NASA CR-135337
R77AEG664

QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE)

Over-the-Wing Engine
Digital Control System Design Report

DECEMBER 1977

(NASA-CR-135337) QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE) OVER-THE-WING CONTROL SYSTEM DESIGN REPORT (General Electric Co.) 249 p HC A11/MF A01 CSCL 21E

N80-15092

Unclas
G3/07 33469

National Aeronautics and Space Administration

JAN 1980
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

NASA Lewis Research Center
Contract NAS3-18021

1. Report No. CR135337	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE) OVER-THE-WING ENGINE DIGITAL CONTROL SYSTEM DESIGN REPORT		5. Report Date December, 1977 6. Performing Organization Code
7. Author(s) Advanced Engineering and Technology Programs Department Advanced Engine Engineering Division		8. Performing Organization Report No. R77AEG664
9. Performing Organization Name and Address General Electric Company 1 Neumann Way Cincinnati, Ohio 45215		10. Work Unit No. 11. Contract or Grant No. NAS3-18021
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Contractor Report 14. Sponsoring Agency Code

15. Supplementary Notes

Design Report, Project Manager, C.C. Ciepluch, QCSEE Project Office
Technical Advisor, A.C. Hoffman and J.R. Mihaloew
NASA-Lewis Research Center, Cleveland, Ohio 44135

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.

17. Key Words (Suggested by Author(s))

Digital Control
Propulsion System
Noise Suppression

19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 237

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

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.

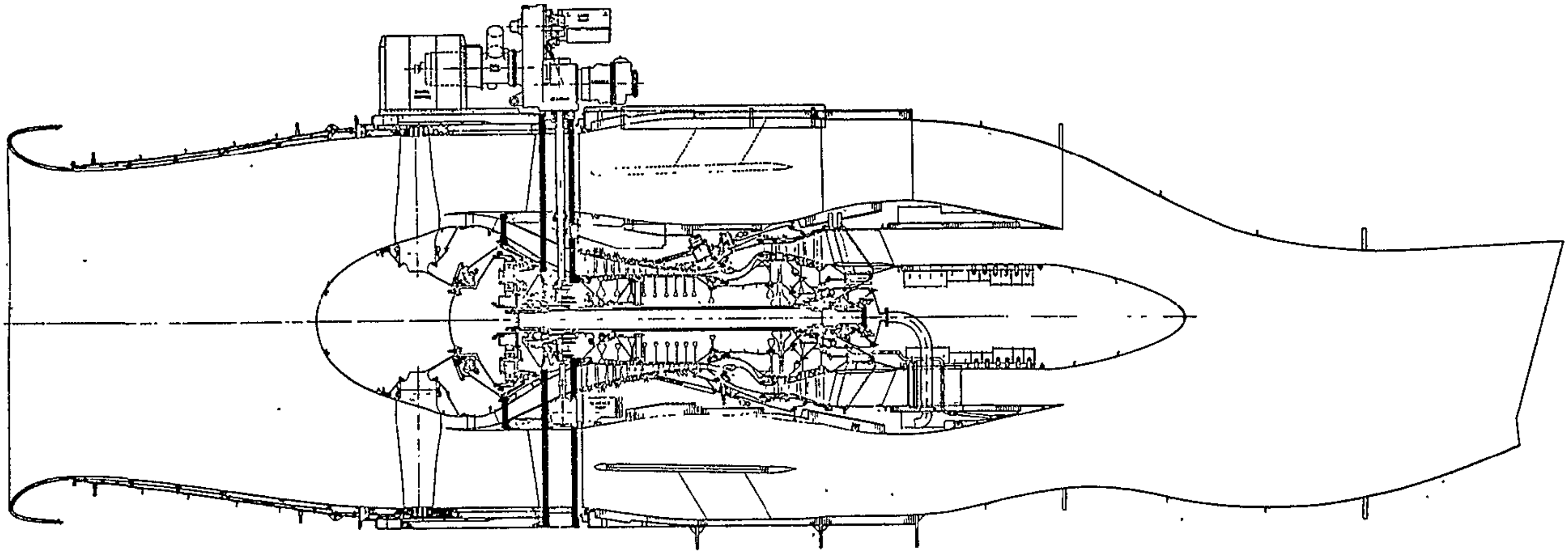


Figure 1. OTW Experimental Propulsion System.

ORIGINAL PAGE IS
OF POOR QUALITY

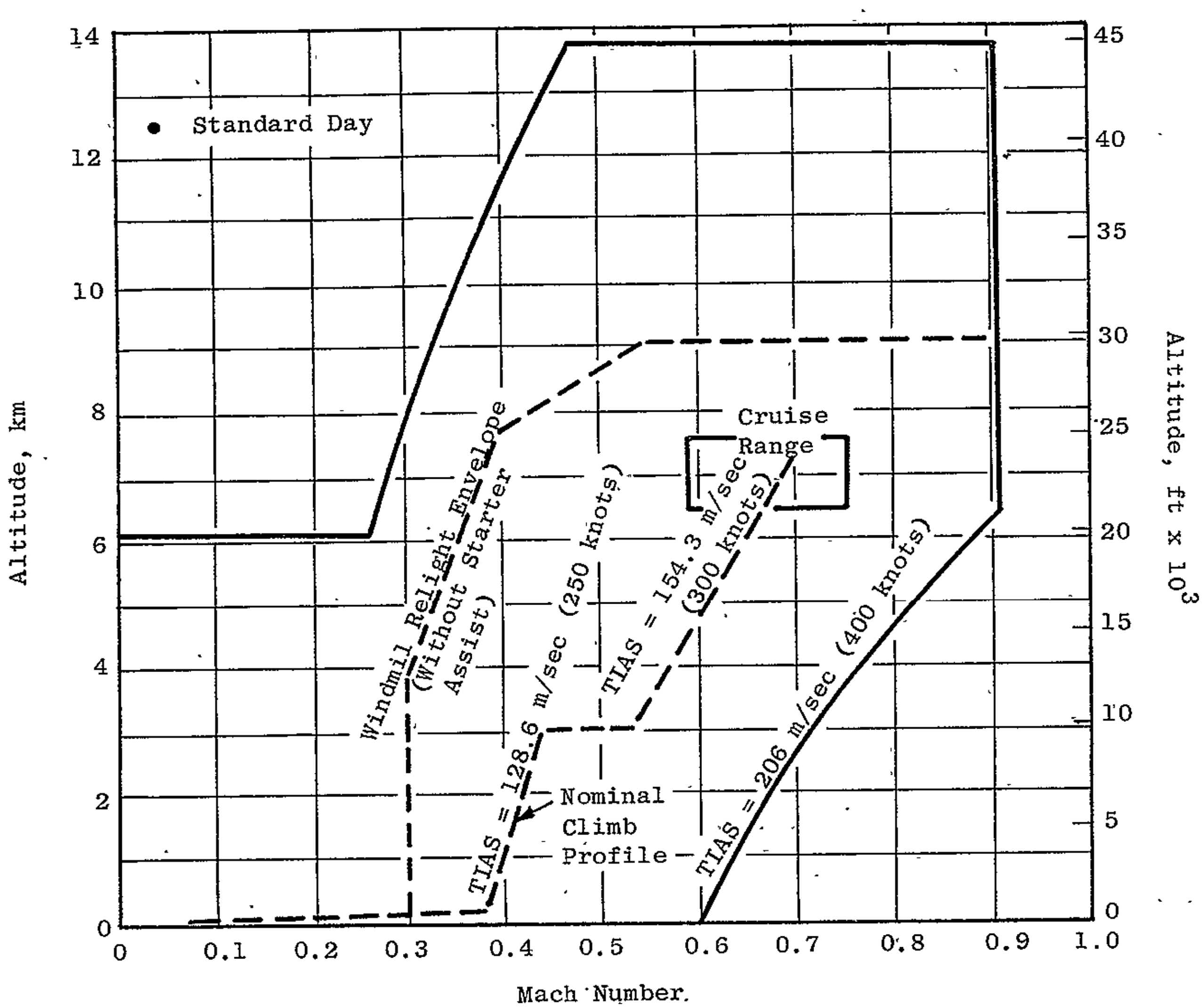


Figure 2. QCSEE OTW Operating Envelope.

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.

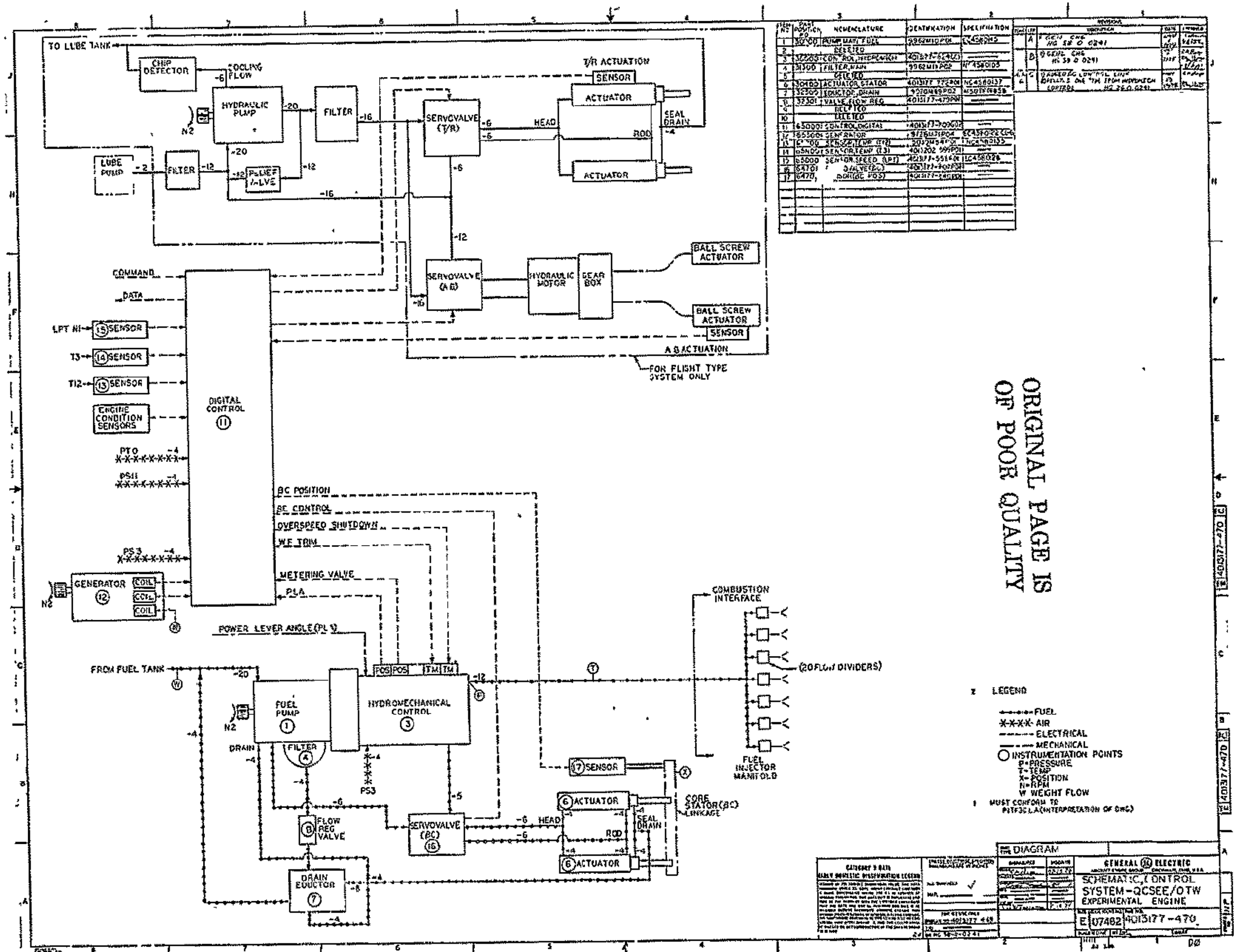


Figure 3. System Schematic.

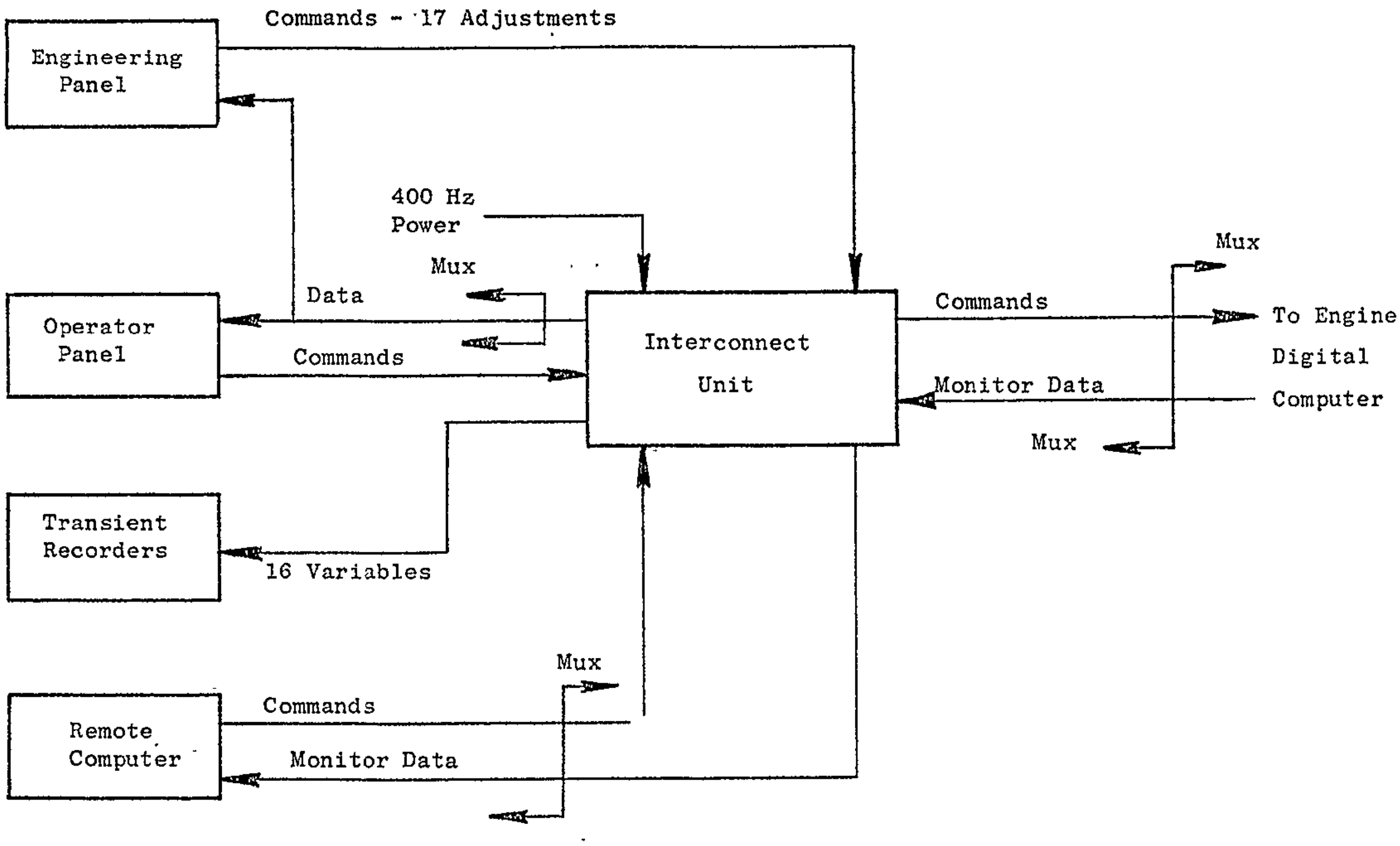


Figure 4. Control Room Elements of QCSEE Digital Control.

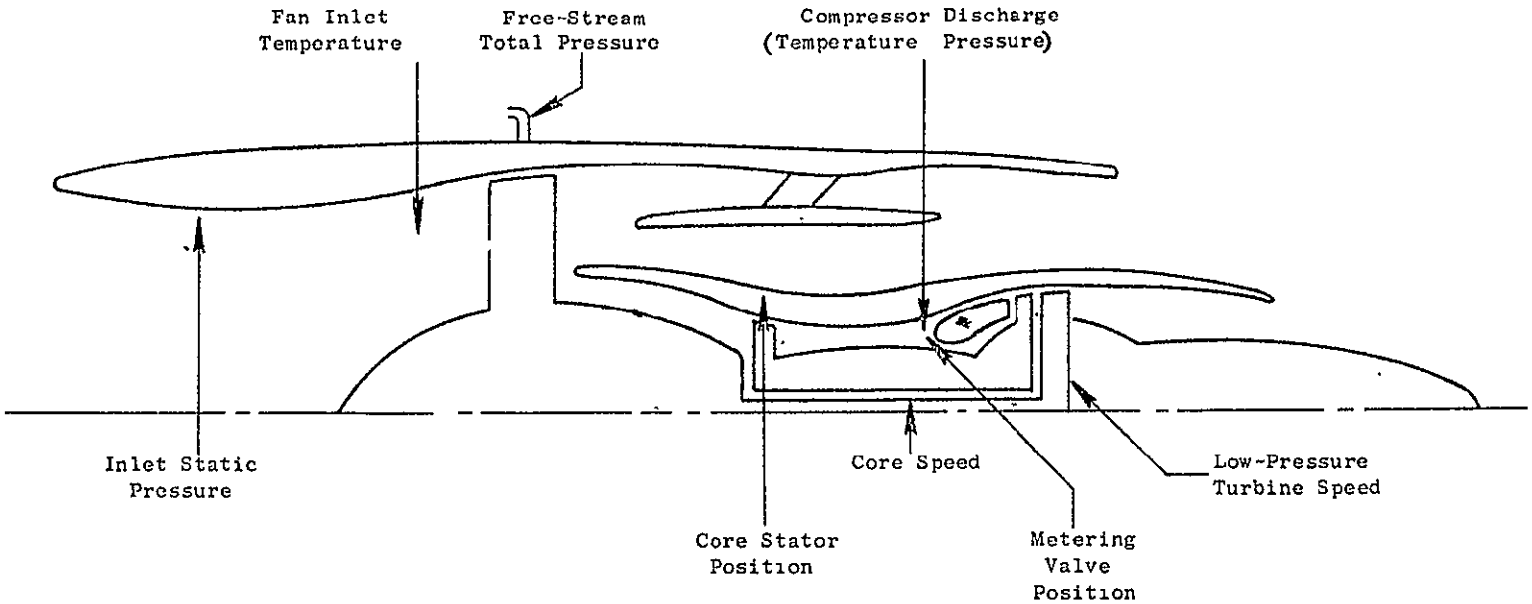


Figure 5. Sensed Engine and Control Variables.

