1443	OUT	0
1444	SUB	4
1445	LMI	1262
1446	MPY	4
1447	ADD	4
1448	SUB	15y
1449	LDA	11
1450	SUB	120
1451	SUB	7
1452	LDA	16
1453	LAI	0
1454	MPY	1
1455	LSH	2
1456	SUB	121
1457	LDA	104
1458	SUB	122
1459	SUB	1
1460	LDA	15
1461	LAI	0
1462	MPY	7
1463	LSH	2
1464	SUB	123
1465	LDA	102
1466	SUB	1y
1467	SUB	124
1468	LDA	104
1469	SUB	15
1470	SUB	125
1471	LDA	5
1472	SUB	8
1473	SUB	126
1474	LMI	2416
1475	MPY	124
1476	SUB	103
1477	ROI	0
1478	SUB	7
1479	LMI	5
1480	MPY	125

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1481	ROI	0
1482	SUB	1
1483	SUB	1
1484	ROI	0
1485	SUBC	105
1486	SUB	108
1487	LMI	204
1488	MPY	126
1489	ROI	0
1490	ADD	7
1491	SUB	1
1492	ROI	0
1493	ADDC	105
1494	SUB	108
1495	LDA	127
1496	ADD	7
1497	SUB	127
1498	LDA	108
1499	ADDC	103
1500	SUB	103
1501	LMI	610
1502	MPY	124
1503	SUB	105
1504	ROI	0
1505	SUB	7
1506	LMI	2955
1507	MPY	125
1508	ROI	0
1509	ADD	1
1510	SUB	7
1511	ROI	0
1512	ADDC	105
1513	SUB	105
1514	LMI	y21
1515	MPY	126
1516	ROI	0
1517	SUB	7
1518	SUB	7
1519	ROI	0
1520	SUBC	105
1521	SUB	105
1522	LDA	126
1523	ADD	1
1524	SUB	126
1525	LDA	105
1526	ADDC	10y
1527	SUB	10y
1528	LMI	13
1529	MPY	124
1530	SUB	110
1531	ROI	0
1532	SUB	1
1533	LMI	1060
1534	MPY	126
1535	ROI	0

FICA

1036	ADD	7
1037	STO	7
1038	BRMH	0
1039	A DC	110
1040	SIO	110
1041	LAI	44
1042	MPY	120
1043	MPY	0
1044	SUB	7
1045	SIO	7
1046	MPY	0
1047	SUB	110
1048	SIO	110
1049	LAI	129
1050	A DC	7
1051	SIO	129
1052	LAI	110
1053	A DC	107
1054	SIO	107
1055	LAI	100
1056	SUB	114
1057	SIO	133
1058	LAI	101
1059	SUB	117
1060	SIO	130
1061	LAI	102
1062	SUB	120
1063	SUB	139
1064	LAI	103
1065	SUB	100
1066	SUB	137
1067	LAI	105
1068	SUB	144
1069	SIO	143
1070	LAI	104
1071	SUB	19
1072	SIO	134
1073	LAI	105
1074	SUB	122
1075	SIO	130
1076	LAI	105
1077	SUB	3
1078	JMPP	4048
1079	LAI	3
1080	SIO	101
1081	LAI	130
1082	SUB	3
1083	JMPP	4040
1084	LAI	3
1085	SIO	102
1086	LAI	139
1087	SUB	3
1088	JMPP	4040
1089	LAI	3
1090	SIO	103

FICA

1091	LDA	136
1092	STO	3
1093	JMPP	4048
1094	LDA	3
1095	STO	164
1096	LDA	137
1097	STO	3
1098	JMPP	4048
1099	LDA	3
1600	STO	105
1601	LDA	143
1602	STO	3
1603	JMPP	4048
1604	LDA	3
1605	SIO	100
1606	LDA	134
1607	STO	3
1608	JMPP	4048
1609	LDA	3
1610	SIO	167
1611	LDA	0
1612	SIO	146
1613	SUB	130
1614	BRMH	7
1615	SUB	1
1616	BRMH	7
1617	LDA	0
1618	SUB	23
1619	BRMH	7
1620	JMPP	7
1621	OUT	0
1622	JMPP	-5
1623	OUT	0
1624	OUT	0
1625	JMPP	-5
1626	JMPP	1725
1627	LAI	77
1628	SUB	161
1629	LDA	2
1630	BRMH	3
1631	OUT	0
1632	JMPP	3
1633	ADD	146
1634	SIO	140
1635	LAI	70
1636	SUB	162
1637	LDA	2
1638	RSIM	2
1639	SIO	174
1640	BRMH	3
1641	OUT	0
1642	JMPP	3
1643	ADD	140
1644	SIO	140
1645	LAI	42

FICA

1646	SUB	163
1647	LDA	114
1648	RSH	2
1649	RSH	2
1650	SIO	175
1651	BRMH	3
1652	OUT	0
1653	JMPP	3
1654	ADD	146
1655	SIO	146
1656	LAI	54
1657	SUB	104
1658	LDA	175
1659	RSH	2
1660	SIO	170
1661	BRMH	3
1662	OUT	0
1663	JMPP	3
1664	ADD	146
1665	SIO	140
1666	LAI	460
1667	SUB	105
1668	LDA	176
1669	RSH	2
1670	RSH	2
1671	SIO	177
1672	BRMH	3
1673	OUT	0
1674	JMPP	3
1675	ADD	146
1676	SIO	140
1677	LAI	77
1678	SUB	100
1679	LDA	177
1680	RSH	2
1681	SIO	178
1682	BRMH	3
1683	OUT	0
1684	JMPP	3
1685	ADD	146
1686	SIO	146
1687	LAI	09
1688	SUB	107
1689	LDA	178
1690	RSH	2
1691	RSH	2
1692	SIO	179
1693	BRMH	3
1694	OUT	0
1695	JMPP	3
1696	ADD	140
1697	SIO	140
1698	LDA	131
1699	ADD	1
1700	SIO	131

FICA

1701	LDA	0
1702	SUB	146
1703	BRMH	7
1704	SUB	1
1705	BRMH	7
1706	LAI	10
1707	SUB	131
1708	BRMH	9
1709	JMPP	7
1710	OUT	0
1711	JMPP	-5
1712	OUT	0
1713	LAI	1
1714	SIO	130
1715	SUB	0
1716	JMPP	3
1717	LDA	0
1718	SIO	131
1719	LAI	1
1720	SIO	1
1721	LAI	43
1722	SUB	1
1723	JMPP	1055
1724	JMPP	-2
1725	LAI	77
1726	SUB	101
1727	LAI	2201
1728	MPY	114
1729	LSN	2
1730	LSN	2
1731	SIO	4
1732	LDA	0
1733	BRMH	7
1734	OUT	0
1735	OUT	0
1736	OUT	0
1737	OUT	0
1738	OUT	0
1739	JMPP	7
1740	SIO	130
1741	LDA	4
1742	SIO	45
1743	LDA	2
1744	ASB	140
1745	SIO	140
1746	LAI	70
1747	SUB	102
1748	LAI	2045
1749	MPY	117
1750	BRMH	3
1751	LAI	0
1752	JMPP	14
1753	LSN	2
1754	LSN	2
1755	SIO	42

FICA

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1136	L A	0
1137	SUB	135
1138	L A	174
1139	SUB	0
1140	SUB	0
1141	ADD	146
1142	SUB	146
1143	SUB	0
1144	SUB	0
1145	SUB	0
1146	LAI	42
1147	SUB	163
1148	LAI	3640
1149	ADD	120
1150	SUB	4
1151	LAI	268
1152	PI	4
1153	BRAR	0
1154	LAI	95
1155	ADD	95
1156	SUB	95
1157	BRAR	-1
1158	JMPH	6
1159	LSH	2
1160	LSH	2
1161	LSH	2
1162	SUB	41
1163	LDA	0
1164	SUB	137
1165	L A	175
1166	A 0	146
1167	SUB	146
1168	LAI	54
1169	SUB	164
1170	LDA	0
1171	SUB	5
1172	SUB	0
1173	SUB	0
1174	SUB	0
1175	JMPH	5
1176	SUB	136
1177	LDA	170
1178	ADD	146
1179	SUB	146
1180	LAI	102
1181	SUB	6
1182	LAI	407
1183	SUB	165
1184	LAI	2267
1185	PI	100
1186	LSH	2
1187	SUB	0
1188	BRAR	5
1189	LDA	1
1190	SUB	1