ORIGINAL PAGE IS
OF POOR QUALITY

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 hydromchanical 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 air-stream.

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 aerodynamnic 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.

<u>T41 Limit</u> - Turbine inlet gas temperature (T41) 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 T41 from exceeding a predetermined limit.

<u>Acceleration Limit</u> - 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.

<u>Deceleration Limit</u> - To prevent loss of combustion during rapid thrust reductions, a function in the digital control prevents WF/PS_3 from dropping below a prescribed minimum limit.

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

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

<u>Backup Core-Speed Governor</u> - 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.

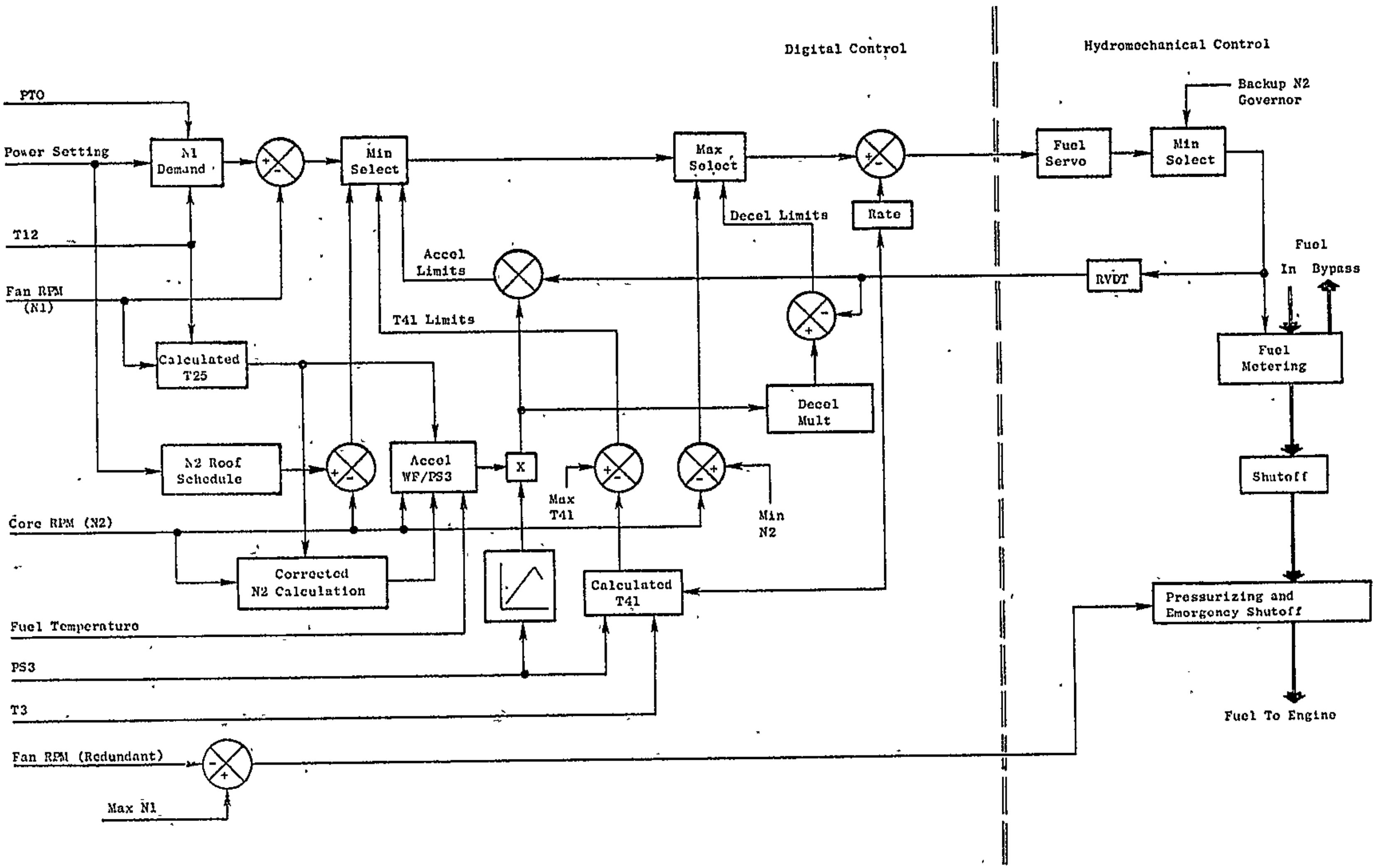


Figure 6. OTW Fuel Control Block Diagram.

ORIGINAL PAGE IS OF POOR QUALITY

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 compresor 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.

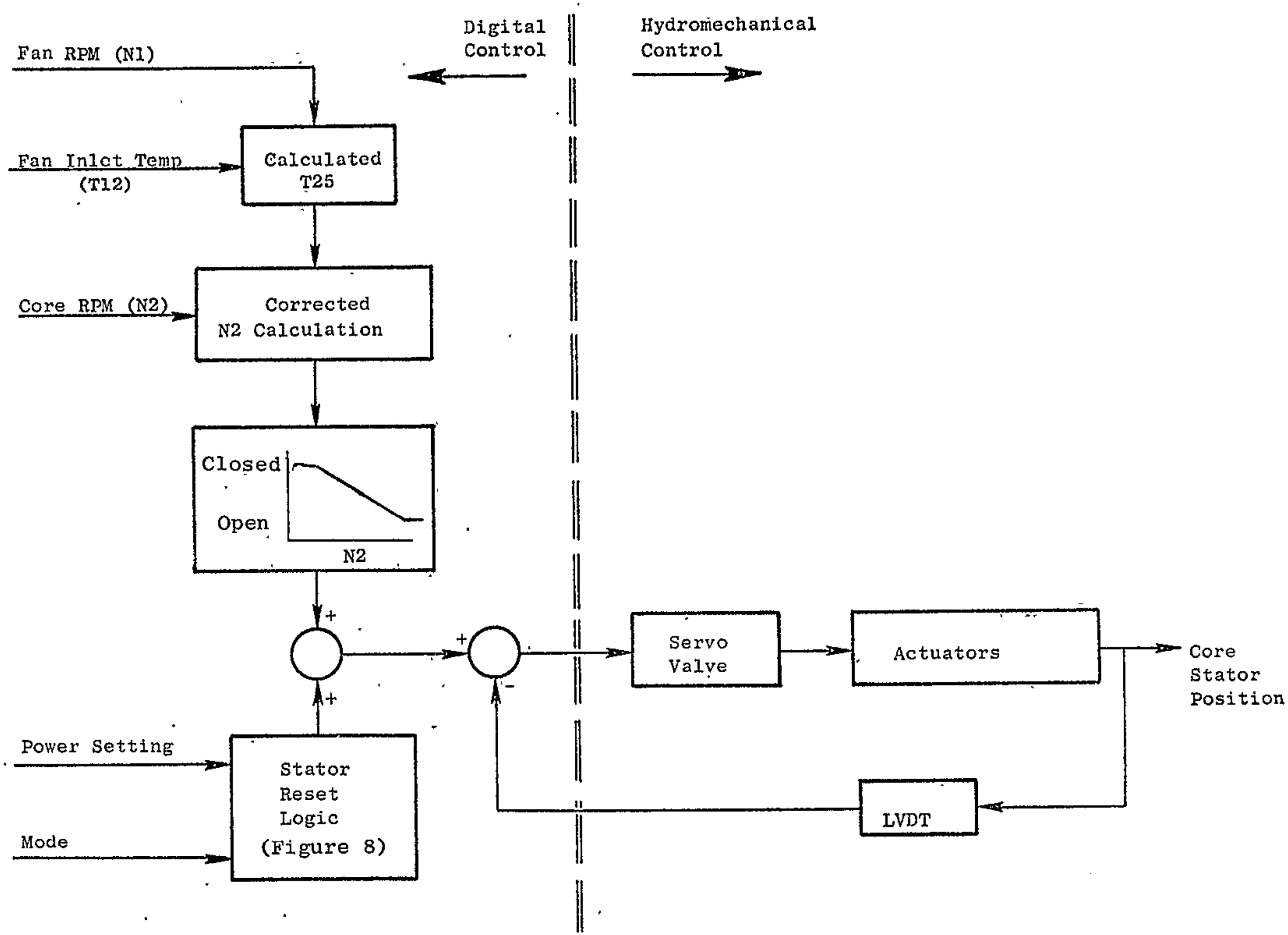


Figure 7. OTW Core Stator Control.

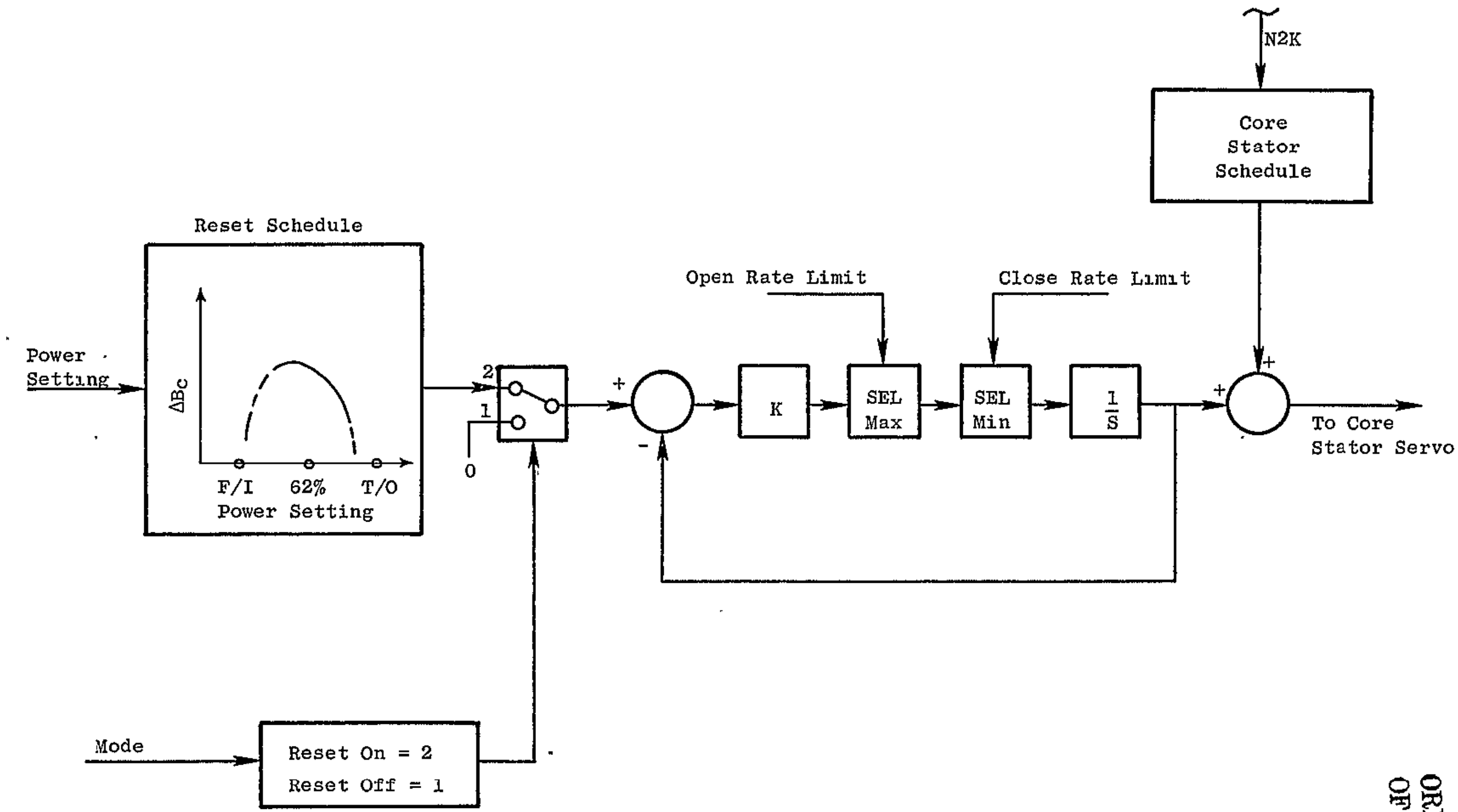


Figure 8. Core Stator Reset Logic.

ORIGINAL PAGE IS
OF POOR QUALITY

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).

TP1 = P49/PTO
TP2 = PS3/PTO
TP3 = f(P8/PTO) x (A8)
TP4 = f(P15/PTO) x (A8)
TP5 = f(M11)/(A8)
TP6 = f(P15/PTO) x f_2(M11)
TP8 = T41C/T1
TP9 = PCNHR
TP10 = PS3/PS8
TP11 = T8/T1
TP12 = (T15-T1)/T15 x f(M11)
TP13 = WFM/PTO

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 measurment 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	±0.52%	±0.57%
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 M0 or as an error in the M0 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	±1.5%	-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: $0 < MO < 0.378$, $10.1 < PTO < 16.22$, $0.74 \leq T2/T\ Ref. < 1.06$

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

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.

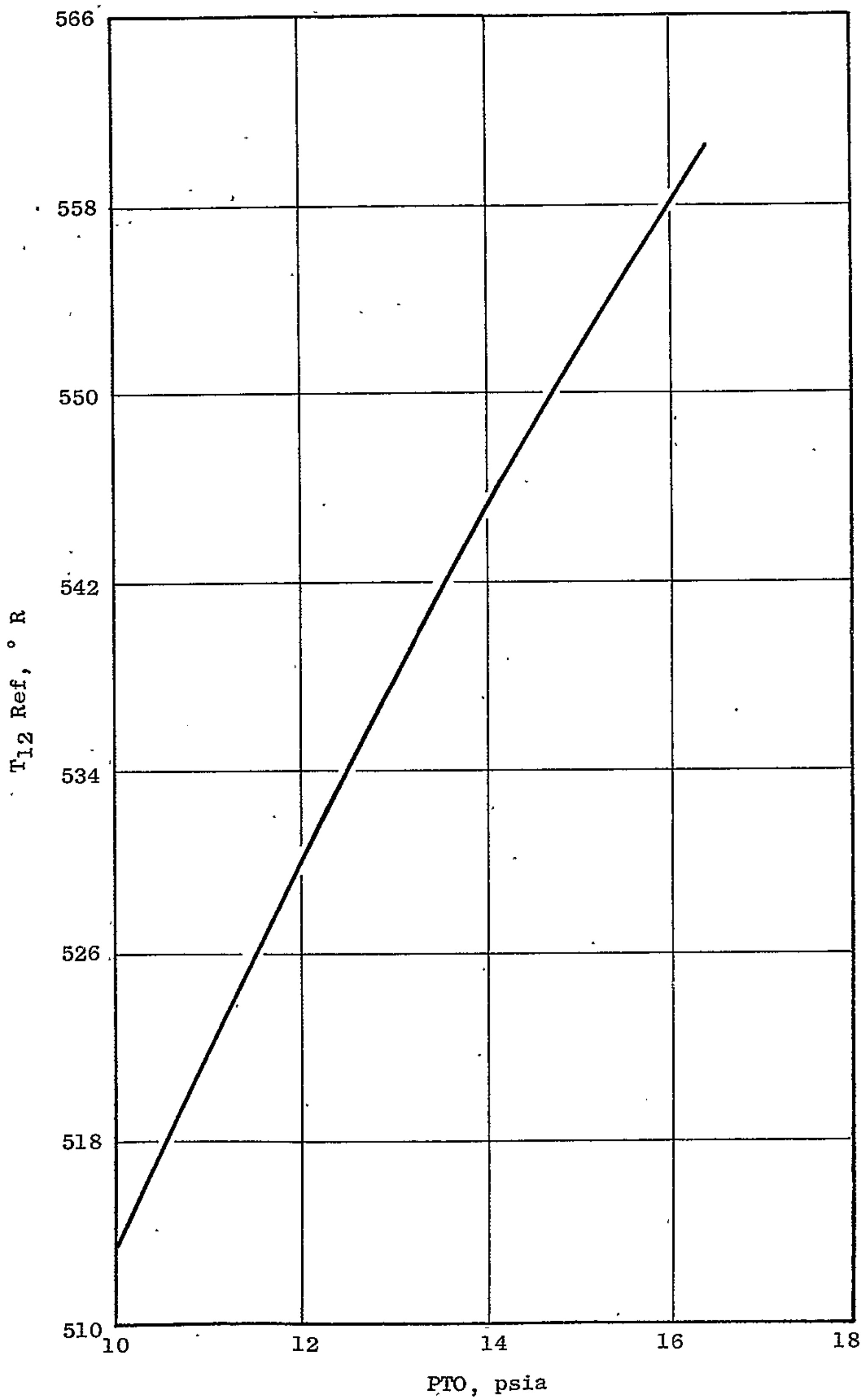


Figure 9. T_{12} Reference.