FICA

1311	BRAR	8
1312	JMPH	-2
1313	SUB	43
1314	LDA	0
1315	SUB	137
1316	LDA	177
1317	ADD	146
1318	SUB	146
1319	LAI	152
1320	SUB	8
1321	LAI	77
1322	SUB	106
1323	LAI	2326
1324	PI	144
1325	LSH	2
1326	ADD	0
1327	BRAR	5
1328	LDA	1
1329	SUB	1
1330	BRAR	8
1331	JMPH	-2
1332	SUB	25
1333	LDA	0
1334	SUB	143
1335	LDA	170
1336	ADD	146
1337	SUB	146
1338	LAI	69
1339	SUB	167
1340	LMI	2731
1341	MPY	102
1342	LSH	2
1343	LSH	2
1344	BRMR	5
1345	LDA	1
1346	SUB	1
1347	BRAR	8
1348	JMPH	-2
1349	SUB	44
1350	LDA	0
1351	SUB	134
1352	LDA	170
1353	ADD	146
1354	SUB	146
1355	LDA	45
1356	HSIM	2
1357	SUB	7
1358	LAI	1792
1359	SUB	0
1360	SUB	164
1361	LDA	164
1362	BRAR	2
1363	JMPH	2
1364	LDA	6
1365	SUB	7

FICA

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1866	SUB	5
1867	INP	1
1868	SUB	203
1869	LAI	662
1870	SUB	7
1871	LAI	3414
1872	MPYM	246
1873	ADD	7
1874	SUB	6
1875	HSIM	2
1876	SUB	7
1877	LAI	1433
1878	LAI	102
1879	DIV	7
1880	OUT	0
1881	SUB	7
1882	INP	0
1883	OUT	14
1884	SUB	62
1885	INP	1
1886	SUB	204
1887	LDA	5
1888	SUB	0
1889	BRMR	5
1890	SUB	7
1891	BRMR	4
1892	LDA	7
1893	JMPH	4
1894	JMPH	-3
1895	LDA	5
1896	OUT	0
1897	SUB	5
1898	LDA	0
1899	SUB	7
1900	SUB	7
1901	INP	0
1902	OUT	14
1903	SUB	63
1904	INP	1
1905	SUB	205
1906	LDA	5
1907	SUB	0
1908	BRMR	2
1909	JMPH	2
1910	SUB	7
1911	BRMR	3
1912	LDA	5
1913	JMPH	3
1914	LDA	7
1915	OUT	0
1916	SUB	5
1917	LAI	2561
1918	MPYM	6
1919	LAI	0
1920	MPY	5

Compute N1
Error Through
KN1

1921	LSH	2
1922	LSH	2
1923	LSH	2
1924	LSH	2
1925	SUB	5
1926	INP	0
1927	OUT	14
1928	SUB	64
1929	INP	1
1930	SUB	206
1931	LAI	111
1932	SUB	7
1933	LAI	3319
1934	MPYM	246
1935	ADD	7
1936	LAI	5
1937	MPYM	0
1938	SUB	0
1939	INP	0
1940	OUT	14
1941	SUB	65
1942	INP	1
1943	SUB	267
1944	LAI	1679
1945	MPYM	6
1946	SUB	6
1947	INP	0
1948	OUT	14
1949	SUB	66
1950	INP	1
1951	SUB	206
1952	LDA	165
1953	SUB	65
1954	SUB	62
1955	LDA	164
1956	SUB	65
1957	LDA	5
1958	SUB	63
1959	LDA	0
1960	BRMR	2
1961	JMPH	2
1962	SUB	65
1963	SUB	0
1964	SUB	0
1965	LDA	62
1966	BRMR	7
1967	SUB	0
1968	BRMR	0
1969	SUB	6
1970	LDA	6
1971	BRMR	7
1972	JMPH	7
1973	SUB	0
1974	BRMR	-5
1975	JMPH	-5

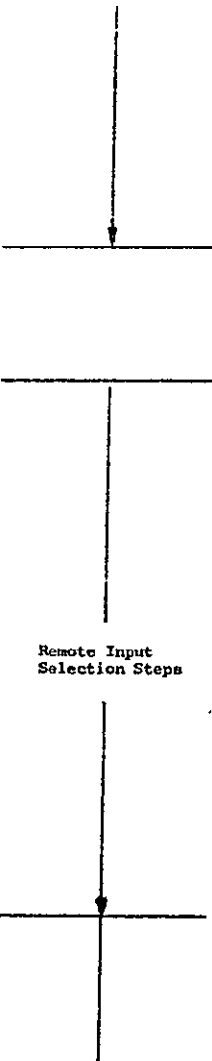
Compute N1
Loop Rate
Feedback

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1910	LDA	5
1911	JMP	50
1912	LDA	52
1913	SIO	7
1914	LDA	7
1915	SUB	0
1916	LDA	0
1917	SUB	7
1918	SUB	7
1919	LDA	7
1920	SUB	2
1921	SUB	2
1922	LDA	0
1923	JMP	0
1924	JMP	0
1925	LDA	0
1926	SUB	0
1927	SUB	7
1928	SUB	7
1929	SUB	2
1930	LDA	7
1931	MPY	1
1932	SIO	7
1933	LDA	53
1934	SUB	0
2000	LDA	0
2001	SUB	3
2002	SUB	6
2003	JMP	5
2004	SUB	0
2005	SUB	25
2006	SIO	0
2007	SUB	0
2008	LDA	7
2009	SUB	7
2010	SUB	0
2011	SUB	8
2012	SUB	6
2013	LDA	7
2014	SUB	7
2015	MPY	7
2016	SUB	0
2017	SUB	5
2018	JMP	5
2019	SUB	0
2020	MPY	50
2021	LDA	7
2022	SIO	6
2023	LDA	111
2024	MPY	53
2025	SIO	8
2026	SUB	0
2027	SUB	5
2028	LDA	54
2029	SUB	5
2030	SIO	54

Compute N1
Loop Rate
Feedback

2031	LDA	53
2032	SUB	8
2033	ADD	0
2034	SIO	55
2035	INP	0
2036	OUT	14
2037	SIO	87
2038	INP	1
2039	SIO	205
2040	LMI	2160
2041	MPY	53
2042	LSH	2
2043	SIO	10
2044	JMP	3795
2045	LDA	5
2046	SIO	0
2047	INP	0
2048	OUT	14
2049	SIO	88
2050	LMI	1491
2051	MPY	234
2052	SIO	5
2053	JMP	3795
2054	LDA	5
2055	SIO	51
2056	INP	0
2057	OUT	14
2058	SIO	89
2059	LDA	2
2060	SUB	1
2061	SIO	7
2062	LDA	0
2063	SUB	20
2064	LDA	7
2065	BRAR	2
2066	JMP	2
2067	LDA	5
2068	SIO	5
2069	RSH	2
2070	SIO	7
2071	LDA	0
2072	RSH	2
2073	SUB	7
2074	LDA	5
2075	BRAR	2
2076	JMP	2
2077	LDA	0
2078	SIO	6
2079	LDA	35
2080	RSH	2
2081	SIO	5
2082	LAI	3584
2083	LAI	255
2084	DIV	5
2085	ROI	0



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2086	SIO	5
2087	ADD	5
2088	LAI	0
2089	MPY	45
2090	SIO	7
2091	INP	0
2092	OUT	14
2093	SIO	71
2094	LAI	1048
2095	SUB	7
2096	BRAR	34
2097	LAI	665
2098	SUB	7
2099	BRAR	16
2100	LAI	1350
2101	MPYM	7
2102	SIO	4
2103	OUT	0
2104	LAI	197
2105	ADD	4
2106	LAI	0
2107	MPYM	7
2108	SIO	4
2109	OUT	0
2110	OUT	0
2111	LAI	18
2112	ADD	4
2113	OUT	0
2114	JMP	49
2115	LAI	521
2116	SIO	8
2117	LAI	2468
2118	MPYM	7
2119	LSH	2
2120	SUB	8
2121	LAI	0
2122	MPYM	7
2123	SIO	4
2124	OUT	0
2125	OUT	0
2126	LAI	40
2127	ADD	4
2128	OUT	0
2129	JMP	34
2130	LAI	1570
2131	SUB	7
2132	BRAR	16
2133	LAI	3595
2134	MPYM	7
2135	SIO	4
2136	OUT	0
2137	LAI	50
2138	ADD	4
2139	LAI	0
2140	MPYM	7