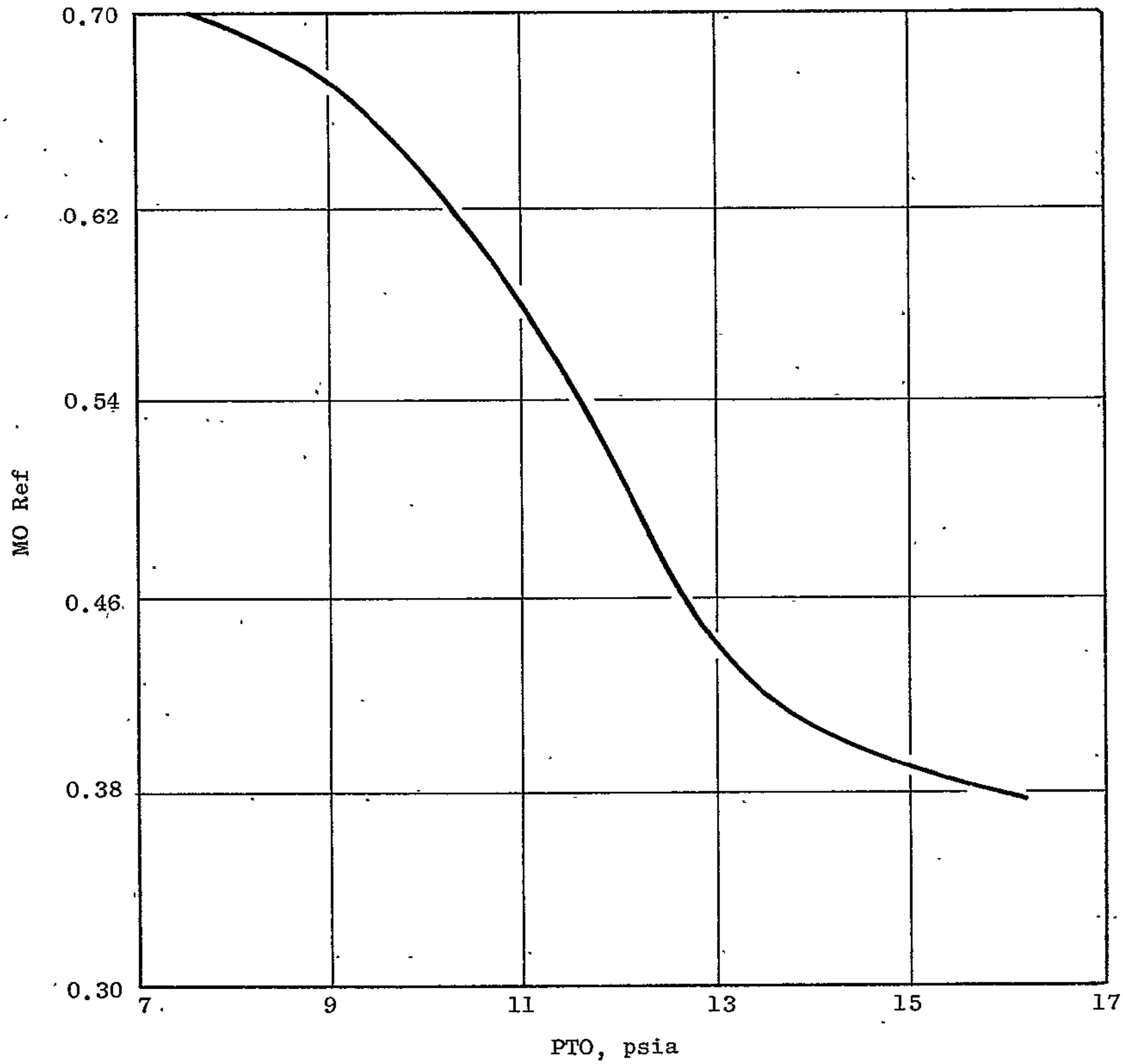


Figure 10. Free-Stream Total Pressure Versus Aircraft Mach Number.

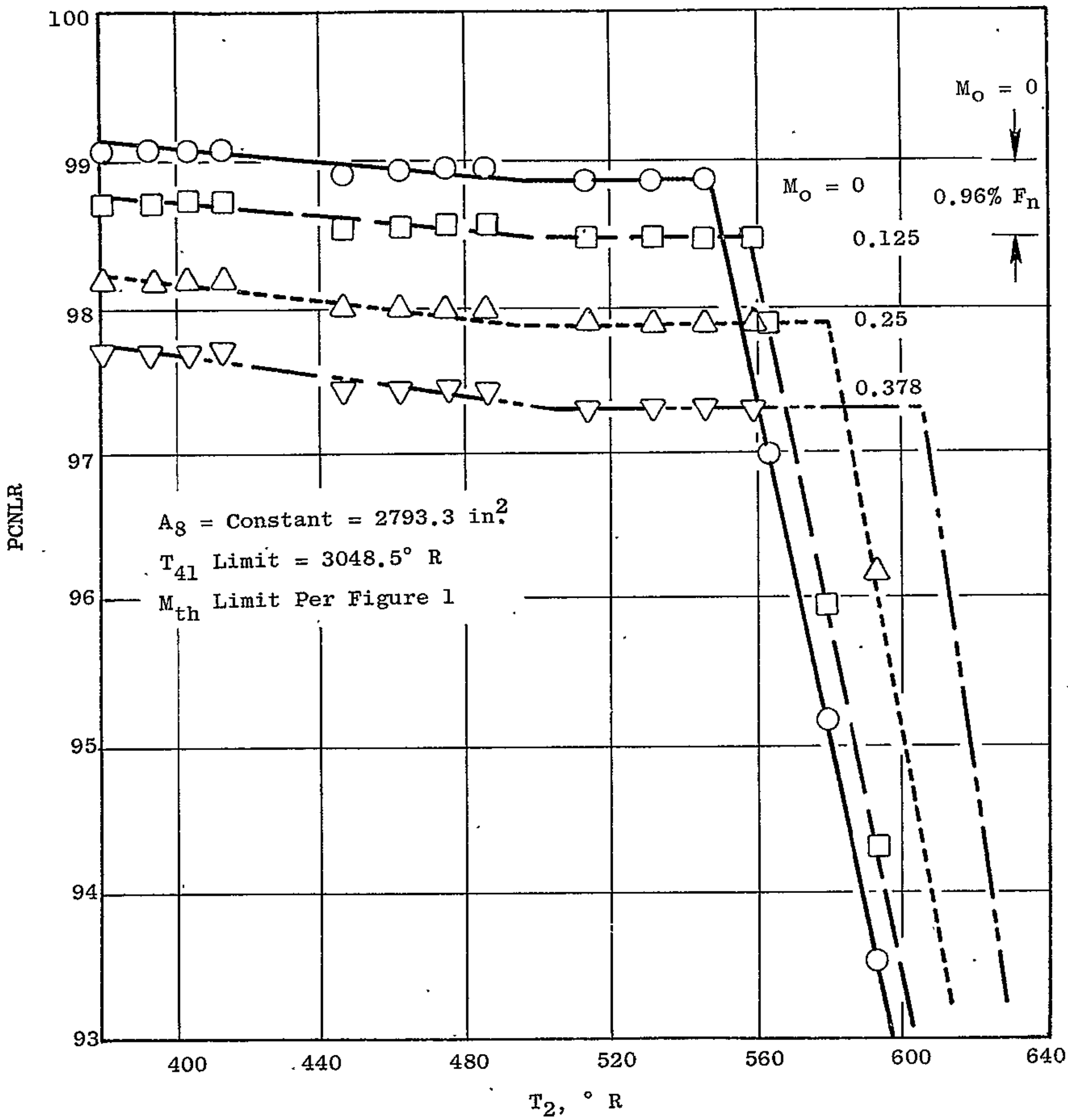


Figure 11. OTW Speed Schedule for Takeoff Rating.

ORIGINAL PAGE IS
OF POOR QUALITY

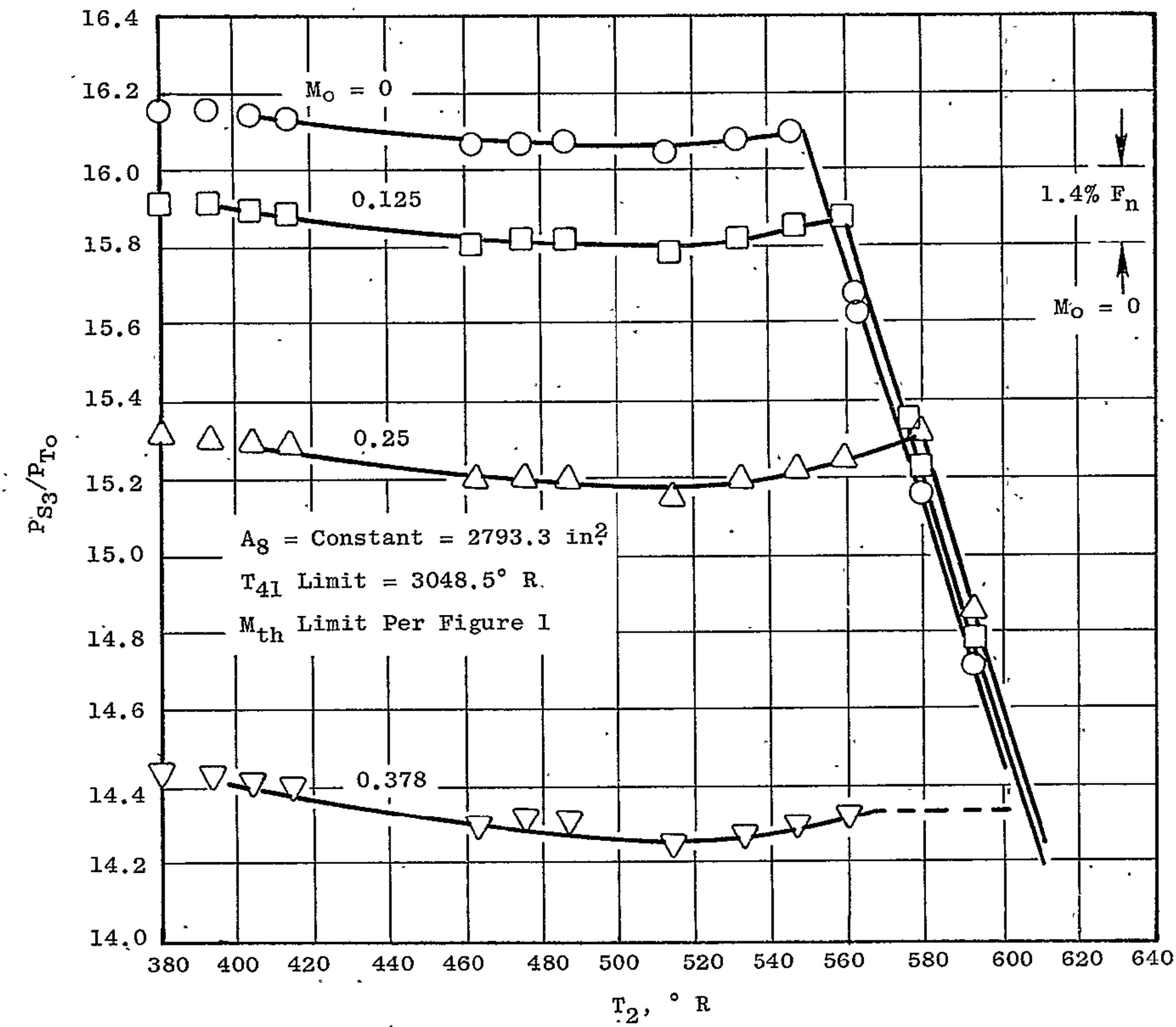


Figure 12. OTW P_{S3}/P_{To} Schedule for Takeoff Rating.

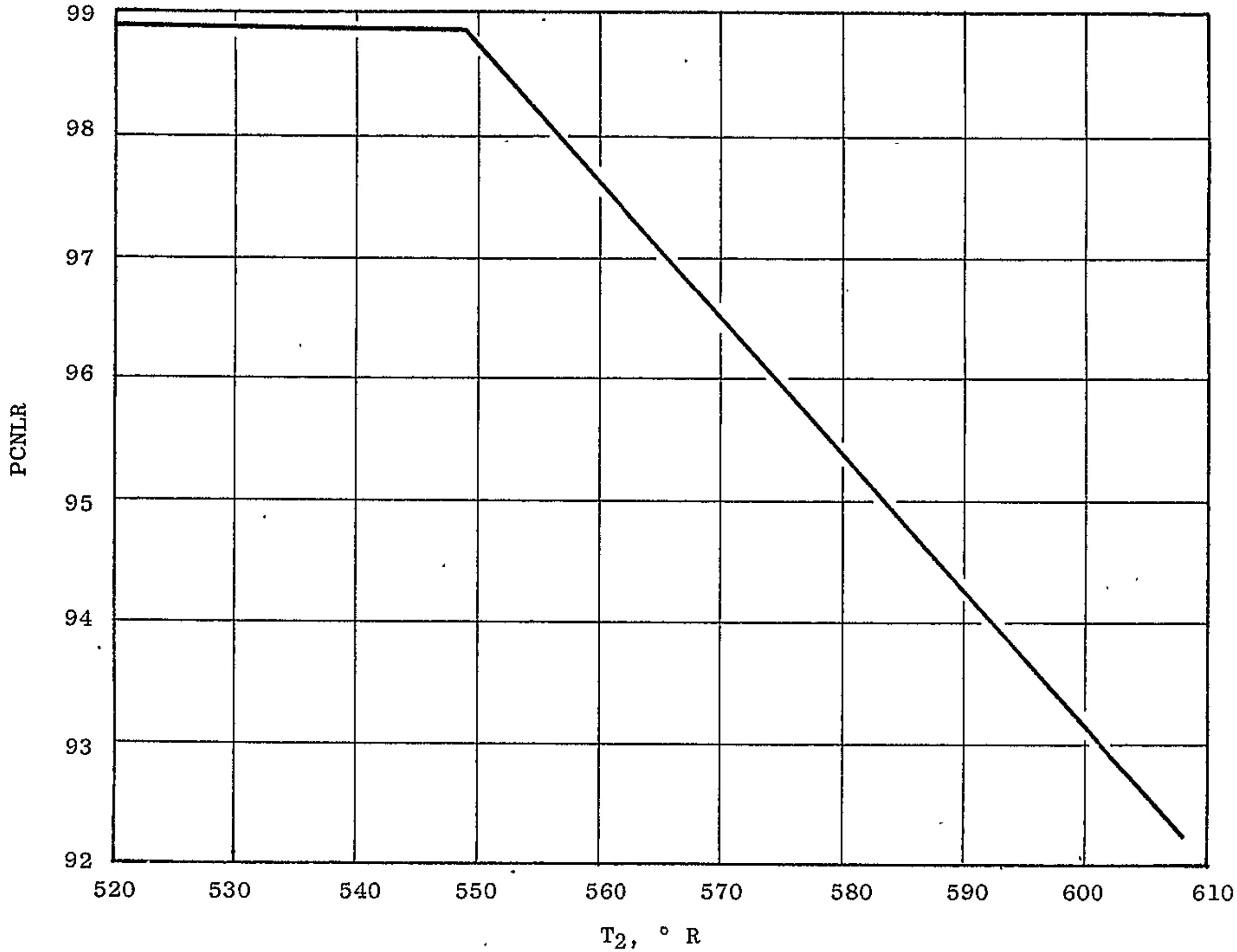


Figure 13. OTW Base Takeoff Schedule for PCNLR.

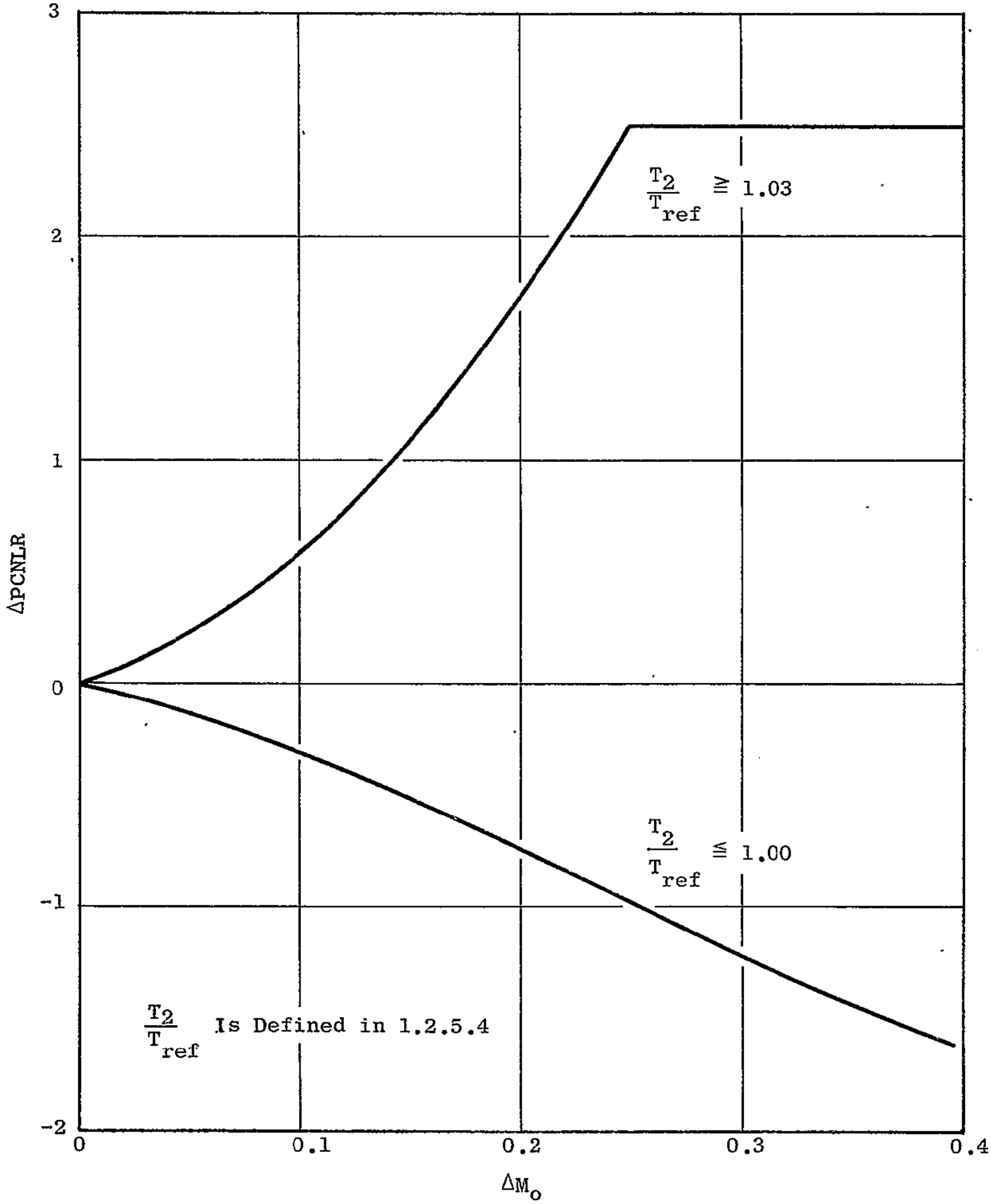


Figure 14. OTW Trim Schedule for PCNLR.