Compute T25

2141	SIO	4
2142	LAI	7
2143	SIO	0
2144	LDA	4
2145	SUB	6
2146	OUT	0
2147	JMP	10
2148	LMI	2373
2149	MPYM	7
2150	LSH	2
2151	SIO	4
2152	LAI	3430
2153	SUB	4
2154	LAI	0
2155	MPYM	7
2156	LSH	2
2157	LSH	2
2158	SIO	4
2159	LAI	2130
2160	SUB	4
2161	SIO	4
2162	ADD	4
2163	SIO	4
2164	INP	0
2165	OUT	14
2166	SIO	70
2167	LDA	255
2168	SUB	2
2169	SIO	8
2170	LAI	1655
2171	MPY	8
2172	SIO	8
2173	INP	0
2174	OUT	14
2175	SIO	90
2176	LDA	4
2177	LAI	0
2178	MPY	0
2179	ADD	4
2180	SIO	4
2181	LAI	3567
2182	MPYM	102
2183	SIO	5
2184	SUB	2
2185	SIO	45
2186	INP	0
2187	OUT	14
2188	SIO	91
2189	LDA	9
2190	LAI	0
2191	MPYM	4
2192	ADD	45
2193	SUB	0
2194	BRAR	0
2195	ADD	2

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2170	JMP	3
2171	LDA	4
2172	SUB	0
2173	SUB	4
2200	LDA	4
2201	LDA	4
2202	SUB	4
2203	LDA	2167
2204	SUB	4
2205	LDA	0
2206	SUB	4
2207	SUB	4
2208	LDA	100
2209	SUB	4
2210	SUB	0
2211	LDA	1907
2212	SUB	4
2213	LDA	202
2214	SUB	0
2215	SUB	7
2216	SUB	4
2217	LDA	4
2218	SUB	2
2219	JMP	2
2220	LDA	202
2221	JMP	0
2222	LDA	4
2223	SUB	0
2224	LDA	0
2225	SUB	0
2226	SUB	0
2227	SUB	4
2228	LDA	1903
2229	SUB	8
2230	LDA	4060
2231	JMP	4
2232	SUB	0
2233	LDA	0
2234	JMP	0
2235	SUB	4
2236	LDA	1740
2237	SUB	0
2238	LDA	100
2239	JMP	240
2240	SUB	0
2241	SUB	0
2242	SUB	4
2243	LDA	4
2244	SUB	2
2245	JMP	2
2246	LDA	0
2247	SUB	4
2248	LDA	42
2249	JMP	2
2250	SUB	11

Compute
N2 Error

2251	LDA	4
2252	SUB	11
2253	SUB	7
2254	LDA	4
2255	ADD	4
2256	LAI	0
2257	JMP	7
2258	SUB	4
2259	LAI	1000
2260	SUB	12
2261	LDA	4
2262	SUB	0
2263	JMP	0
2264	SUB	12
2265	JMP	4
2266	LDA	12
2267	JMP	4
2268	JMP	-3
2269	LDA	4
2270	SUB	0
2271	SUB	4
2272	LDA	0
2273	SUB	12
2274	SUB	13
2275	LDA	4
2276	SUB	0
2277	JMP	2
2278	JMP	2
2279	SUB	13
2280	JMP	3
2281	LDA	4
2282	JMP	3
2283	LDA	13
2284	SUB	0
2285	SUB	4
2286	LDA	97
2287	SUB	2
2288	SUB	13
2289	LAI	3924
2290	JMP	4
2291	LDA	2
2292	SUB	0
2293	LAI	148
2294	JMP	239
2295	SUB	0
2296	LDA	114
2297	SUB	13
2298	LAI	181
2299	SUB	0
2300	SUB	0
2301	SUB	0
2302	SUB	0
2303	LAI	3904
2304	SUB	10
2305	LDA	02

Compute
N2 Error

2306	SUB	0
2307	LDA	0
2308	JMP	1
2309	SUB	02
2310	LDA	02
2311	JMP	2
2312	JMP	2
2313	LDA	0
2314	JMP	0
2315	SUB	0
2316	LDA	10
2317	SUB	02
2318	ADD	02
2319	JMP	2
2320	JMP	2
2321	LDA	02
2322	SUB	7
2323	SUB	0
2324	LDA	0
2325	JMP	2
2326	JMP	2
2327	LDA	7
2328	SUB	10
2329	LDA	10
2330	SUB	0
2331	SUB	0
2332	SUB	1
2333	LDA	9
2334	JMP	2
2335	JMP	2
2336	LDA	7
2337	SUB	0
2338	LDA	06
2339	SUB	2
2340	SUB	13
2341	LAI	111
2342	JMP	0
2343	SUB	0
2344	SUB	0
2345	SUB	10
2346	LDA	02
2347	SUB	10
2348	LDA	02
2349	SUB	0
2350	SUB	10
2351	LDA	02
2352	SUB	0
2353	ADD	0
2354	SUB	0
2355	LAI	2100
2356	JMP	0
2357	LDA	2
2358	SUB	10
2359	LDA	140
2360	SUB	13

Compute
N2 Error

2361	JMP	3199
2362	LDA	0
2363	SUB	2
2364	SUB	1
2365	LDA	0
2366	SUB	2
2367	SUB	1
2368	LDA	0
2369	JMP	2
2370	SUB	0
2371	LDA	0
2372	SUB	0
2373	LAI	012
2374	JMP	2
2375	JMP	2
2376	LDA	0
2377	SUB	73
2378	LDA	20
2379	ADD	20
2380	SUB	13
2381	LAI	051
2382	SUB	7
2383	LAI	794
2384	JMP	241
2385	ADD	7
2386	SUB	1
2387	SUB	11
2388	SUB	11
2389	LDA	0
2390	SUB	13
2391	LDA	7
2392	ADD	7
2393	LAI	0
2394	JMP	11
2395	SUB	11
2396	SUB	0
2397	JMP	0
2398	SUB	12
2399	JMP	4
2400	LDA	12
2401	JMP	4
2402	JMP	0
2403	LDA	11
2404	SUB	0
2405	SUB	11
2406	LAI	3924
2407	JMP	11
2408	LDA	2
2409	SUB	0
2410	LDA	31
2411	SUB	13
2412	JMP	3199
2413	LDA	0
2414	SUB	1
2415	LAI	1944

Compute N2
Idle Error

2410	STO	4
2411	STO	100
2412	LDA	100
2413	BRCH	2
2420	JMPR	2
2421	LDA	4
2422	STO	3
2423	LDA	37
2424	STO	13
2425	LDA	100
2426	STO	3
2427	STO	10
2428	LDA	33
2429	STO	3
2430	LAI	2207
2431	STO	3
2432	LAI	0
2433	STO	3
2434	LAI	2
2435	LDA	2
2436	STO	2
2437	A J	3
2438	STO	4
2439	STO	3
2440	LAI	3
2441	STO	10
2442	LAI	102
2443	STO	3
2444	LAI	3719
2445	STO	3
2446	LAI	0
2447	STO	3
2448	STO	2
2449	LAI	2
2450	STO	3
2451	STO	3
2452	LAI	1400
2453	STO	3
2454	STO	3
2455	STO	3
2456	STO	3
2457	STO	3
2458	STO	3
2459	STO	3
2460	STO	3
2461	STO	3
2462	STO	3
2463	STO	3
2464	STO	3
2465	STO	3
2466	STO	3
2467	STO	3
2468	STO	3
2469	STO	3
2470	STO	3
2471	STO	3
2472	STO	3
2473	STO	3
2474	STO	3
2475	STO	3
2476	STO	3
2477	STO	3
2478	STO	3
2479	STO	3
2480	STO	3
2481	STO	3
2482	STO	3
2483	STO	3
2484	STO	3
2485	STO	3
2486	STO	3
2487	STO	3
2488	STO	3
2489	STO	3
2490	STO	3
2491	STO	3
2492	STO	3
2493	STO	3
2494	STO	3
2495	STO	3
2496	STO	3
2497	STO	3
2498	STO	3
2499	STO	3
2500	STO	3
2501	STO	3
2502	STO	3
2503	STO	3
2504	STO	3
2505	STO	3
2506	STO	3
2507	STO	3
2508	STO	3
2509	STO	3
2510	STO	3
2511	STO	3
2512	STO	3
2513	STO	3
2514	STO	3
2515	STO	3
2516	STO	3
2517	STO	3
2518	STO	3
2519	STO	3
2520	STO	3
2521	STO	3
2522	STO	3
2523	STO	3
2524	STO	3
2525	STO	3

Compute WF

(Cont'd to 2559)

2411	BRCH	2
2412	STO	8
2413	LDA	202
2414	STO	10
2415	LMI	993
2416	MPYM	32
2417	STO	7
2418	STO	7
2419	STO	1
2420	STO	1
2481	STO	5
2482	STO	8
2483	LDA	3
2484	BRMR	2
2485	JMPR	2
2486	LDA	8
2487	STO	5
2488	LDA	7
2489	DIV	3
2490	ROI	3
2491	STO	3
2492	LAI	70
2493	STO	10
2494	STO	3
2495	LDA	10
2496	BRMR	2
2497	JMPR	2
2498	LDA	3
2499	STO	3
2500	LDA	74
2501	OUT	13
2502	LAI	57
2503	STO	10
2504	LMI	2420
2505	MPYM	5
2506	STO	9
2507	LDA	40
2508	OUT	13
2509	LAI	3900
2510	STO	7
2511	LAI	3
2512	MPYM	3
2513	STO	7
2514	LDA	42
2515	OUT	13
2516	LAI	2290
2517	ADD	7
2518	LAI	3
2519	MPYM	2
2520	STO	2
2521	STO	10
2522	STO	3
2523	LAI	490
2524	STO	7
2525	LDA	111

Compute T41C Error

2520	OUT	13
2527	LMI	1400
2528	MPYM	41
2529	ADD	7
2530	STO	7
2531	LDA	3
2532	STO	3
2533	LDA	93
2534	BRMR	3
2535	OUT	0
2536	OUT	0
2537	OUT	0
2538	JMPR	3
2539	STO	3
2540	STO	10
2541	STO	7
2542	BRMR	3
2543	LDA	7
2544	JMPR	3
2545	LDA	10
2546	OUT	0
2547	ADD	3
2548	STO	31
2549	BRMR	2
2550	STO	7
2551	LDA	100
2552	OUT	13
2553	LAI	1301
2554	STO	3
2555	LMI	393
2556	MPYM	251
2557	ADD	3
2558	STO	7
2559	STO	7
2560	LDA	3
2561	OUT	13
2562	LMI	2645
2563	MPY	3
2564	STO	3
2565	LAI	33
2566	STO	7
2567	STO	27
2568	STO	4
2569	LDA	32
2570	STO	3
2571	LDA	7
2572	BRMR	1
2573	STO	32
2574	LDA	32
2575	BRMR	2
2576	JMPR	2
2577	LDA	7
2578	JMPR	0
2579	LDA	3
2580	STO	7

Compute T41C Error

Compute T41C Rate Feedback

2581	STO	32
2582	ADD	52
2583	BRMR	2
2584	JMPR	2
2585	LDA	52
2586	STO	12
2587	STO	4
2588	LDA	4
2589	BRMR	2
2590	JMPR	2
2591	LDA	12
2592	STO	12
2593	LDA	7
2594	STO	7
2595	STO	7
2596	STO	27
2597	STO	4
2598	STO	12
2599	LDA	4
2600	BRMR	2
2601	JMPR	2
2602	LDA	12
2603	STO	7
2604	LDA	6
2605	OUT	13
2606	LMI	304
2607	MPY	27
2608	STO	4
2609	ROI	0
2610	STO	12
2611	LDA	30
2612	STO	12
2613	STO	30
2614	LDA	27
2615	STO	4
2616	ADD	9
2617	STO	27
2618	LDA	67
2619	OUT	13
2620	LDA	3
2621	STO	67
2622	LMI	221
2623	MPY	27
2624	ADD	27
2625	STO	10
2626	LDA	3
2627	STO	10
2628	STO	3
2629	STO	3
2630	STO	2
2631	STO	4
2632	LDA	0
2633	STO	2
2634	LDA	4
2635	BRMR	2

Compute T41C Rate Feedback

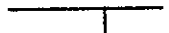
Select max. WF Channel Error

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2530	PH	4
2531	LDA	0
2532	SIO	6
2533	LAI	1024
2534	JMPR	2
2535	JMPR	2
2536	LJA	73
2537	SIO	13
2538	LJA	46
2539	UUI	13
2540	LAI	1030
2541	SIO	12
2542	LJA	71
2543	UUI	2
2544	SUB	12
2545	UUI	16
2546	LJA	79
2547	UUI	4
2548	SUB	12
2549	LJA	10
2550	LJA	72
2551	SUB	1
2552	SIO	72
2553	BRMR	10
2554	LJA	0
2555	UUI	0
2556	UUI	0
2557	UUI	0
2558	UUI	0
2559	UUI	0
2560	UUI	0
2561	LAI	9
2562	SIO	72
2563	JMPR	12
2564	LJA	95
2565	SIO	12
2566	LJA	0
2567	SUB	101
2568	LJA	2
2569	BRMR	2
2570	JMPR	2
2571	SIO	0
2572	BRMR	2
2573	AUI	01
2574	SIO	01
2575	LJA	0
2576	BRMR	2
2577	SIO	4
2578	LJA	48
2579	UUI	13
2580	LJA	7

Select Max. WF Channel Error



Check for Excess Vibration

2091	KON	4
2092	SUB	4
2093	LDA	7
2094	BRMR	2
2095	JMPR	2
2096	LDA	0
2097	SIO	6
2098	LAI	1536
2099	BRMR	2
2100	JMPR	2
2101	LDA	73
2102	SIO	73
2103	LDA	67
2104	LSH	2
2105	SUB	0
2106	LDA	13
2107	BRMR	2
2108	JMPR	2
2109	LDA	95
2110	SIO	73
2111	LDA	38
2112	UUI	13
2113	LAI	433
2114	SIO	4
2115	LAI	427
2116	MPYM	49
2117	SIO	0
2118	LDA	47
2119	UUI	13
2120	LAI	2632
2121	SUB	0
2122	LAI	0
2123	MPYM	49
2124	ADJ	4
2125	SIO	4
2126	LDA	44
2127	UUI	13
2128	LAI	3400
2129	MPYM	50
2130	SIO	0
2131	LDA	2
2132	RSRM	2
2133	RSRM	2
2134	ADJ	1
2135	LAI	101
2136	UUI	0
2137	KUI	0
2138	SIO	0
2139	LMI	2273
2140	MPYM	0
2141	LSH	2
2142	LAI	0
2143	MPYM	42
2144	SIO	92
2145	LAI	344

Check for Excess Vibration



Compute Accel WF

2746	SIO	7
2747	LAI	055
2748	SIO	9
2749	LAI	400
2750	SIO	10
2751	LDA	43
2752	ADD	43
2753	UUI	13
2754	LDA	92
2755	SUB	7
2756	BRMR	91
2757	SIO	7
2758	SUB	9
2759	JMPR	58
2760	SIO	7
2761	SUB	10
2762	BRMR	28
2763	SIO	7
2764	LAI	1108
2765	SIO	9
2766	LAI	2799
2767	MPY	7
2768	LSH	2
2769	SIO	10
2770	LAI	2028
2771	SUB	10
2772	LAI	0
2773	MPY	7
2774	LSH	2
2775	LSH	2
2776	LSH	2
2777	ADD	10
2778	SIO	10
2779	LVA	7
2780	LAI	0
2781	MPY	10
2782	LAI	7
2783	LSH	2
2784	LSH	2
2785	ADD	9
2786	UUI	0
2787	UUI	0
2788	UUI	0
2789	JMPR	09
2790	LAI	2092
2791	MPY	7
2792	LSH	2
2793	LSH	2
2794	LSH	2
2795	SIO	10
2796	LAI	3120
2797	SUB	10
2798	LAI	0
2799	MPY	7
2800	LSH	2

Compute Accel WF

2801	LSH	2
2802	LSH	2
2803	SIO	10
2804	LAI	4044
2805	ADD	10
2806	SIO	10
2807	LDA	7
2808	LAI	0
2809	MPY	10
2810	LSH	2
2811	LSH	2
2812	SIO	10
2813	LAI	1570
2814	SUB	10
2815	UUI	0
2816	JMPR	42
2817	LAI	2994
2818	MPY	92
2819	LSH	2
2820	SIO	10
2821	LAI	2040
2822	SUB	10
2823	LAI	0
2824	MPY	92
2825	LSH	2
2826	LSH	2
2827	LSH	2
2828	SIO	10
2829	LAI	2030
2830	SUB	10
2831	LAI	0
2832	MPY	92
2833	LSH	2
2834	LSH	2
2835	LSH	2
2836	LSH	2
2837	SIO	10
2838	LAI	1909
2839	SUB	10
2840	UUI	0
2841	UUI	0
2842	UUI	0
2843	UUI	0
2844	UUI	0
2845	UUI	0
2846	JMPR	12
2847	KUI	0
2848	KUI	0
2849	KUI	0
2850	KUI	0
2851	KUI	0
2852	KUI	0
2853	KUI	0
2854	KUI	0
2855	KUI	0