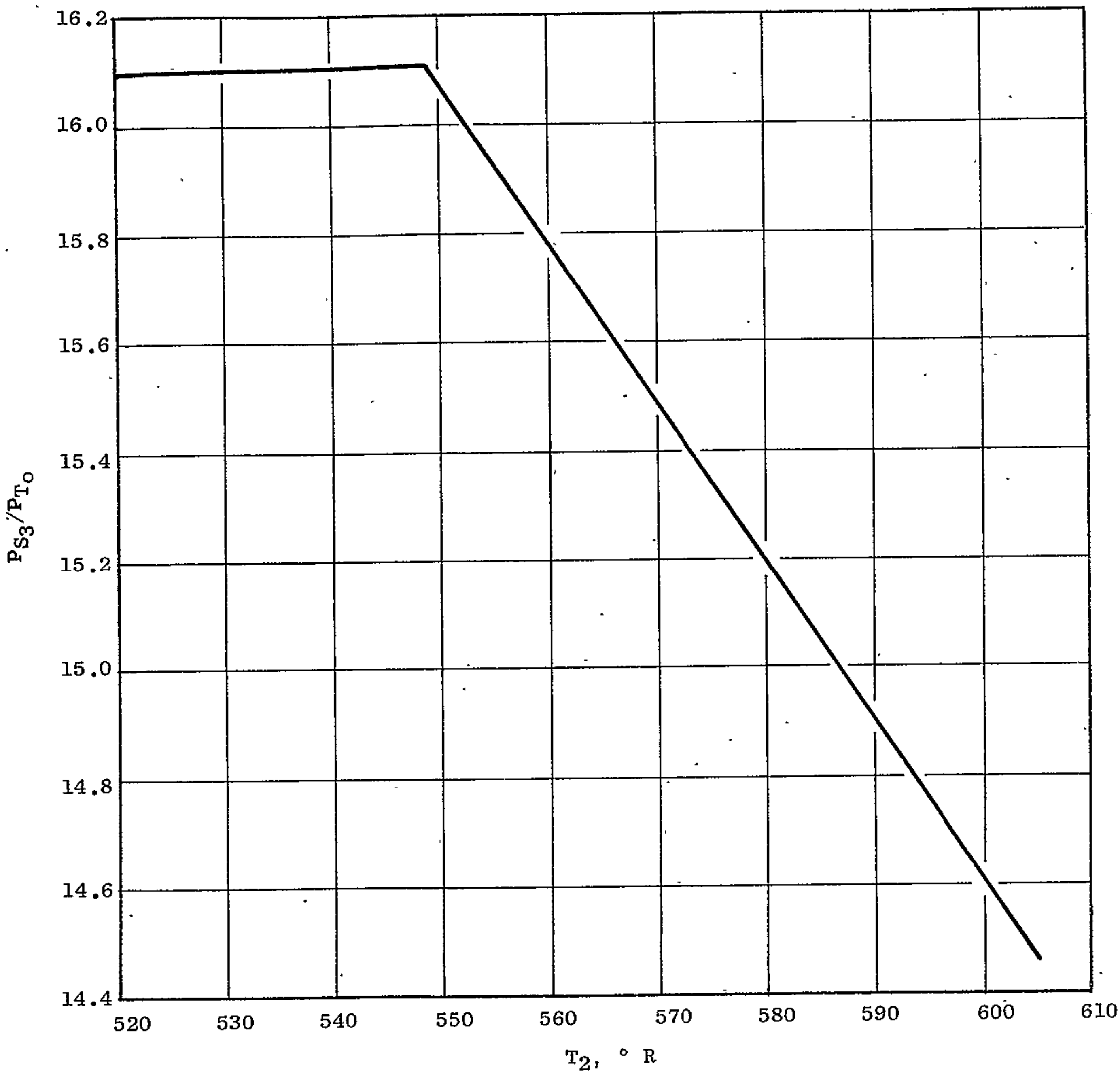


Figure 15. OTW Base Takeoff Schedule for P_{S_3}/P_{T_0}.

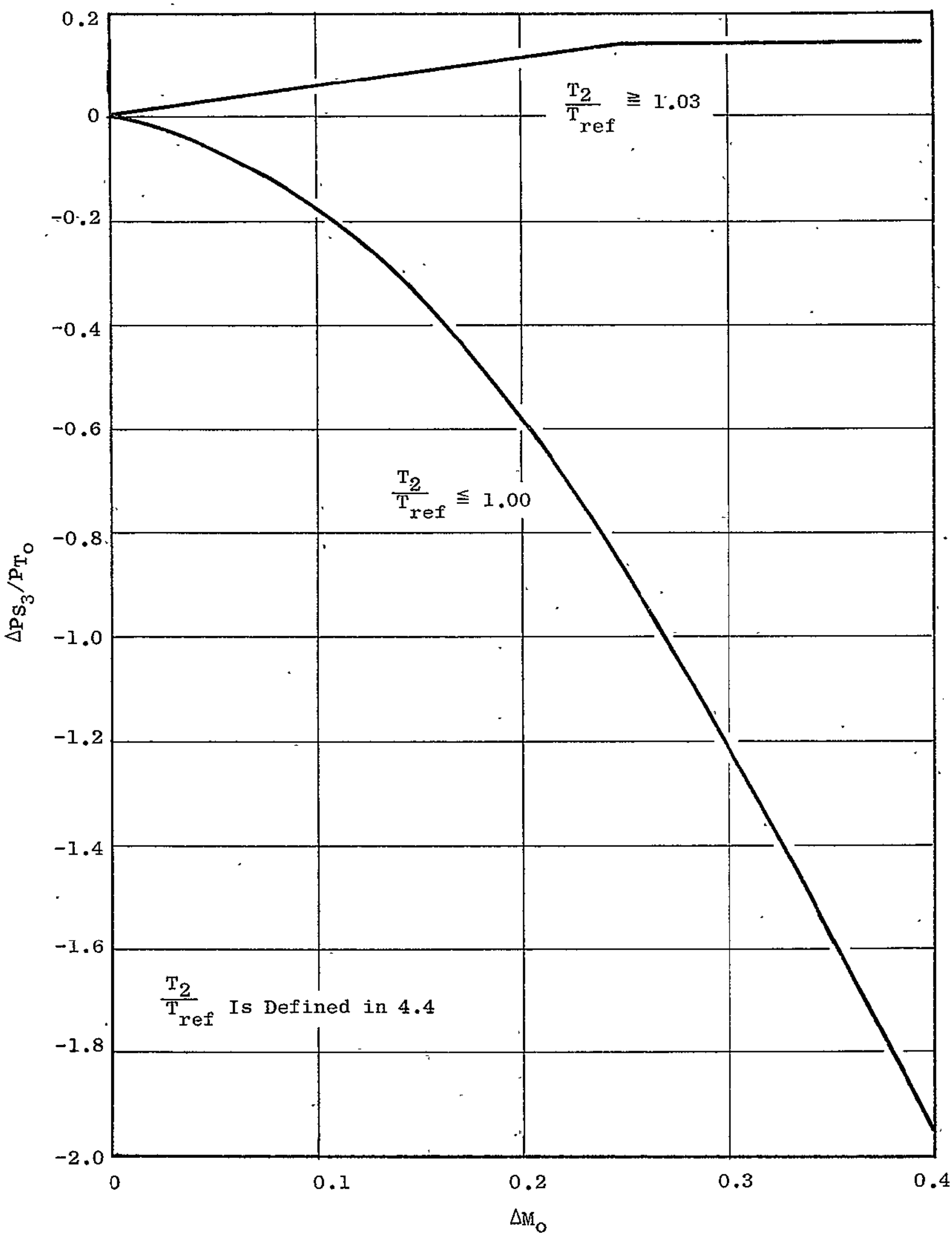


Figure 16. OTW Trim Schedule for P_{S_3}/P_{T_0}.

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 UTW; 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 conrolled 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 schdule 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.

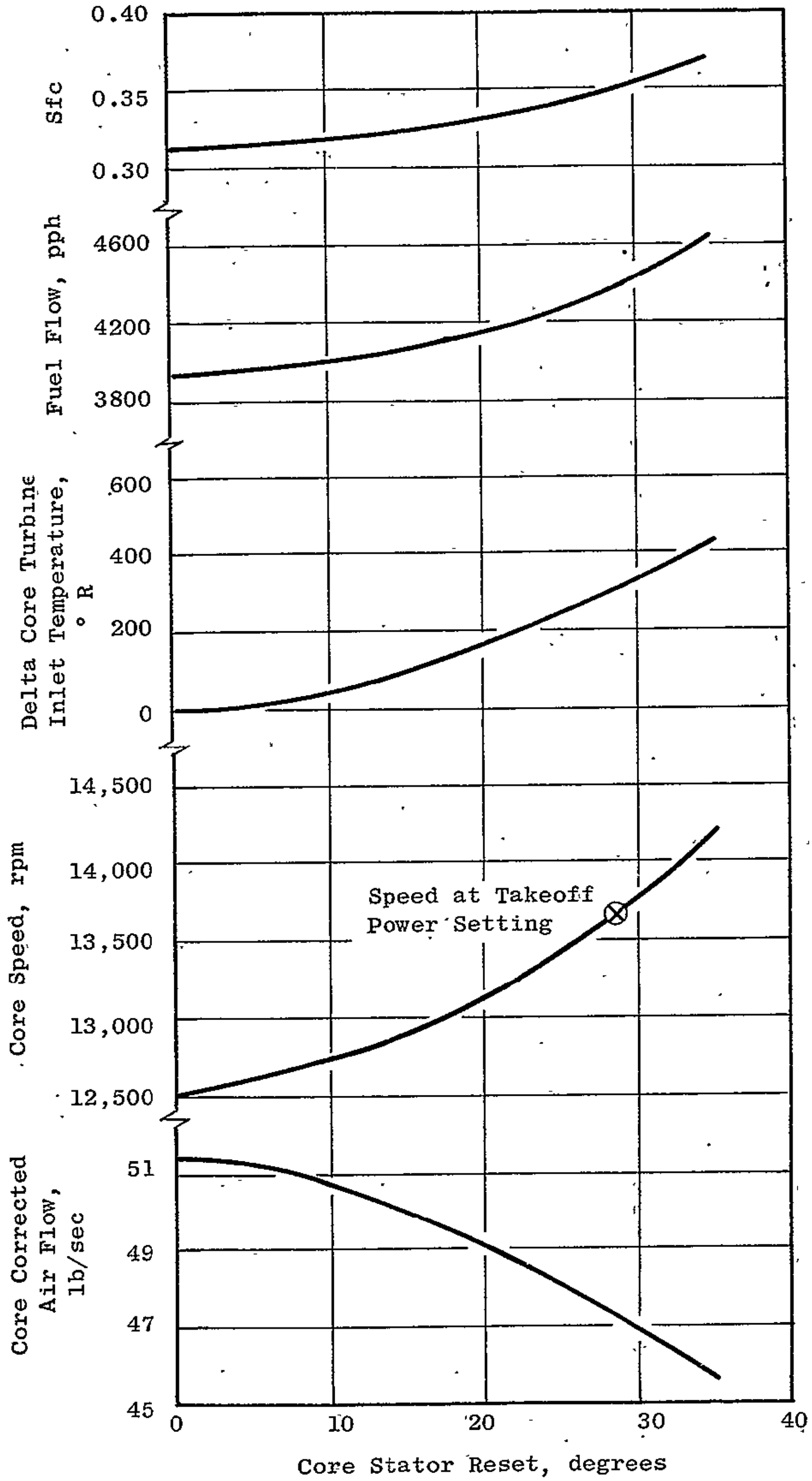


Figure 17. QCSEE OTW Engine Variables at 62% Net Thrust Vs. Core Stator Reset.

ORIGINAL PAGE IS
OF POOR QUALITY

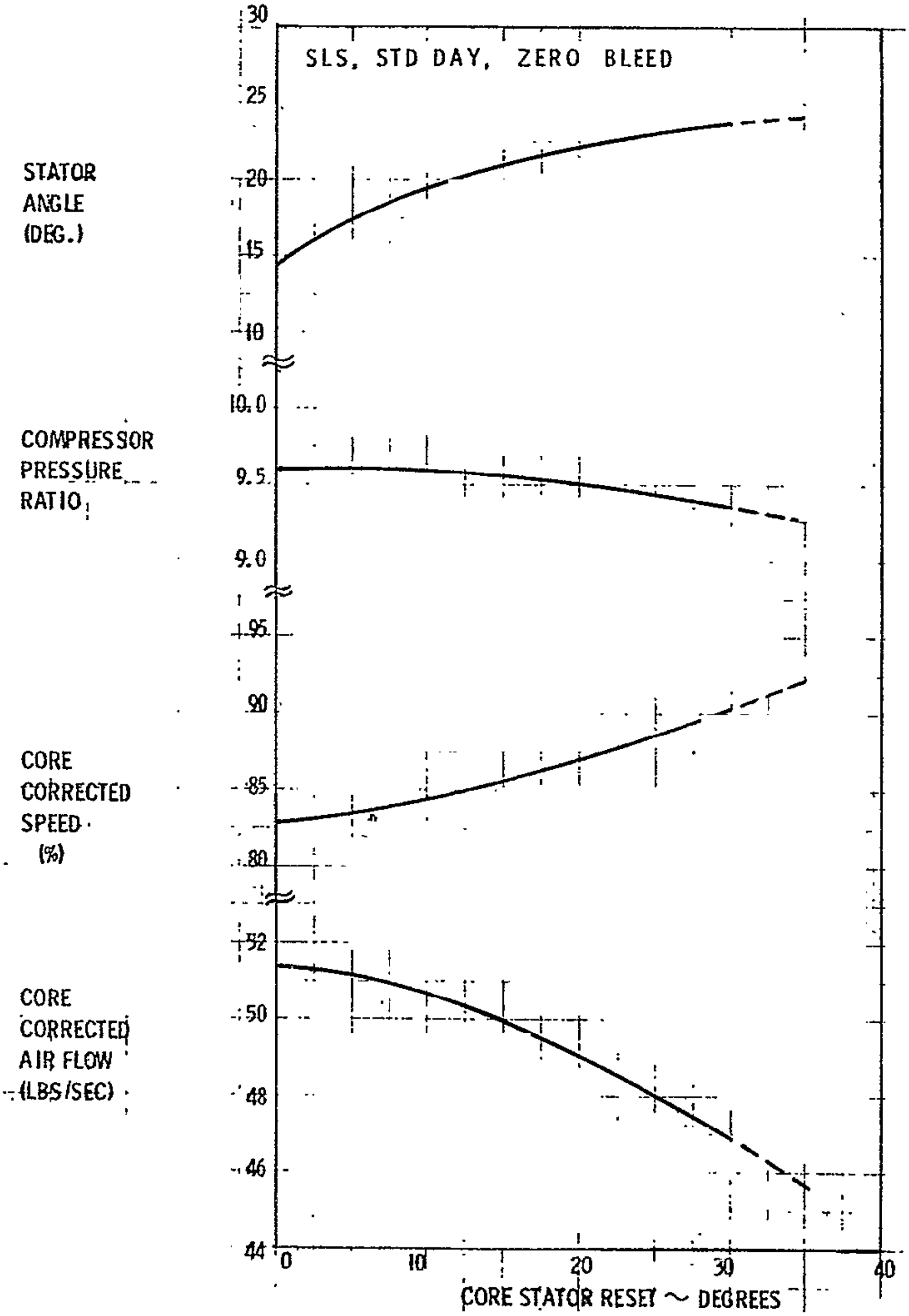


Figure 17. QCSEE OTW Engine Variables at 62% Net Thrust Versus Core Stator Reset (Concluded).