Compute Accel WF

2330	RUI	3
2331	LAI	124
2332	SIO	1
2333	L I	2333
2334	RUI	72
2335	SIO	3
2336	LDA	10
2337	L I	13
2338	L I	2211
2339	RUI	49
2340	SIO	10
2341	LAI	12
2342	SUB	10
2343	SUB	3
2344	SIO	3
2345	LAI	2390
2346	SIO	10
2347	A J	1
2348	SIO	11
2349	LDA	10
2350	SIO	13
2351	LDA	3
2352	SIO	10
2353	SUB	11
2354	LDA	1
2355	RUI	2
2356	JMPH	2
2357	LDA	3
2358	LDA	0
2359	LDA	0
2360	MPIM	4
2361	SKM	2
2362	LAI	0
2363	RUI	44
2364	SIO	4
2365	L I	1040
2366	RUI	242
2367	SIO	0
2368	L A	120
2369	SIO	13
2370	L I	1223
2371	A J	0
2372	LAI	0
2373	RUI	4
2374	SIO	0
2375	SIO	3
2376	SIO	0
2377	JMPH	3
2378	LDA	2
2379	SUB	1
2380	RUI	2
2381	SIO	0
2382	JMPH	3
2383	LDA	2

Compute Accel
WF

2911	SUB	1
2912	LSD	2
2913	SIO	4
2914	LDA	100
2915	SIO	13
2916	LAI	631
2917	MPYM	44
2918	SIO	0
2919	LAI	1040
2920	MPYM	243
2921	SIO	1
2922	LDA	41
2923	SIO	13
2924	LAI	2816
2925	SUB	1
2926	LAI	0
2927	MPY	0
2928	LSD	2
2929	LSD	2
2930	SIO	0
2931	LDA	28
2932	SIO	8
2933	SIO	13
2934	JMPH	3840
2935	LDA	0
2936	SIO	10
2937	LDA	4
2938	SIO	0
2939	LDA	233
2940	SIO	13
2941	JMPH	3040
2942	LDA	8
2943	SUB	10
2944	SIO	4
2945	LDA	0
2946	SIO	8
2947	LDA	144
2948	SIO	13
2949	JMPH	3840
2950	LDA	8
2951	SUB	10
2952	SIO	8
2953	SIO	0
2954	LDA	62
2955	SIO	10
2956	LDA	19
2957	SIO	13
2958	JMPH	3900
2959	LDA	8
2960	SIO	62
2961	LDA	0
2962	SIO	11
2963	LDA	4
2964	SIO	0
2965	LDA	63

Compute
Decel WF

Compare WF to
Accel/Decel
Schedules

Accel/Decel
Load
Compensation

(cont'd to 2974)

2966	SIO	10
2967	LDA	30
2968	SIO	13
2969	JMPH	3900
2970	LDA	4
2971	SIO	03
2972	LDA	0
2973	RSH	2
2974	SIO	3
2975	LDA	81
2976	SIO	13
2977	LDA	0
2978	RSH	2
2979	SUB	3
2980	LDA	0
2981	BRMH	2
2982	JMPH	2
2983	LDA	0
2984	SIO	0
2985	LDA	2
2986	BRMH	2
2987	JMPH	2
2988	LDA	10
2989	SIO	13
2990	LDA	0
2991	RSH	2
2992	SIO	3
2993	LDA	11
2994	RSH	2
2995	SUB	3
2996	LDA	11
2997	BRMH	2
2998	JMPH	2
2999	LDA	0
3000	SIO	0
3001	LAI	2560
3002	BRMH	2
3003	JMPH	2
3004	LDA	13
3005	SIO	13
3006	LAI	120
3007	SIO	3
3008	LDA	0
3009	SUB	0
3010	BRMH	0
3011	SUB	3
3012	JMPH	4
3013	LDA	3
3014	JMPH	4
3015	JMPH	-3
3016	LDA	0
3017	SIO	0
3018	SIO	0
3019	LDA	0
3020	SUB	3

Select Controlling
WF Channel Error

Apply WF Channel
Overflow Limits

(cont'd to 3032)

3021	SIO	3
3022	LDA	0
3023	SUB	0
3024	BRMH	2
3025	JMPH	2
3026	SUB	3
3027	BRMH	3
3028	LDA	0
3029	JMPH	3
3030	LDA	3
3031	SIO	0
3032	SIO	0
3033	LDA	80
3034	SIO	13
3035	LAI	2800
3036	MPY	0
3037	LSD	2
3038	LSD	2
3039	SIO	0
3040	SUB	20
3041	SIO	1
3042	LAI	103
3043	MPY	1
3044	SIO	1
3045	RUI	0
3046	ADD	21
3047	SIO	21
3048	LDA	1
3049	ADD	20
3050	SIO	20
3051	SUB	02
3052	SIO	3
3053	LDA	80
3054	SIO	13
3055	LAI	13
3056	MPY	3
3057	RSH	2
3058	RSH	2
3059	SIO	8
3060	RUI	0
3061	SIO	3
3062	LDA	63
3063	SIO	13
3064	LAI	20
3065	SIO	0
3066	LDA	0
3067	SUB	24
3068	LAI	102
3069	withmt	2
3070	JMPH	2
3071	LDA	0
3072	SIO	0
3073	LDA	64
3074	SIO	13
3075	LDA	0

Generate WF
Torque Motor
Signal

(cont'd on
next page)

ORIGINAL PAGE IS
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3076	SUB	05
3077	S10	10
3078	L'A	8
3079	S'B	0
3080	L'A	10
3081	B'AK	7
3082	SUB	0
3083	B'AK	0
3084	SUB	8
3085	LDA	8
3086	B'AK	7
3087	JMPK	7
3088	SUB	0
3089	B'AK	0
3090	J'PR	0
3091	UUI	0
3092	JMPK	0
3093	LDA	0
3094	S10	0
3095	L'A	0
3096	SUB	0
3097	SUB	0
3098	S10	0
3099	LDA	8
3100	SUB	0
3101	LDA	0
3102	B'AK	7
3103	SUB	0
3104	B'AK	8
3105	SUB	0
3106	LDA	0
3107	JMPK	7
3108	JMPK	7
3109	SUB	0
3110	B'AK	0
3111	JMPK	0
3112	UUI	0
3113	JMPK	0
3114	LDA	8
3115	S10	8
3116	L'A	8
3117	SUB	8
3118	S10	00
3119	LDA	00
3120	B'AK	8
3121	S10	00
3122	LDA	37
3123	UUI	13
3124	LAI	3032
3125	SUB	00
3126	LAI	2
3127	L'A	2
3128	S10	10
3129	S10	110
3130	LDA	0

Generate WF
Torque Motor
Signal

3131	ADD	118
3132	S10	118
3133	LAI	205
3134	ADD	10
3135	S10	10
3136	LDA	88
3137	UUI	13
3138	LDA	0
3139	SUB	0
3140	B'AK	0
3141	ADD	10
3142	SUB	0
3143	B'AK	8
3144	UUI	8
3145	JMPK	8
3146	ADD	10
3147	UUI	0
3148	UUI	0
3149	UUI	0
3150	JMPK	0
3151	LDA	2
3152	SUB	1
3153	S10	10
3154	UUI	1
3155	S10	90
3156	LAI	1099
3157	MPYK	238
3158	S10	9
3159	LDA	89
3160	UUI	13
3161	LAI	1380
3162	MPY	0
3163	S10	0
3164	S10	119
3165	SUB	0
3166	B'AK	3
3167	ADD	9
3168	JMPK	3
3169	SUB	9
3170	UUI	0
3171	ADD	05
3172	S10	0
3173	LDA	05
3174	ADD	119
3175	S10	119
3176	LAI	3270
3177	MPY	119
3178	S10	119
3179	LDA	0
3180	SUB	24
3181	LDA	119
3182	B'AK	2
3183	JMPK	2
3184	LDA	110
3185	S10	110