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

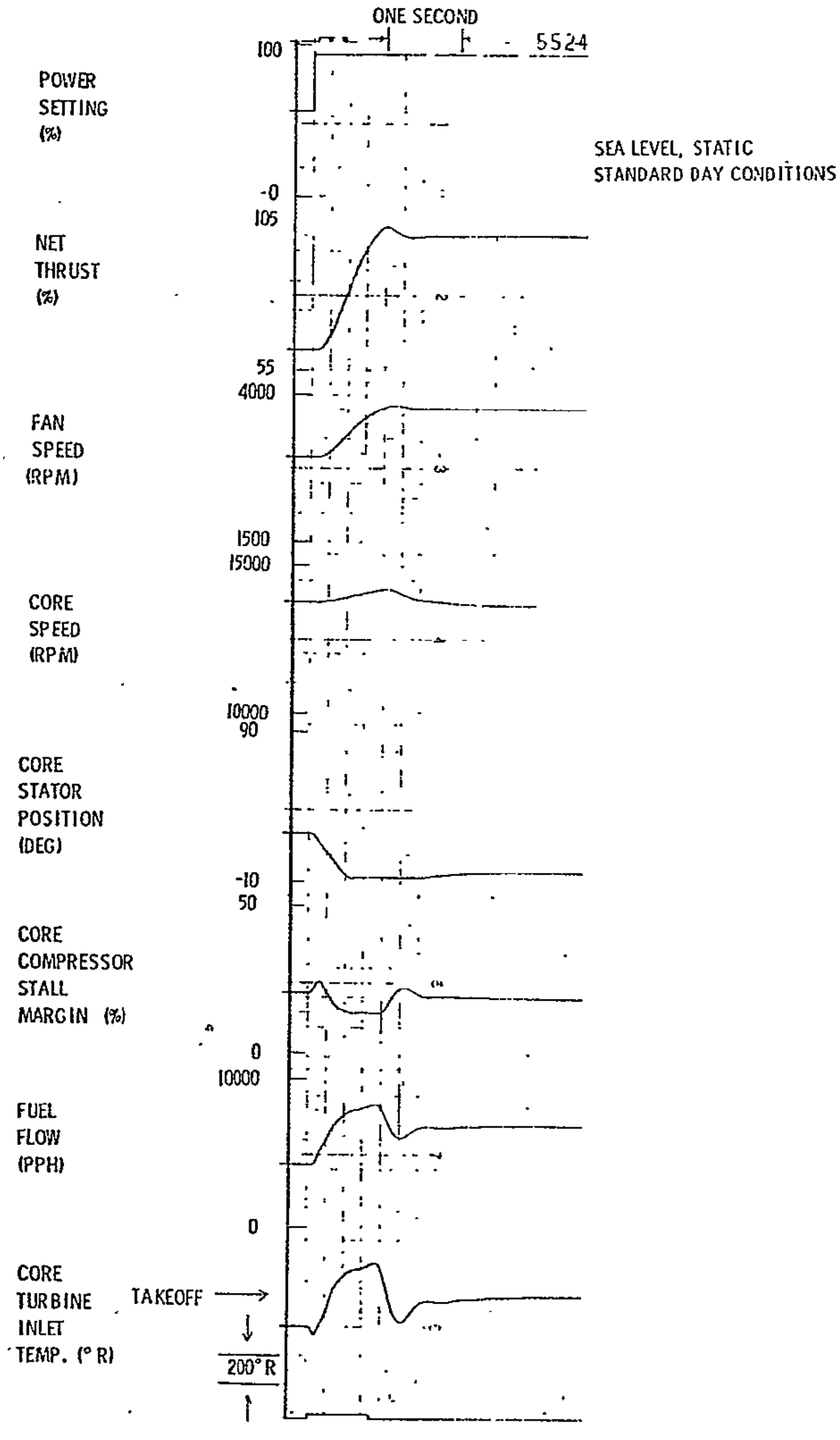
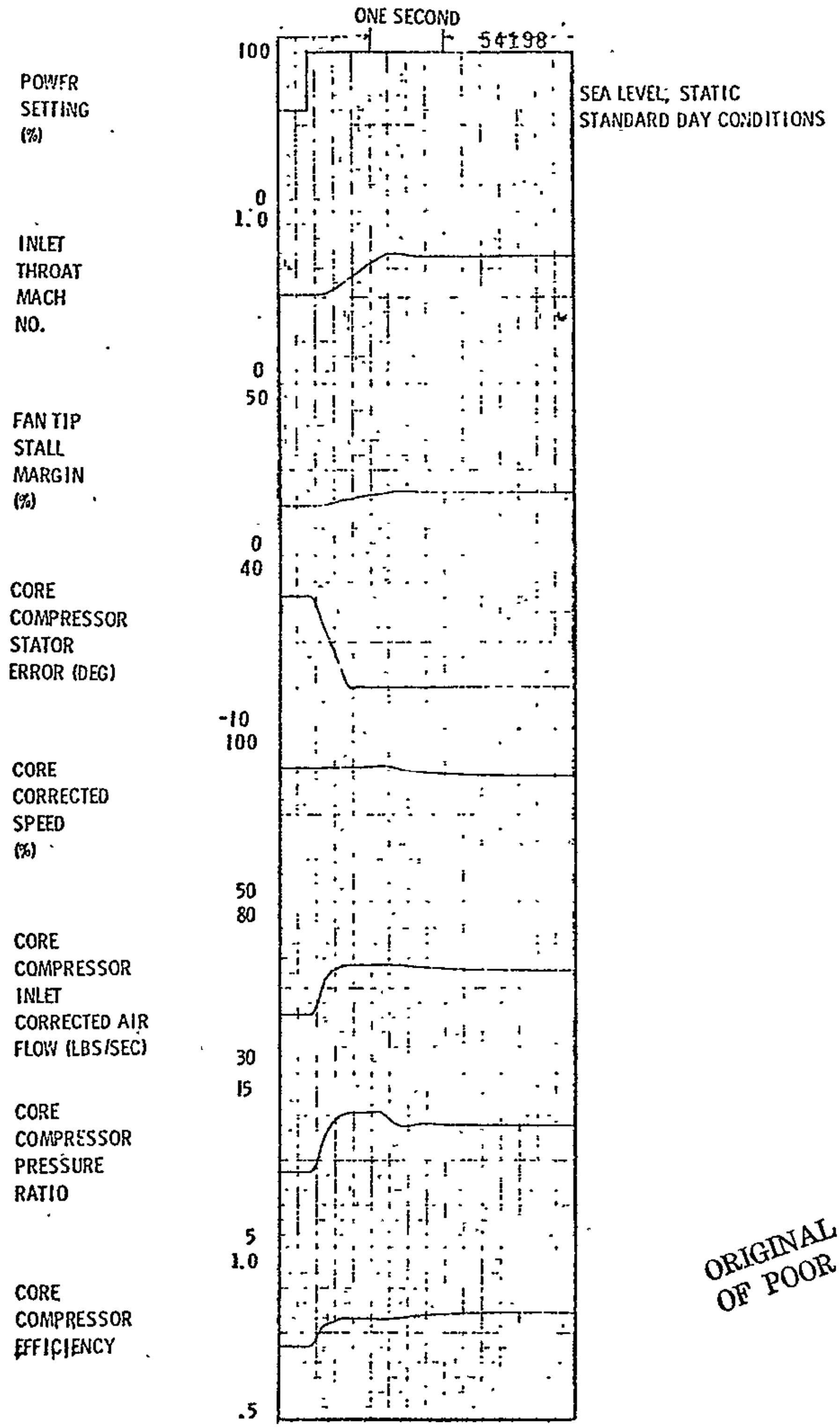


Figure 18. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Linear Servovalve and Core Stator Reset.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 18. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Linear Servovalve 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 titanum 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 acelerations.

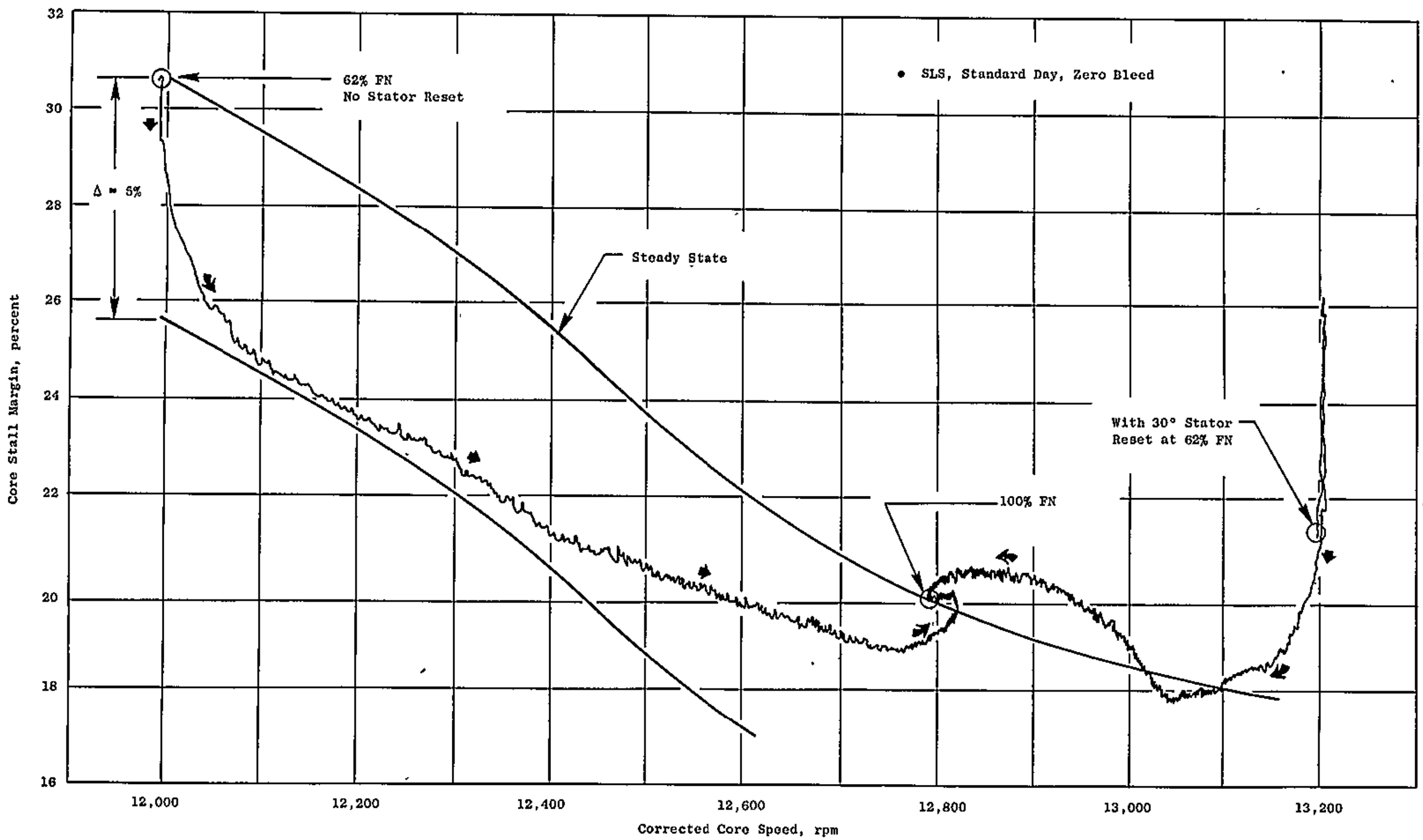


Figure 19. Initial Predictions of Core Stall Margin for Throttle Burst from 62 to 100% FN.

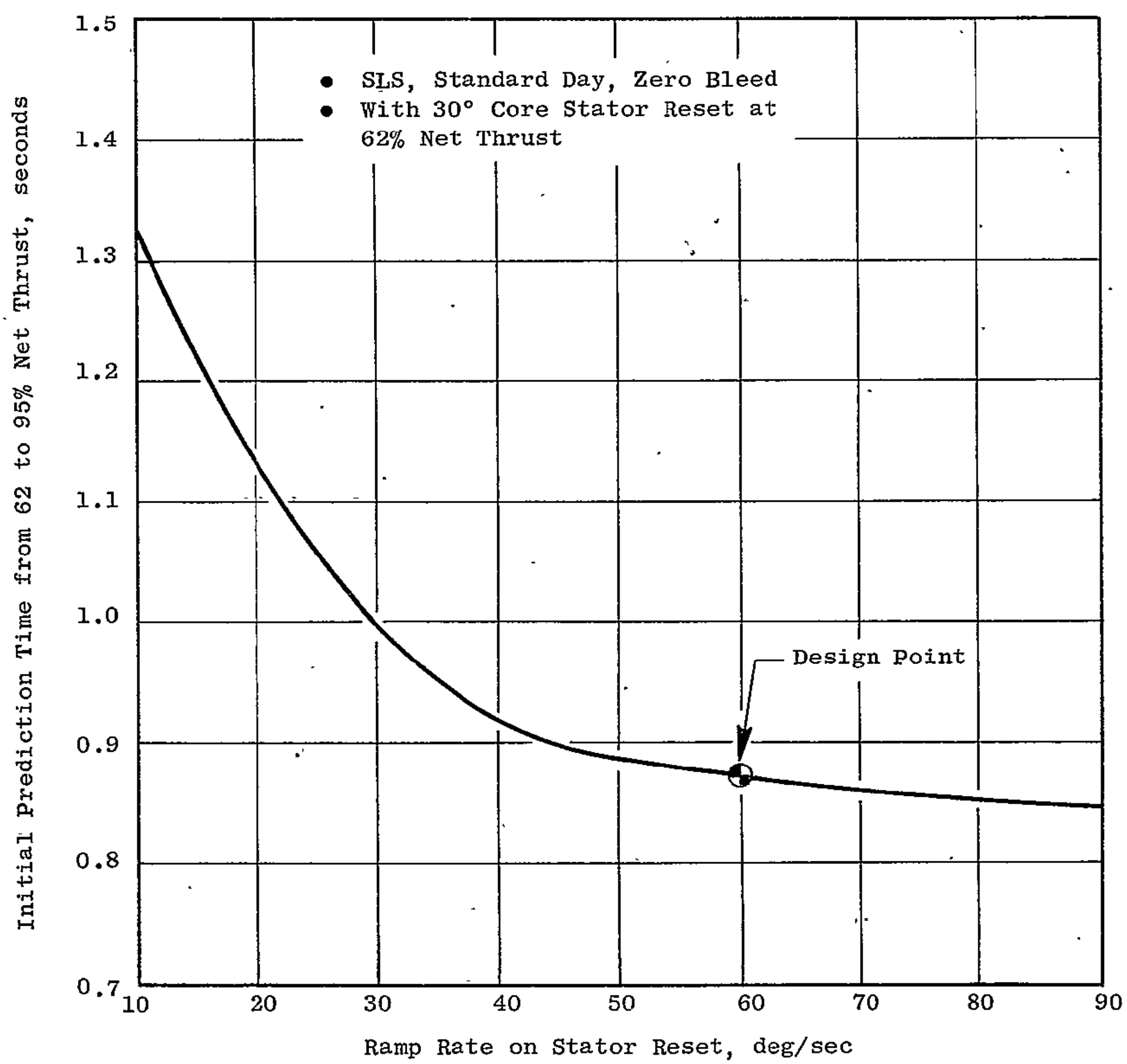


Figure 20. OTW Transient Response Accel Time Vs. Rate of Removing Core Stator Reset.

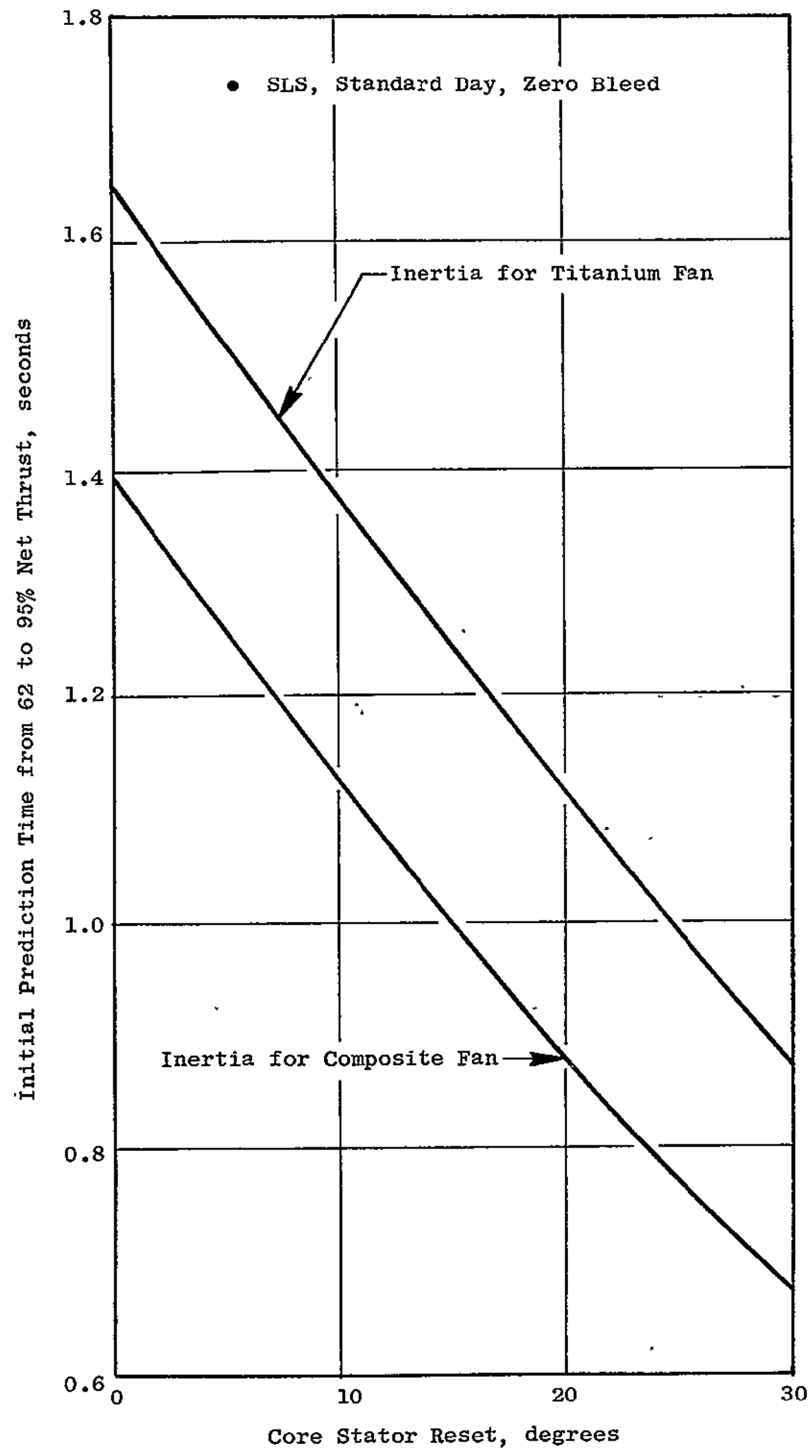


Figure 21. Initial Predictions - OTW Transient Response Accel Time Versus Core Stator Reset and Fan Rotor Inertia.

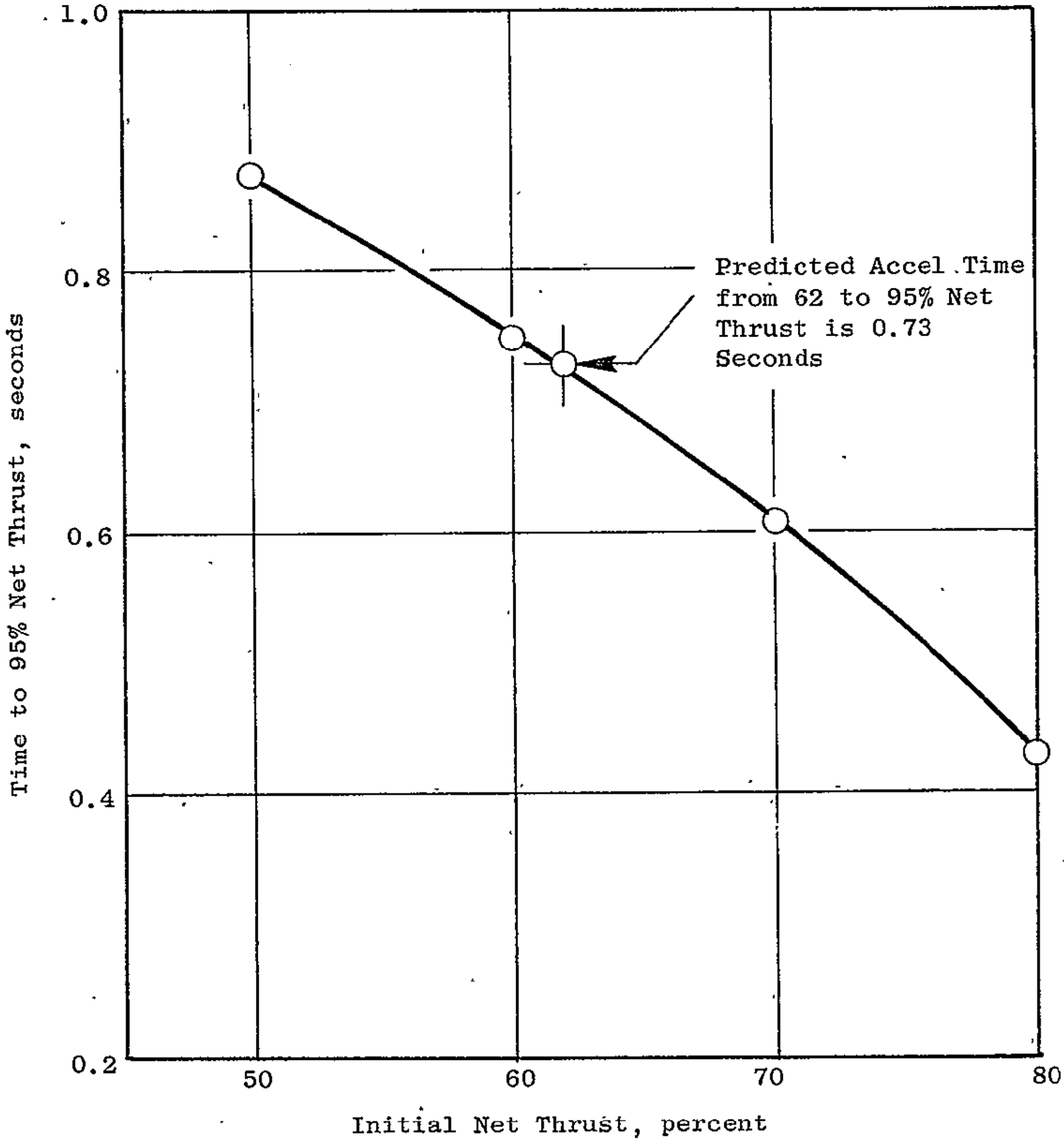


Figure 22. Final Prediction of OTW Transient Response for Throttle Bursts to 100% Net Thrust at Sea Level, Static, Standard Day, Zero Bleed Conditions.