Generate WF
Torque Motor
Signal

Modify for
Fail-Fixed
Servovalve

3186	LDA	71
3187	UUI	13
3188	LAI	3094
3189	S10	4
3190	LAI	1011
3191	S10	5
3192	LDA	6
3193	SUB	0
3194	B'AK	0
3195	SUB	0
3196	LDA	0
3197	B'AK	8
3198	JMPK	8
3199	SUB	8
3200	LDA	6
3201	B'AK	2
3202	JMPK	4
3203	LDA	4
3204	JMPK	3
3205	LDA	0
3206	UUI	0
3207	ADD	2
3208	S10	0
3209	LAI	1177
3210	S10	0
3211	LAI	3070
3212	MPYK	0
3213	B'AK	2
3214	S10	4
3215	LDA	10
3216	UUI	13
3217	LAI	2298
3218	SUB	4
3219	LAI	0
3220	MPYK	0
3221	LSH	2
3222	S10	4
3223	LDA	122
3224	UUI	13
3225	LAI	2026
3226	SUB	4
3227	LAI	0
3228	MPYK	6
3229	LSH	2
3230	LSH	2
3231	SUB	0
3232	LSH	2
3233	SUB	2
3234	S10	6
3235	LDA	102
3236	UUI	13
3237	LDA	09
3238	SUB	107
3239	LDA	2
3240	B'AK	2

Modify for
Fail-Fixed
Servovalve

(cont'd to 3242)

3241	LDA	0
3242	UUI	7
3243	B'AK	2
3244	UUI	2
3245	LDA	90
3246	B'AK	2
3247	LDA	73
3248	S10	180
3249	LAI	732
3250	S10	7
3251	LAI	410
3252	S10	4
3253	LAI	1220
3254	S10	0
3255	LDA	252
3256	SUB	2
3257	S10	0
3258	B'AK	12
3259	SUB	0
3260	S10	0
3261	B'AK	11
3262	SUB	4
3263	B'AK	12
3264	LAI	0
3265	UUI	0
3266	UUI	0
3267	UUI	0
3268	UUI	0
3269	JMPK	12
3270	UUI	0
3271	JMPK	-10
3272	LAI	132
3273	UUI	0
3274	JMPK	-9
3275	LAI	3000
3276	MPY	0
3277	LSH	2
3278	S10	0
3279	LDA	7
3280	SUB	0
3281	S10	4
3282	LAI	237
3283	LAI	0
3284	MPY	4
3285	S10	4
3286	LDA	234
3287	UUI	13
3288	LDA	0
3289	SUB	21
3290	LDA	0
3291	B'AK	2
3292	JMPK	2
3293	LDA	4
3294	S10	4
3295	SUB	93

Stator Re-set
Generation and
Activation

(cont'd on
next page)

3296 SIO	6
3297 LAI	3
3298 SIO	3
3299 LSH	6
3300 SUB	0
3301 JMPR	0
3302 SUB	4
3303 JMPR	4
3304 LSH	0
3305 SIO	4
3306 JMPR	3
3307 LSH	0
3308 SIO	0
3309 SIO	0
3310 LAI	4044
3311 SIO	0
3312 LDA	0
3313 SUB	0
3314 JMPR	2
3315 JMPR	2
3316 SUB	0
3317 LDA	3
3318 LDA	0
3319 JMPR	3
3320 LDA	0
3321 SIO	0
3322 SIO	0
3323 LAI	1108
3324 SIO	0
3325 SIO	0
3326 SIO	0
3327 SIO	94
3328 SIO	94
3329 LDA	6
3330 SIO	93
3331 SIO	93
3332 SUB	0
3333 SIO	2
3334 SIO	3
3335 SIO	3
3336 SIO	1
3337 SIO	67
3338 SIO	67
3339 LDA	3
3340 SIO	20
3341 LAI	530
3342 SIO	10
3343 LAI	173
3344 SIO	9
3345 LAI	304
3346 SIO	4
3347 LAI	195
3348 SIO	0
3349 LAI	230
3350 SIO	6
3351 LAI	806

Stator Re-set
Generation and
Activation

3351 SIO	6
3352 SUB	35
3353 SIO	7
3354 DRMH	3
3355 OUI	0
3356 JMPR	3
3357 LDA	0
3358 SUB	7
3359 SUB	0
3360 SIO	4
3361 LAI	190
3362 SIO	0
3363 SUB	4
3364 DRMH	10
3365 LDA	0
3366 SUB	0
3367 SUB	4
3368 LDA	3
3369 DRMH	2
3370 JMPR	10
3371 HSHM	2
3372 SIO	3
3373 LDA	0
3374 HSHM	2
3375 ADD	3
3376 OUI	0
3377 OUI	0
3378 OUI	0
3379 JMPR	10
3380 LDA	0
3381 OUI	0
3382 OUI	0
3383 OUI	0
3384 OUI	0
3385 OUI	0
3386 SIO	3
3387 LDA	1
3388 ADD	1
3389 ADD	1
3390 ADD	1
3391 ADD	67
3392 SIO	67
3393 LDA	3
3394 SIO	20
3395 LAI	530
3396 SIO	10
3397 LAI	173
3398 SIO	9
3399 LAI	304
3400 SIO	4
3401 LAI	195
3402 SIO	0
3403 LAI	230
3404 SIO	6
3405 LAI	806

Average or Select
Between Stator
Feedbacks

Generate
Stator
Schedule

3406 SIO	7
3407 LDA	92
3408 SUB	7
3409 SIO	7
3410 DRMH	90
3411 SUB	0
3412 SIO	0
3413 DRMH	01
3414 SUB	0
3415 SIO	0
3416 DRMH	42
3417 SUB	4
3418 SIO	4
3419 DRMH	23
3420 SUB	9
3421 LDA	9
3422 DRMH	3
3423 SIO	9
3424 JMPR	2
3425 OUI	0
3426 LAI	2100
3427 MPY	4
3428 LSH	2
3429 LSH	2
3430 LSH	2
3431 SIO	0
3432 LAI	3442
3433 SUB	0
3434 LAI	0
3435 MPY	4
3436 LSH	2
3437 LSH	2
3438 SIO	0
3439 LAI	488
3440 SUB	0
3441 JMPR	18
3442 LAI	2714
3443 MPY	0
3444 LSH	2
3445 LSH	2
3446 LSH	2
3447 SIO	0
3448 LAI	1031
3449 ADD	0
3450 LAI	0
3451 MPY	0
3452 LSH	2
3453 LSH	2
3454 SIO	0
3455 LAI	1276
3456 SUB	0
3457 JMPR	37
3458 LAI	2070
3459 MPY	0
3460 LSH	2

Generate
Stator
Schedule

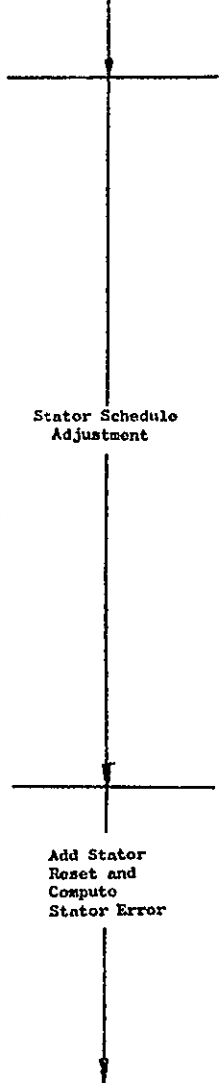
3461 LSH	2
3462 LSH	2
3463 LSH	2
3464 SIO	0
3465 LAI	4092
3466 SUB	0
3467 LAI	0
3468 MPY	0
3469 LSH	2
3470 SIO	0
3471 LAI	1019
3472 SUB	0
3473 JMPR	20
3474 LAI	3200
3475 MPY	7
3476 SIO	0
3477 SIO	0
3480 LAI	1204
3481 ADD	0
3482 LAI	0
3483 MPY	7
3484 SIO	0
3485 LAI	1692
3486 SUB	0
3487 OUI	0
3488 OUI	0
3489 OUI	0
3490 OUI	0
3491 OUI	0
3492 OUI	0
3493 OUI	0
3494 OUI	0
3495 OUI	0
3496 OUI	0
3497 OUI	0
3498 OUI	0
3499 JMPR	20
3500 LDA	92
3501 SUB	10
3502 LDA	92
3503 DRMH	2
3504 JMPR	2
3505 LDA	10
3506 SIO	10
3507 LAI	3208
3508 MPY	10
3509 LSH	2
3510 SIO	0
3511 LAI	3070
3512 SUB	0
3513 LAI	0
3514 MPY	10
3515 SIO	0