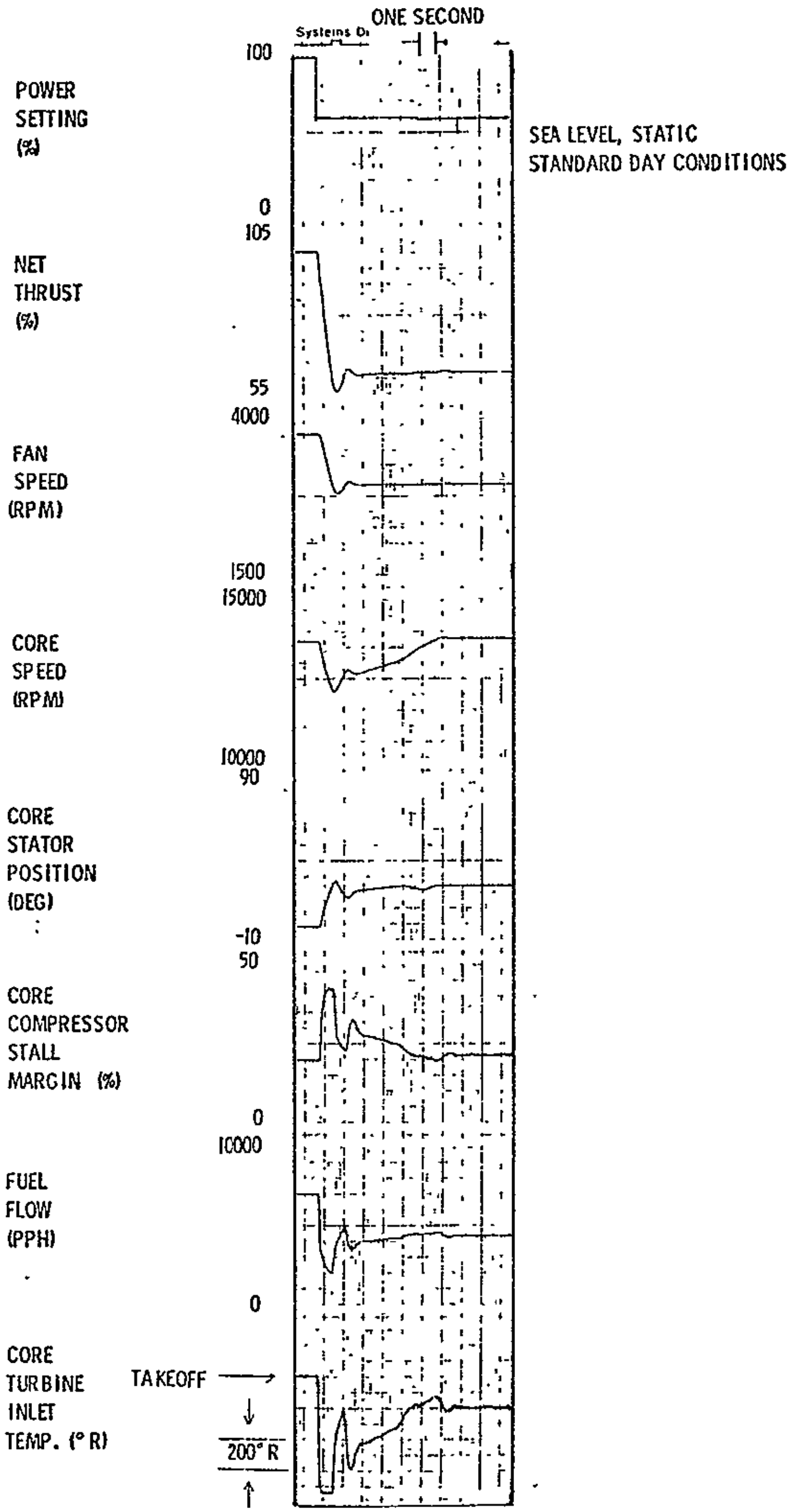


Figure 23. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Linear Servovalve and Core Stator Reset.

ORIGINAL PAGE IS OF POOR QUALITY

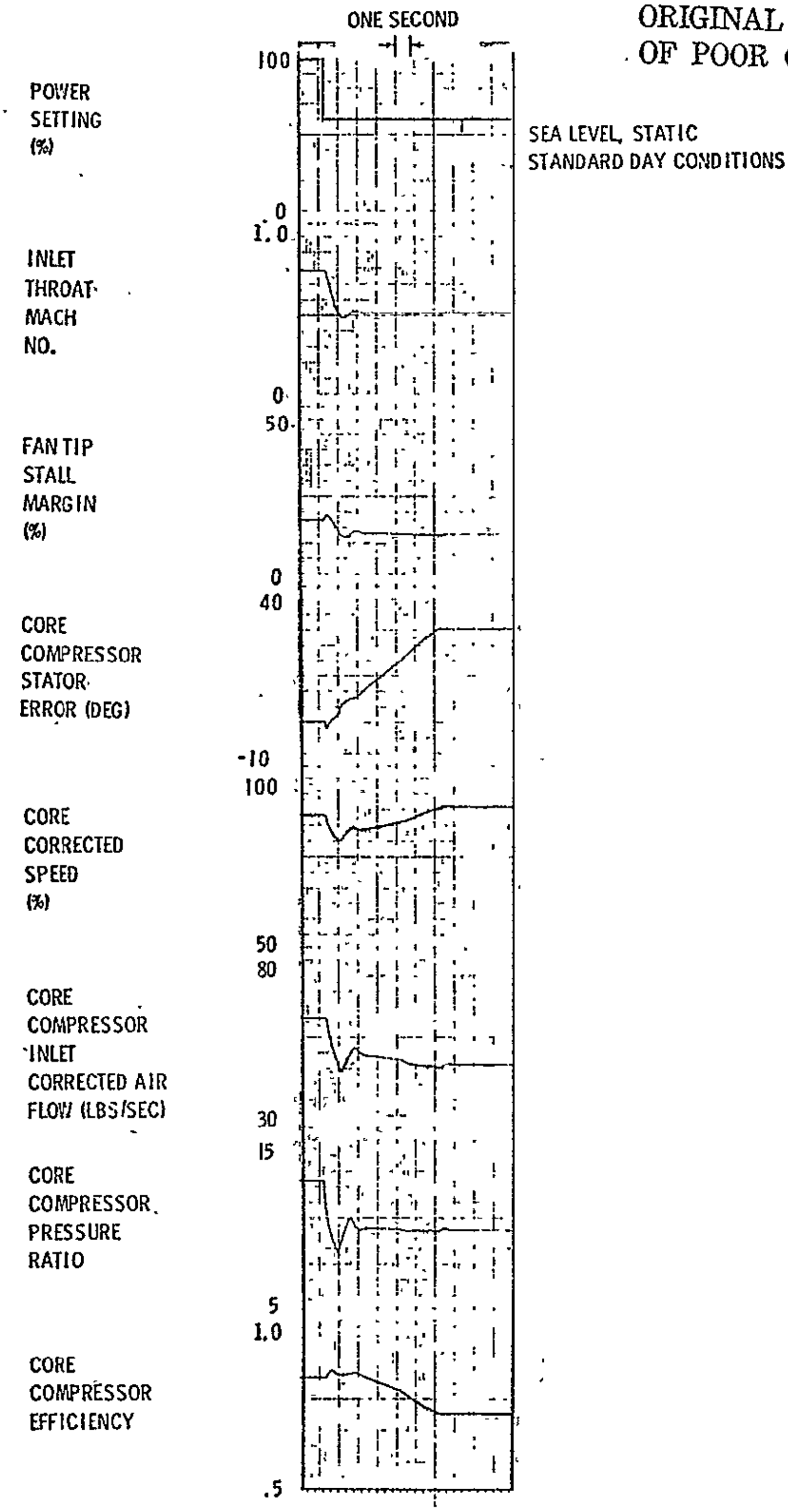


Figure 23. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Linear Servovalve and Core Stator Reset (Concluded).

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 W=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

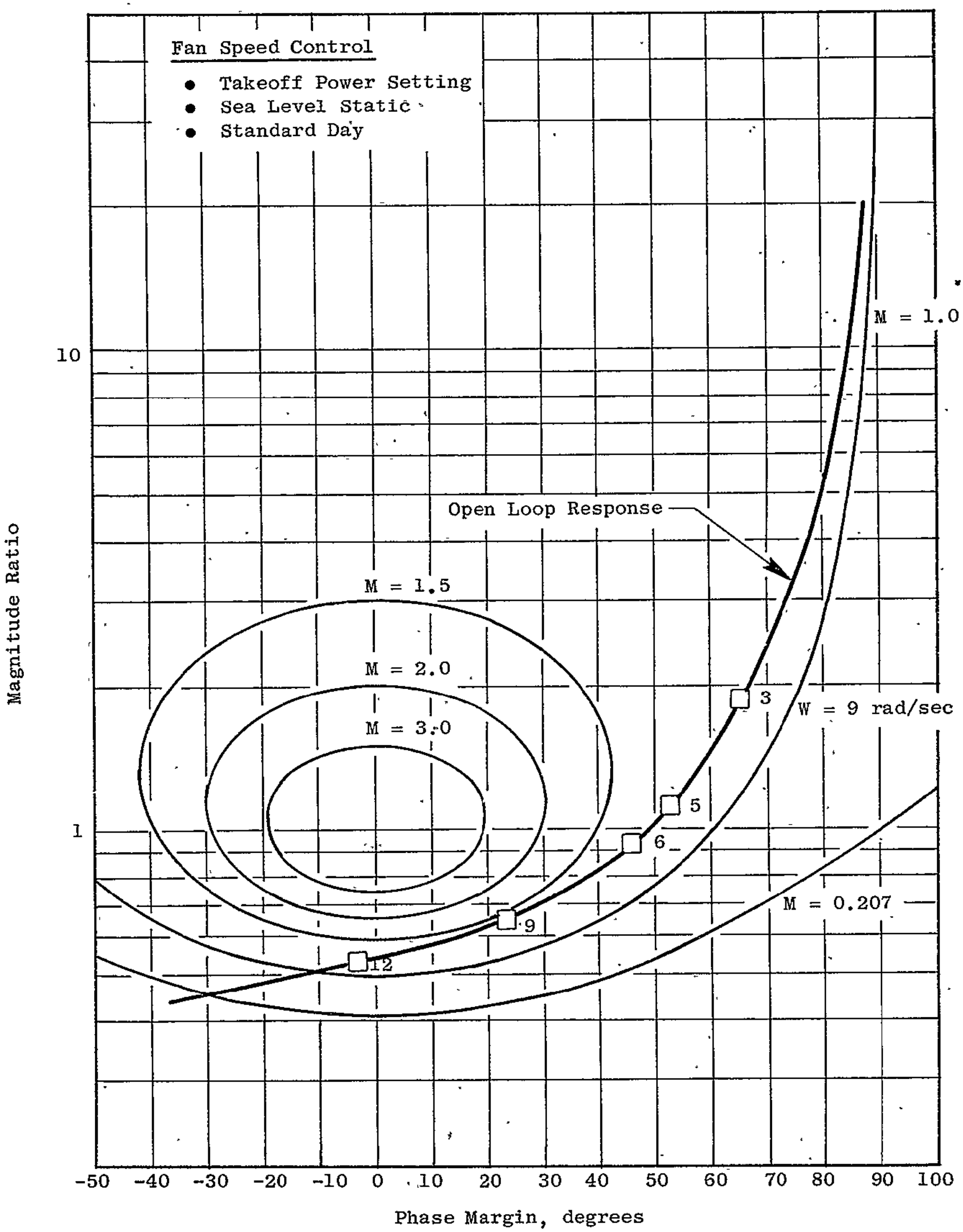


Figure 24. Phase Magnitude Ratio Diagram, Fan Speed Control.

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

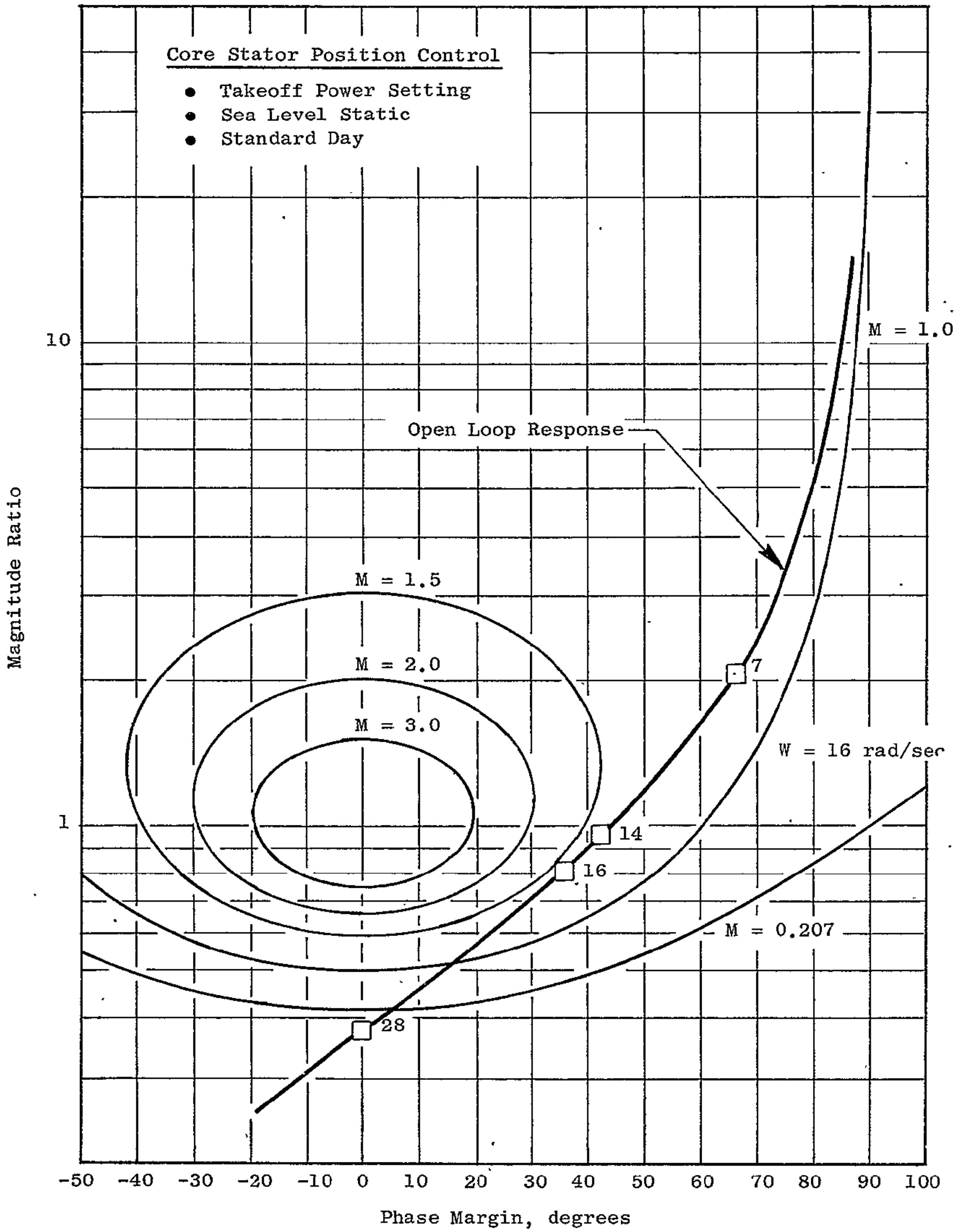


Figure 25. Phase Magnitude Ratio Diagram, Core Stator Position Control.

ORIGINAL PAGE IS
OF POOR QUALITY

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 x 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 charateristics 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 amplifer 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 amplifers and the servovalve were assumed to respond like first-order lags, with respective time constants of 0.01 and

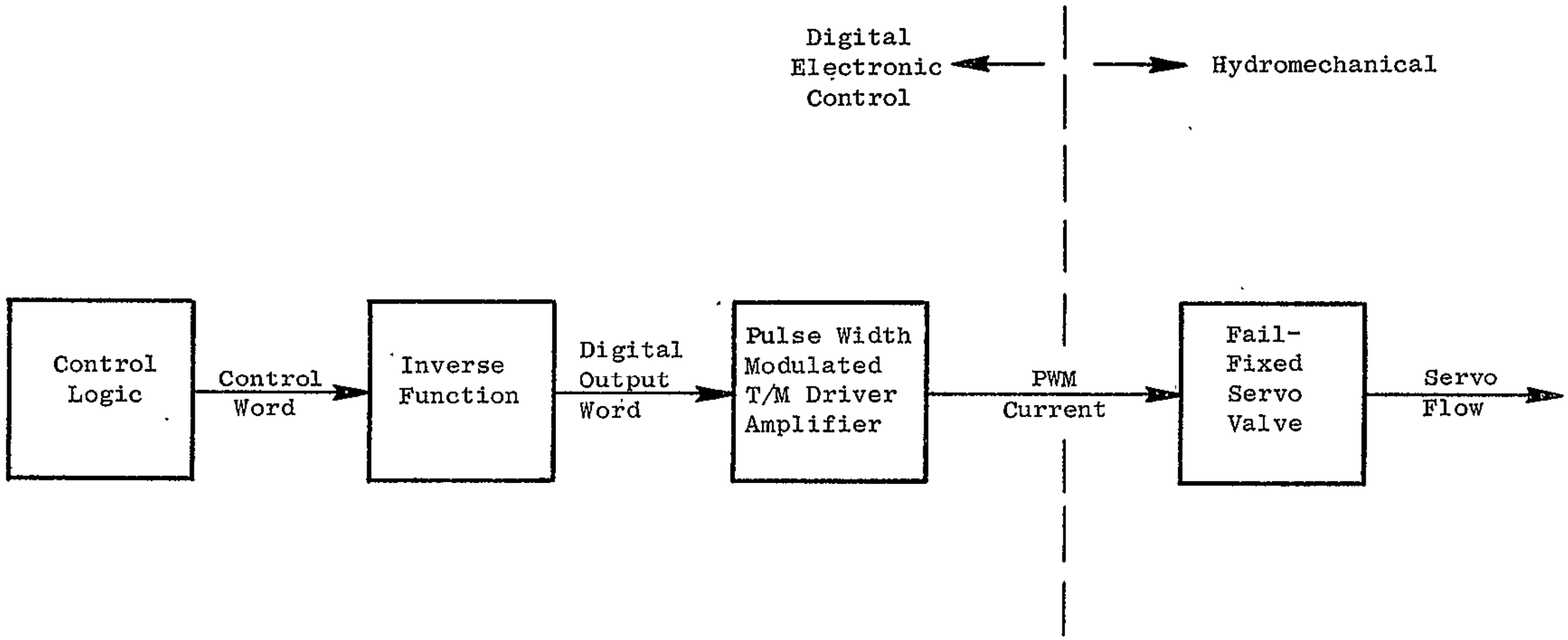


Figure 26. Functional Schematic for Digital Control and Fail-Fixed Servo Valve.

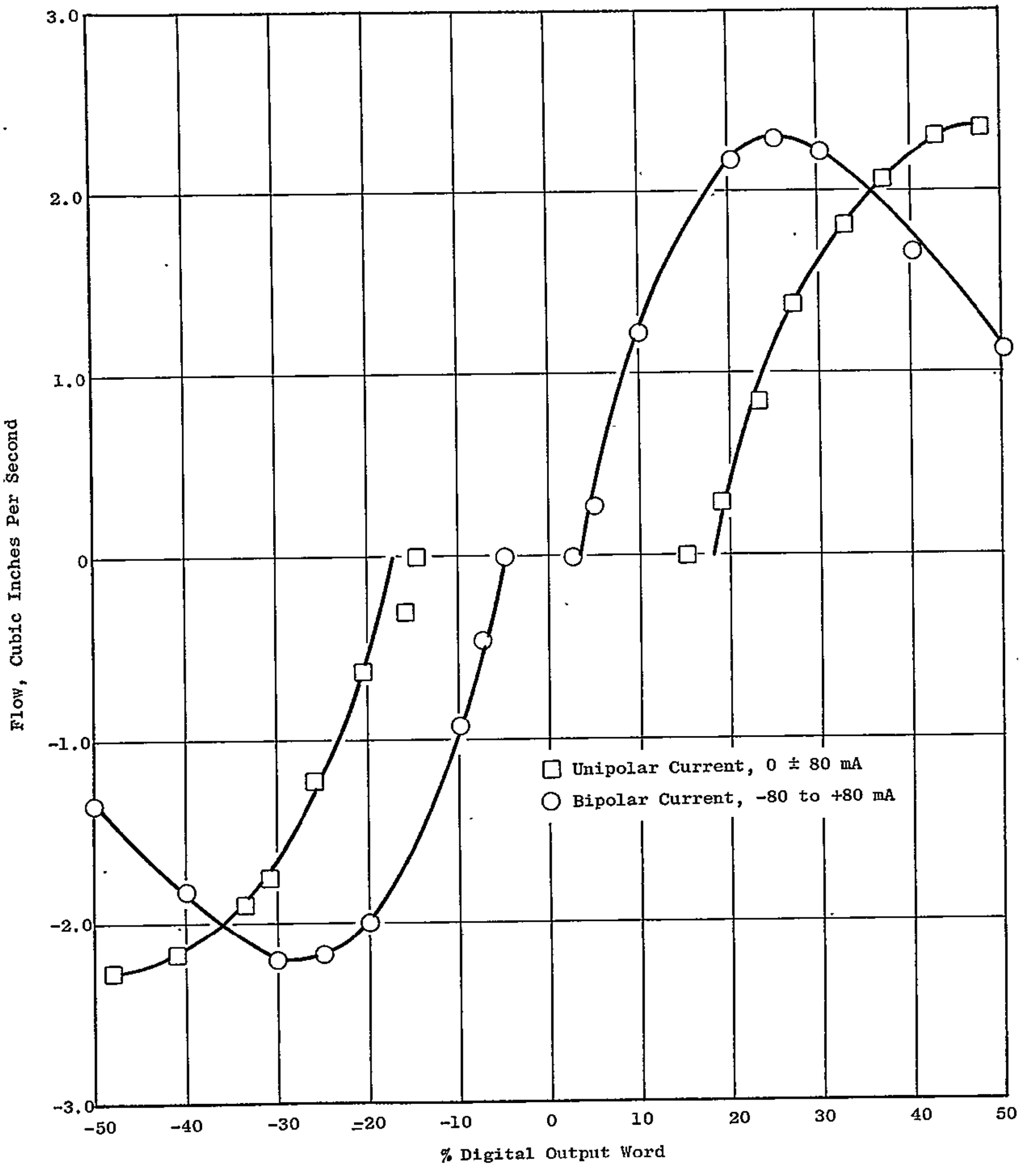


Figure 27. Fail-Fixed Servovalve Characteristics, Digital Amplifier and Servovalve, 500 Hz, Pulse Width Modulation.

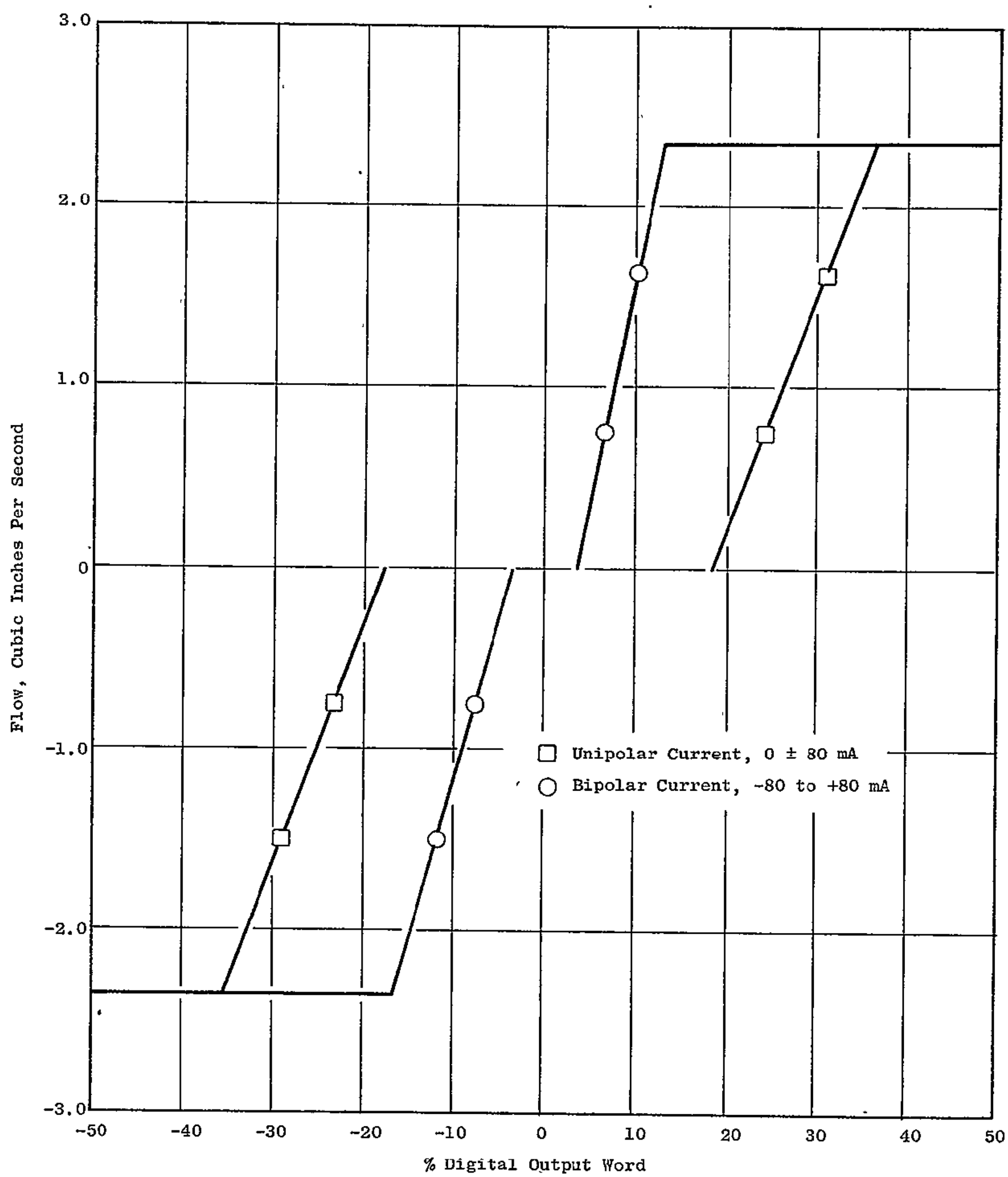


Figure 28. Simulation of Fail-Fixed Servovalve Characteristics.

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.)

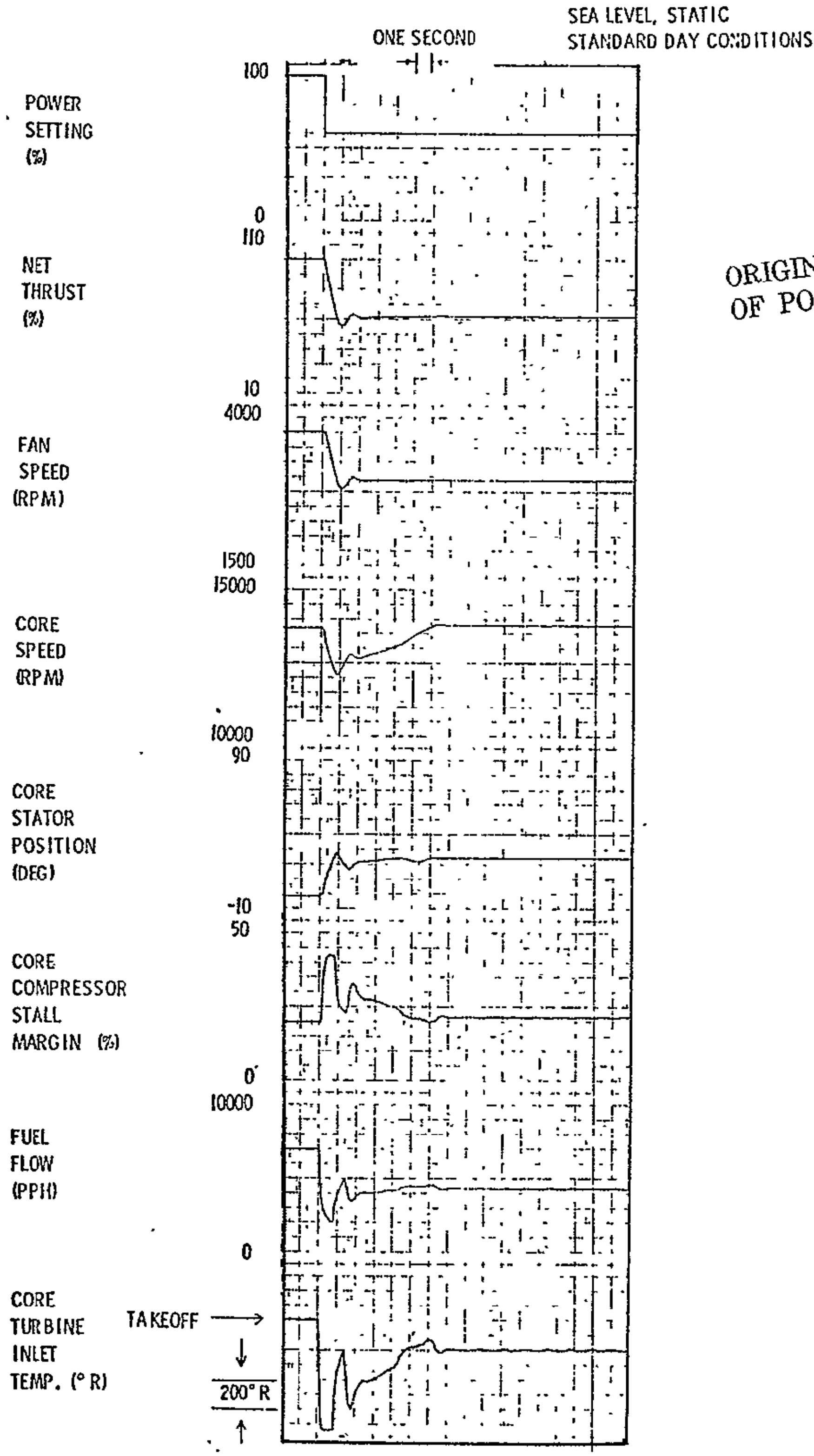
4.7.2 FFSV Simulation Results

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 comnpensation, 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 amplifer, 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.



ORIGINAL PAGE IS OF POOR QUALITY

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

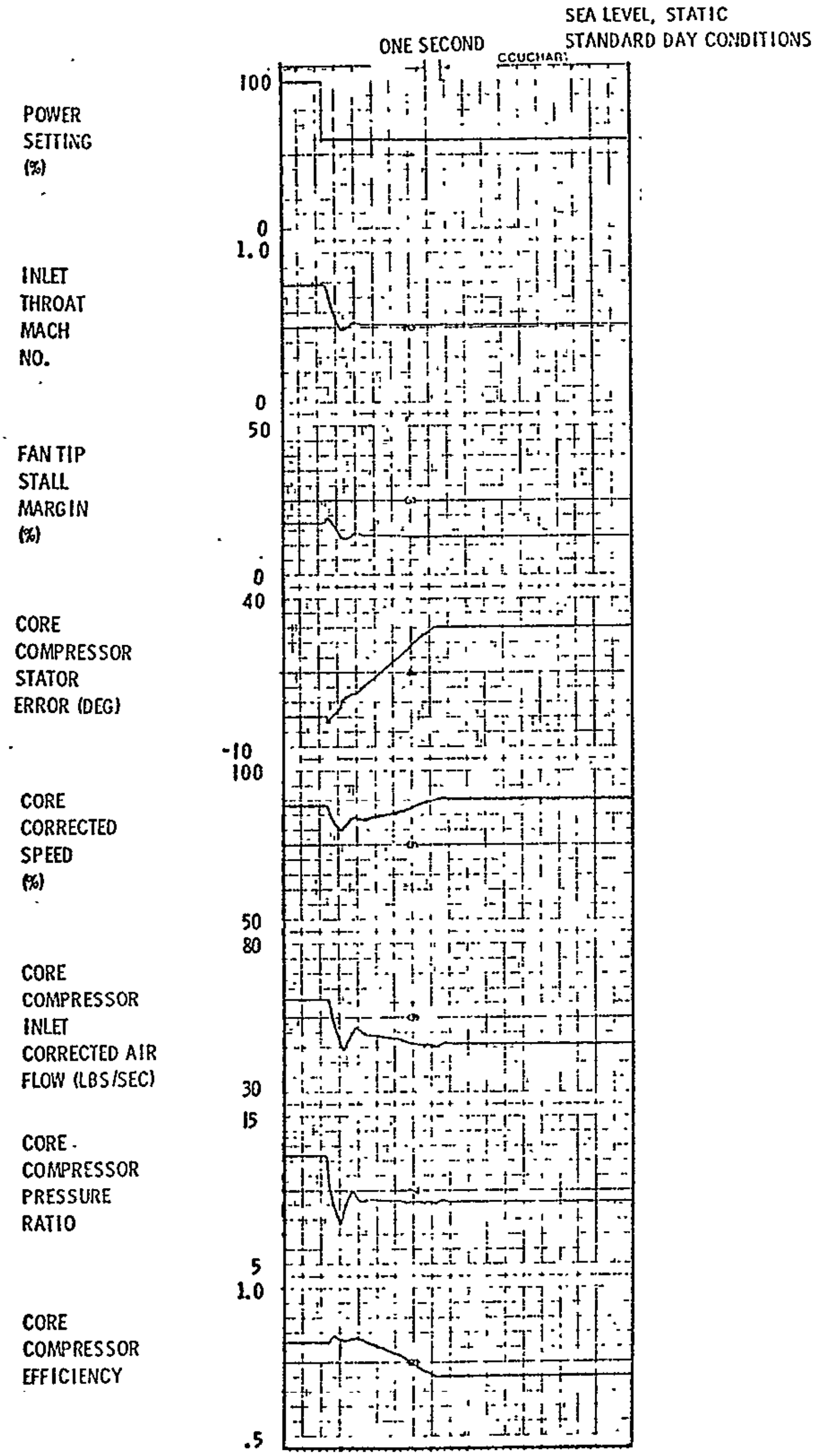
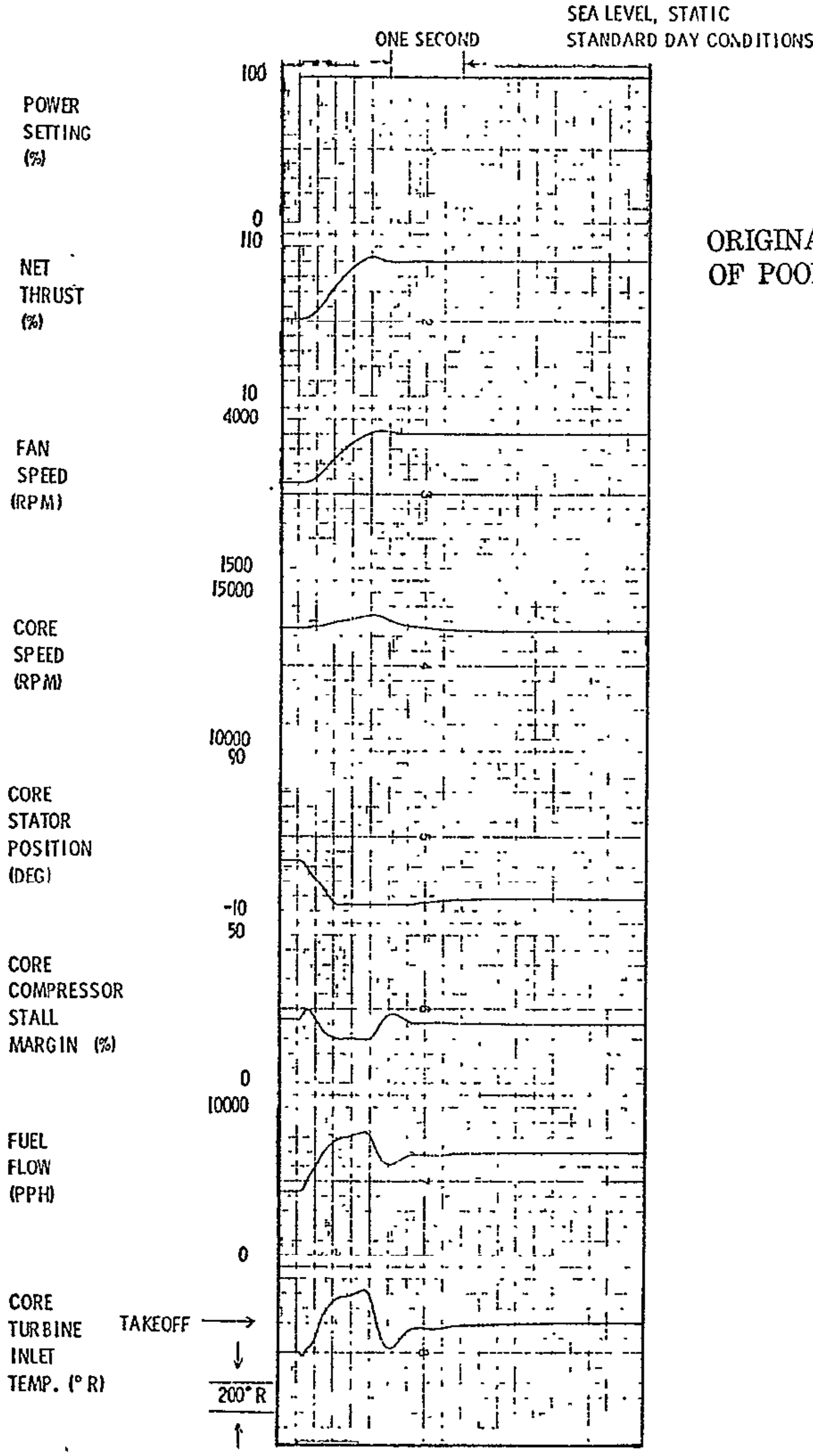