Generate
Stator
Schedule

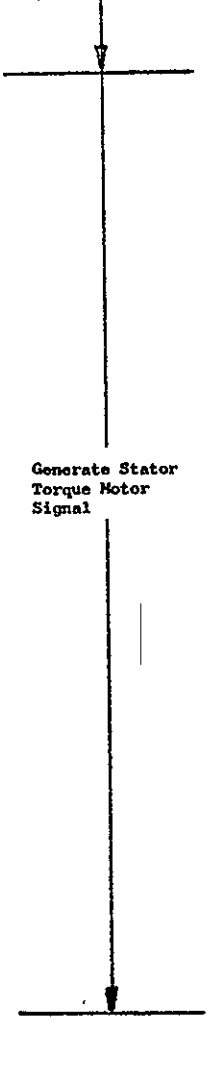
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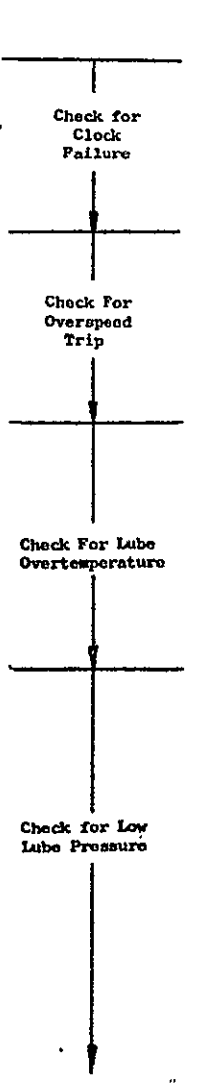
3516	LAI	2197
3517	SUB	8
3518	JMPR	-29
3519	SUB	4
3520	LAI	139
3521	SIO	9
3522	LAI	571
3523	PTV	236
3524	SUB	0
3525	LAI	380
3526	SUB	0
3527	SIO	0
3528	SUB	0
3529	BKMK	14
3530	LDA	4
3531	SUB	9
3532	SUB	0
3533	SIO	1
3534	LAI	1103
3535	SIO	8
3536	SUB	1
3537	LAI	1
3538	BKMK	2
3539	JMPR	2
3540	LDA	8
3541	ADD	9
3542	JMPR	14
3543	LAI	190
3544	SIO	0
3545	ADD	4
3546	ADD	0
3547	SIO	1
3548	SUB	8
3549	LDA	1
3550	SIO	0
3551	BKMK	2
3552	JMPR	2
3553	LDA	8
3554	SUB	8
3555	SUB	0
3556	SUB	0
3557	LAI	102
3558	ADD	93
3559	ADD	4
3560	SIO	4
3561	SUB	0
3562	LAI	1944
3563	SIO	5
3564	BKMK	1
3565	SUB	4
3566	LDA	4
3567	BKMK	2
3568	JMPR	2
3569	LDA	5
3570	JMPR	3



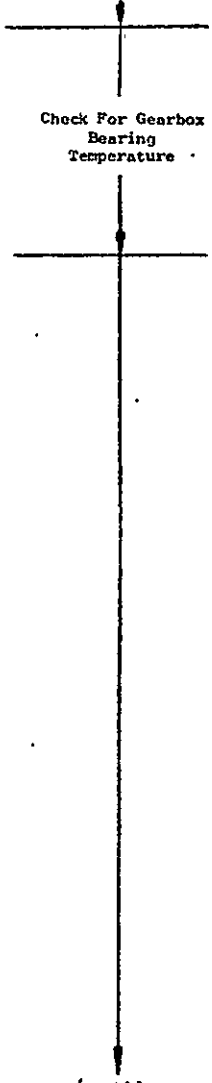
3571	OUT	0
3572	JMPR	-5
3573	SUB	25
3574	SIO	4
3575	LAI	209
3576	SIO	5
3577	LDA	4
3578	SUB	0
3579	BKMK	5
3580	SUB	5
3581	BKMK	4
3582	LDA	5
3583	JMPR	4
3584	JMPR	-3
3585	LDA	4
3586	OUT	0
3587	SIO	4
3588	LDA	0
3589	SUB	5
3590	SIO	5
3591	LDA	4
3592	SUB	0
3593	BKMK	2
3594	JMPR	2
3595	SUB	5
3596	BKMK	3
3597	LDA	4
3598	JMPR	3
3599	LDA	5
3600	OUT	0
3601	SIO	4
3602	LAI	410
3603	SIO	5
3604	LAI	2500
3605	MPY	4
3606	LSH	2
3607	LSH	2
3608	LSH	2
3609	LSH	2
3610	SIO	4
3611	SIO	119
3612	SUB	0
3613	BKMK	3
3614	SUB	5
3615	JMPR	6
3616	SUB	5
3617	BKMK	3
3618	LDA	2
3619	JMPR	3
3620	SIO	4
3621	OUT	0
3622	SIO	91
3623	OUT	1
3624	LDA	69
3625	SUB	151



3626	BKMK	2
3627	OUT	4
3628	LDA	35
3629	SUB	91
3630	LDA	0
3631	BKMK	2
3632	JMPR	2
3633	LDA	1
3634	ADD	61
3635	SIO	61
3636	LAI	409
3637	SIO	5
3638	LDA	11
3639	RSHM	2
3640	SUB	5
3641	LAI	128
3642	SIO	4
3643	BKMK	2
3644	JMPR	2
3645	LAI	0
3646	ADD	61
3647	SIO	61
3648	LAI	1414
3649	SIO	3
3650	LDA	65
3651	RSHM	2
3652	SUB	3
3653	LDA	4
3654	RSHM	2
3655	SIO	4
3656	BKMK	2
3657	JMPR	2
3658	LDA	0
3659	ADD	61
3660	SIO	61
3661	LDA	83
3662	RSHM	2
3663	SUB	5
3664	LDA	4
3665	RSHM	2
3666	SIO	4
3667	LAI	1529
3668	SIO	6
3669	LDA	42
3670	RSHM	2
3671	BKMK	4
3672	OUT	0
3673	OUT	0
3674	JMPR	5
3675	SUB	6
3676	LDA	4
3677	BKMK	2
3678	JMPR	2
3679	LDA	0
3680	ADD	61



3681	SIO	61
3682	LAI	1802
3683	SIO	3
3684	LDA	89
3685	RSHM	2
3686	SUB	3
3687	LDA	4
3688	RSHM	2
3689	BKMK	2
3690	JMPR	2
3691	LDA	0
3692	ADD	61
3693	SIO	61
3694	OUT	0
3695	LDA	0
3696	SUB	61
3697	BKMK	0
3698	OUT	0
3699	OUT	1
3700	LAI	1
3701	SIO	1
3702	LAI	21
3703	SUB	1
3704	BKMK	94
3705	JMPR	-2
3706	LDA	216
3707	SIO	233
3708	LDA	211
3709	SIO	234
3710	LDA	212
3711	SIO	235
3712	LDA	213
3713	SIO	236
3714	LDA	214
3715	SIO	237
3716	LDA	215
3717	SIO	238
3718	LDA	216
3719	SIO	239
3720	LDA	217
3721	SIO	240
3722	LDA	218
3723	SIO	241
3724	LDA	219
3725	SIO	242
3726	LDA	220
3727	SIO	243
3728	LDA	221
3729	SIO	244
3730	LDA	222
3731	SIO	245
3732	LDA	223
3733	SIO	246
3734	LDA	224
3735	SIO	247



3130 LDA	225
3131 SIO	228
3138 LDA	220
3139 SIO	229
3140 LDA	221
3141 SIO	220
3142 LDA	228
3143 SIO	221
3144 LDA	229
3145 SIO	222
3146 LDA	233
3147 SIO	223
3148 LDA	231
3149 SIO	224
3150 LDA	232
3151 SIO	225
3152 LDA	187
3153 SIO	210
3154 LDA	188
3155 SIO	211
3156 LDA	189
3157 SIO	212
3158 LDA	190
3159 SIO	213
3160 LDA	191
3161 SIO	214
3162 LDA	192
3163 SIO	215
3164 LDA	193
3165 SIO	216
3166 LDA	194
3167 SIO	217
3168 LDA	195
3169 SIO	218
3170 LDA	196
3171 SIO	219
3172 LDA	197
3173 SIO	220
3174 LDA	198
3175 SIO	221
3176 LDA	199
3177 SIO	222
3178 LDA	200
3179 SIO	223
3180 LDA	201
3181 SIO	224
3182 LDA	202
3183 SIO	225
3184 LDA	203
3185 SIO	226
3186 LDA	204
3187 SIO	227
3188 LDA	205
3189 SIO	228
3190 LDA	206

Transfer Data To
Peripheral Units

3191 SIO	229
3192 LDA	207
3193 SIO	230
3194 LDA	208
3195 SIO	231
3196 LDA	209
3197 SIO	232
3198 OUI	15
3199 LAI	1
3200 SIO	1
3201 ADD	26
3202 SIO	26
3203 LDA	2
3204 SUB	0
3205 BRHR	17
3206 LDA	10
3207 SUB	0
3208 BRHR	7
3209 LDA	2
3210 SUB	10
3211 OUI	0
3212 OUI	0
3213 OUI	0
3214 JMPR	17
3215 LDA	2
3216 SUB	10
3217 BRHR	2
3218 JMPR	-5
3219 LDA	2
3220 SUB	1
3221 JMPR	10
3222 LDA	10
3223 SUB	0
3224 BRHR	-15
3225 LDA	2
3226 SUB	10
3227 BRHR	-15
3228 LDA	2
3229 OUI	0
3230 OUI	0
3231 SIO	2
3232 LDA	26
3233 SUB	1
3234 BRHP	2045
3235 SUB	1
3236 BRMP	2054
3237 SUB	1
3238 BRHP	2302
3239 JMPR	2413
3240 LAI	1
3241 SIO	1
3242 ADD	27
3243 SIO	27
3244 LDA	8
3245 RSHM	2

Transfer Data To
Peripheral Units

Reset P-Counter & Input Analog
Counter - Program Complete

Subroutine For
Subtraction Without
Overflow

Subroutine For Computing
Metering Valve Position
From WF

3246 SIO	9
3247 LAI	223
3248 SUB	9
3249 BRHR	26
3250 LAI	379
3251 SUB	8
3252 BRHR	22
3253 LAI	2032
3254 MPY	d
3255 LSH	2
3256 LSH	2
3257 SIO	9
3258 LAI	2245
3259 SUB	9
3260 LAI	0
3261 MPY	d
3262 LSH	2
3263 LSH	2
3264 ADD	1
3265 ADD	1
3266 OUI	0
3267 OUI	0
3268 OUI	0
3269 OUI	0
3270 OUI	0
3271 OUI	0
3272 OUI	0
3273 JMPR	26
3274 LAI	2310
3275 MPY	8
3276 SIO	9
3277 LAI	3178
3278 SUB	9
3279 LAI	0
3280 MPY	8
3281 SIO	9
3282 LAI	297
3283 ADD	9
3284 JMPR	15
3285 LAI	430
3286 MPY	d
3287 SIO	9
3288 LAI	1834
3289 SUB	9
3290 LAI	0
3291 MPY	8
3292 SIO	9
3293 LAI	242
3294 ADD	9
3295 SIO	9
3296 OUI	0
3297 LDA	9
3298 SIO	0
3299 SIO	d
3300 LDA	27

(cont'd to 1905)

3901 SUB	1
3902 BRMP	2730
3903 SUB	1
3904 BRMP	2742
3905 JMPR	2750
3906 LAI	1
3907 SIO	1
3908 ADD	26
3909 SIO	26
3910 LAI	223
3911 SIO	9
3912 LAI	3207
3913 MPY	10
3914 SIO	10
3915 LDA	2
3916 SUB	10
3917 SIO	2
3918 BRHR	2
3919 SUB	9
3920 BRHR	4
3921 LDA	9
3922 JMPR	4
3923 JMPR	15
3924 LDA	2
3925 OUI	0
3926 SIO	0
3927 LDA	0
3928 SUB	9
3929 SIO	9
3930 LDA	2
3931 SUB	2
3932 BRHR	2
3933 JMPR	2
3934 SUB	9
3935 BRHR	3
3936 LDA	3
3937 JMPR	3
3938 LDA	2
3939 OUI	0
3940 SIO	0
3941 LSH	940
3942 MPY	2
3943 LSH	2
3944 LSH	2
3945 LSH	2
3946 LSH	2
3947 SIO	2
3948 LAI	447
3949 SIO	9
3950 LDA	0
3951 SUB	0
3952 BRHR	2
3953 SUB	9
3954 LSH	4
3955 LDA	9

Subroutine For Rate
Feedback With Lag

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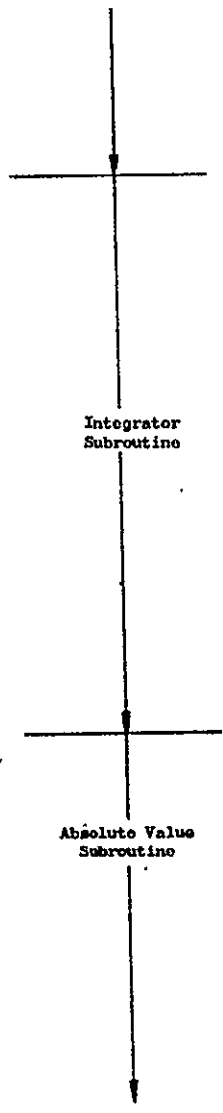
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next page)

3926	JMPR	4
3927	JMPR	-3
3928	LDA	0
3929	SUB	0
3930	SUB	0
3931	LDA	0
3932	SUB	0
3933	SUB	0
3934	LDA	0
3935	SUB	0
3936	SUB	2
3937	JMPR	2
3938	SUB	2
3939	SUB	3
3940	LDA	3
3941	JMPR	3
3942	LDA	0
3943	SUB	0
3944	SUB	0
3945	LAI	2060
3946	SUB	0
3947	SUB	2
3948	SUB	5
3949	LDA	50
3950	SUB	1
3951	JMPR	2929
3952	JMPR	2970
3953	LAI	1
3954	SUB	1
3955	SUB	111
3956	SUB	111
3957	LAI	2010
3958	SUB	0
3959	SUB	10
3960	LAI	3250
3961	SUB	10
3962	LAI	0
3963	SUB	0
3964	SUB	10
3965	LAI	2269
3966	SUB	10
3967	LAI	0
3968	SUB	0
3969	SUB	2
3970	SUB	2
3971	SUB	10
3972	LAI	3700
3973	SUB	10
3974	LAI	0
3975	SUB	0
3976	SUB	2
3977	SUB	10
3978	LAI	325
3979	SUB	10
3980	SUB	0



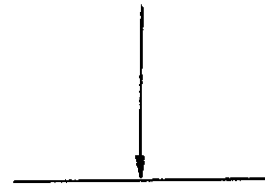
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4011	LDA	111
4012	SUB	1
4013	BRMP	407
4014	SUB	1
4015	BRMP	095
4016	SUB	1
4017	BRMP	709
4018	JMPR	1117
4019	LAI	1
4020	STO	1
4021	ADD	140
4022	STO	140
4023	STO	10
4024	LDA	0
4025	SUB	0
4026	BRMP	2
4027	JMPR	2
4028	LDA	0
4029	BRMP	3
4030	LDA	0
4031	AND	6
4032	SIO	0
4033	LDA	7
4034	ADDC	0
4035	SIO	7
4036	LDA	140
4037	SUB	1
4038	BRMP	476
4039	SUB	1
4040	BRMP	014
4041	SUB	1
4042	BRMP	000
4043	SUB	1
4044	BRMP	000
4045	SUB	1
4046	BRMP	037
4047	JMPR	070
4048	LAI	1
4049	SIO	1
4050	AND	160
4051	SIO	160
4052	LDA	3
4053	SUB	0
4054	BRMP	3
4055	JMPR	0
4056	JMPR	3
4057	LDA	0
4058	SUB	3
4059	STO	3
4060	LDA	160
4061	SUB	1
4062	BRMP	1079
4063	SUB	1
4064	BRMP	1094
4065	SUB	1



(cont'd to 4073)

4066	BRMP	1089
4067	SUB	1
4068	BRMP	1094
4069	SUB	1
4070	BRMP	1099
4071	SUB	1
4072	BRMP	1004
4073	JMPR	1009



APPENDIX D

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3. The General Electric Company, "Quiet Clean Short-Haul Experimental Engine (QCSEE) Under-The-Wing Engine Digital Control System Design Report", NASA CR 134920, August, 1977.
4. The General Electric Company, "Quiet Clean Short-Haul Experimental Engine (QCSEE) Over-The-Wing Engine and Control Simulation Results", NASA CR 135049, (Date TBD).

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