Figure 29. QCSEE OTW Throttle Chop from 100 to 62% Thrust Using Fail-Fixed Servovalve with Perfect Dead-Zone Compensation (Concluded).



ORIGINAL PAGE IS OF POOR QUALITY

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

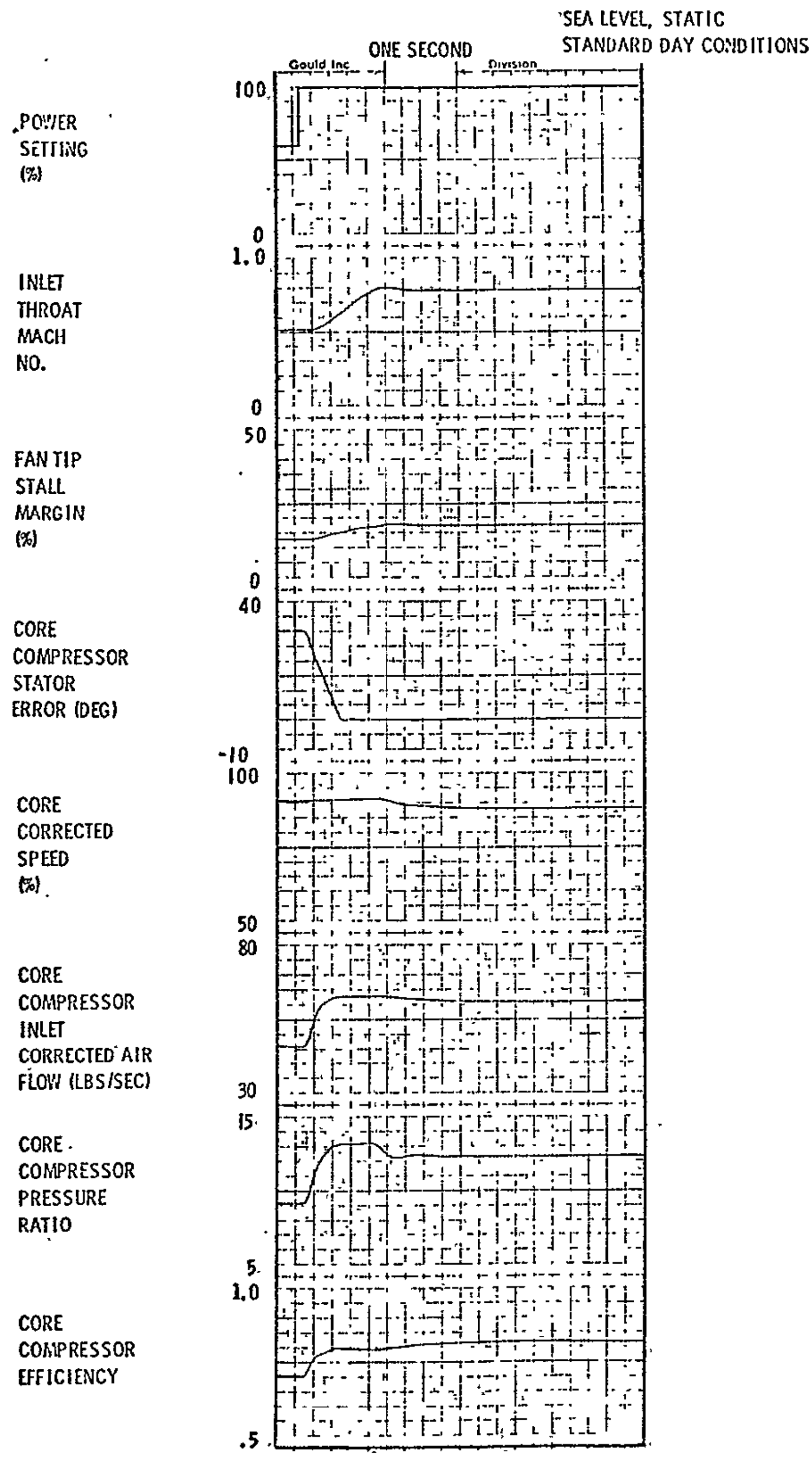
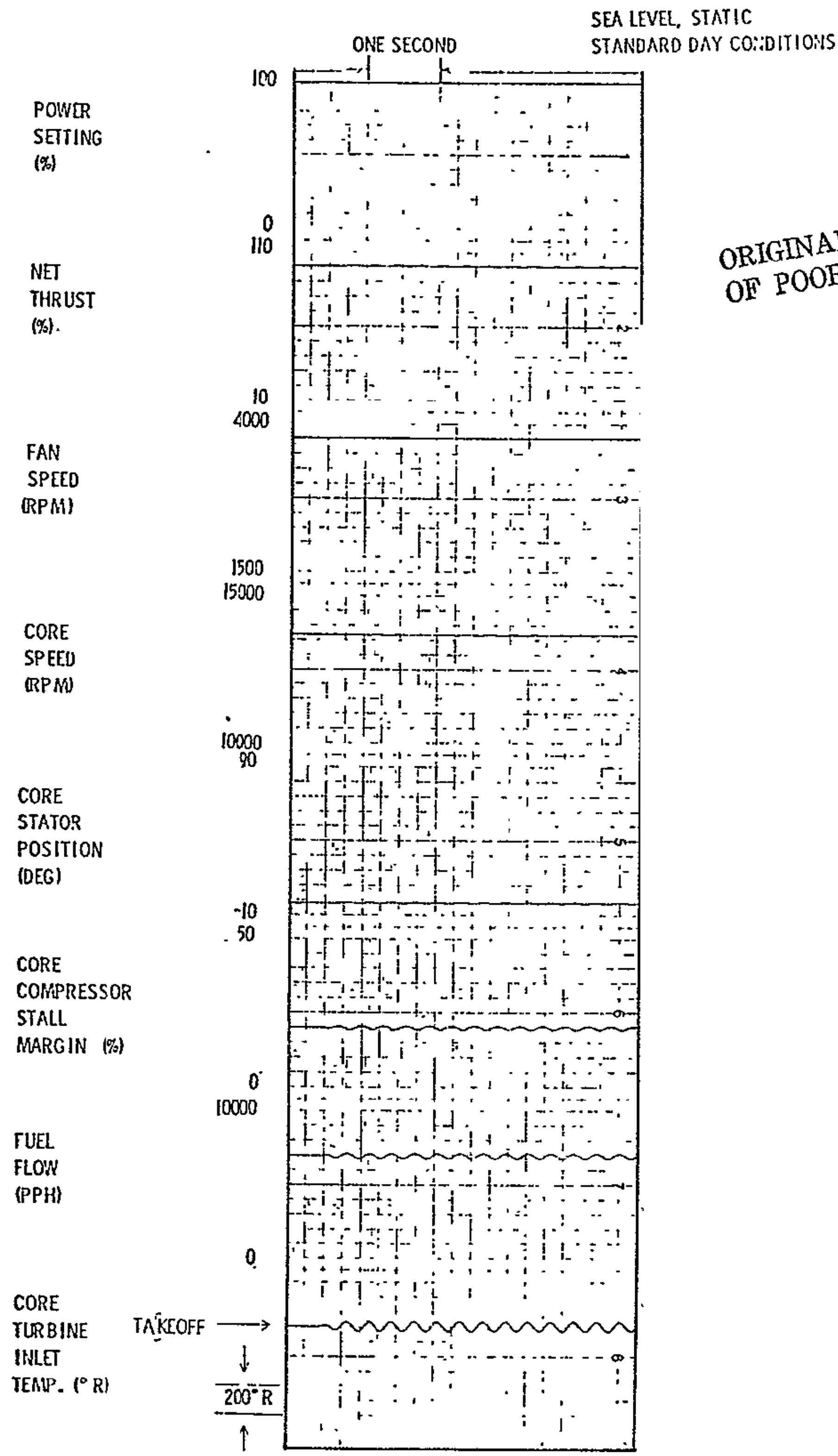


Figure 30. QCSEE OTW Throttle Burst from 62 to 100% Thrust Using Fail-Fixed Servovalve with Perfect Dead-zone Compensation (Concluded).



ORIGINAL PAGE IS
OF POOR QUALITY

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

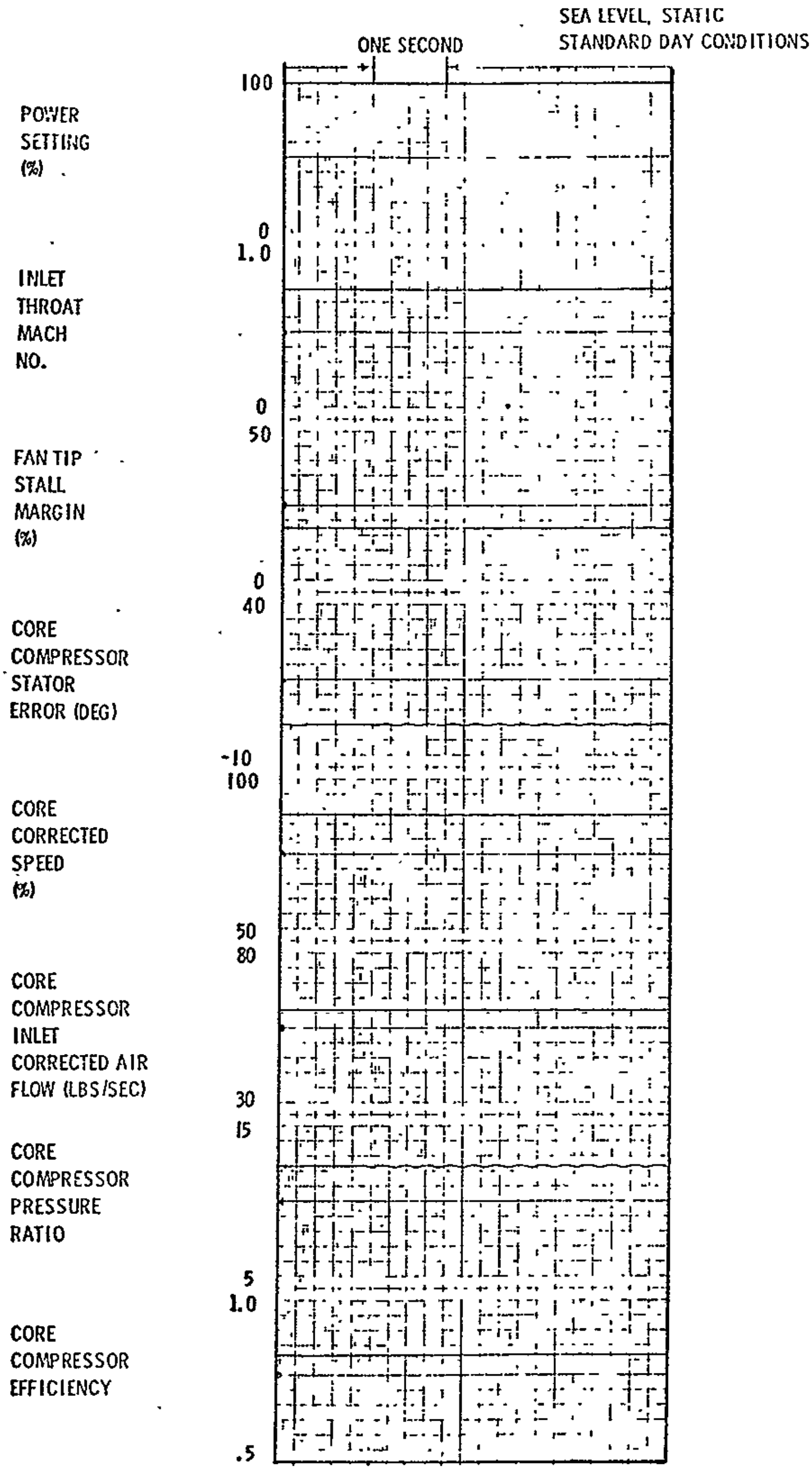


Figure 31. QCSEE OTW at Takeoff Thrust Using Fail-Fixed Servovalve with Deadzone Compensation 10% High (Concluded).

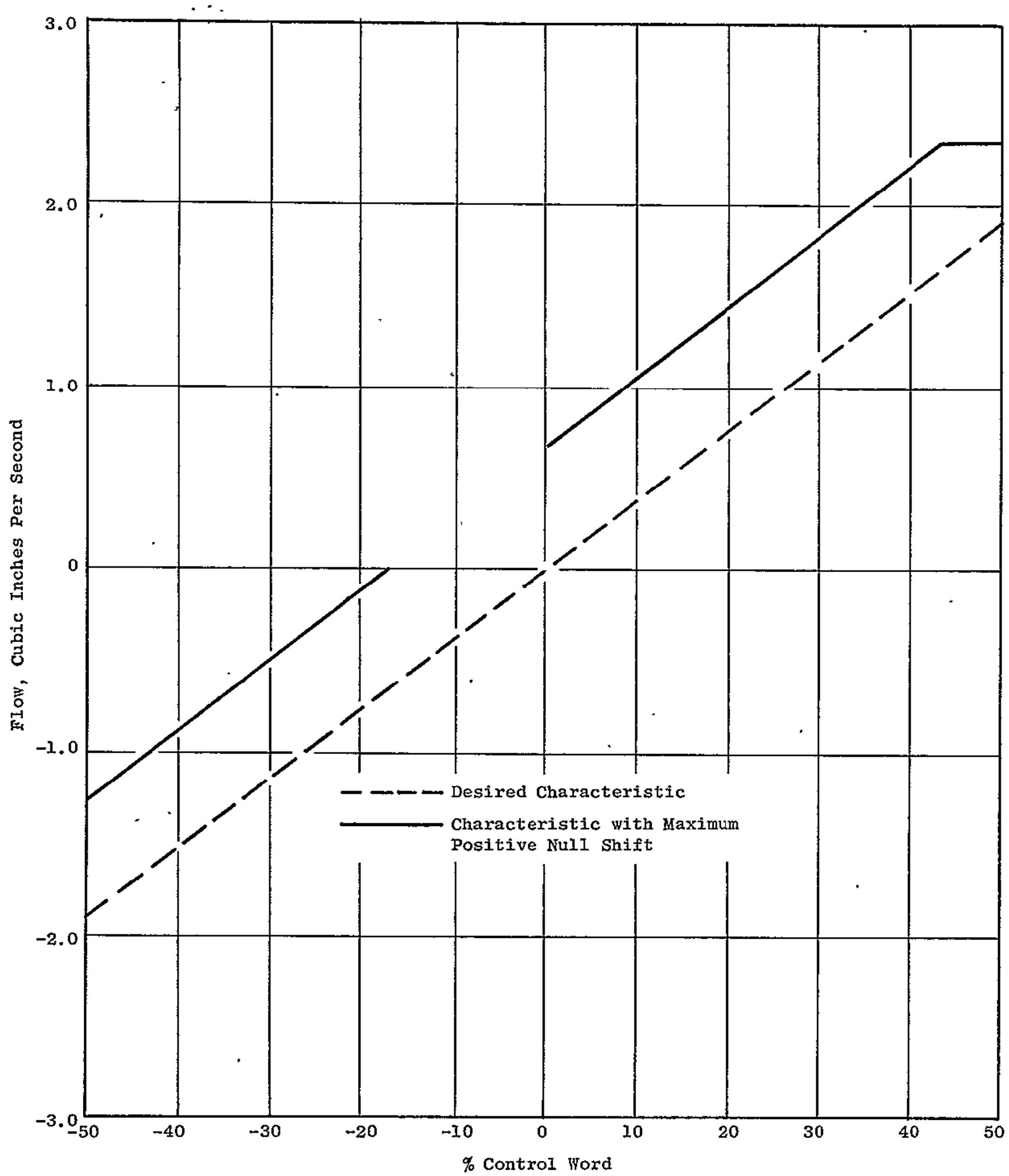


Figure 32. Effect of Null Shift on Simulation of Overall Fail-Fixed Servo Characteristic.

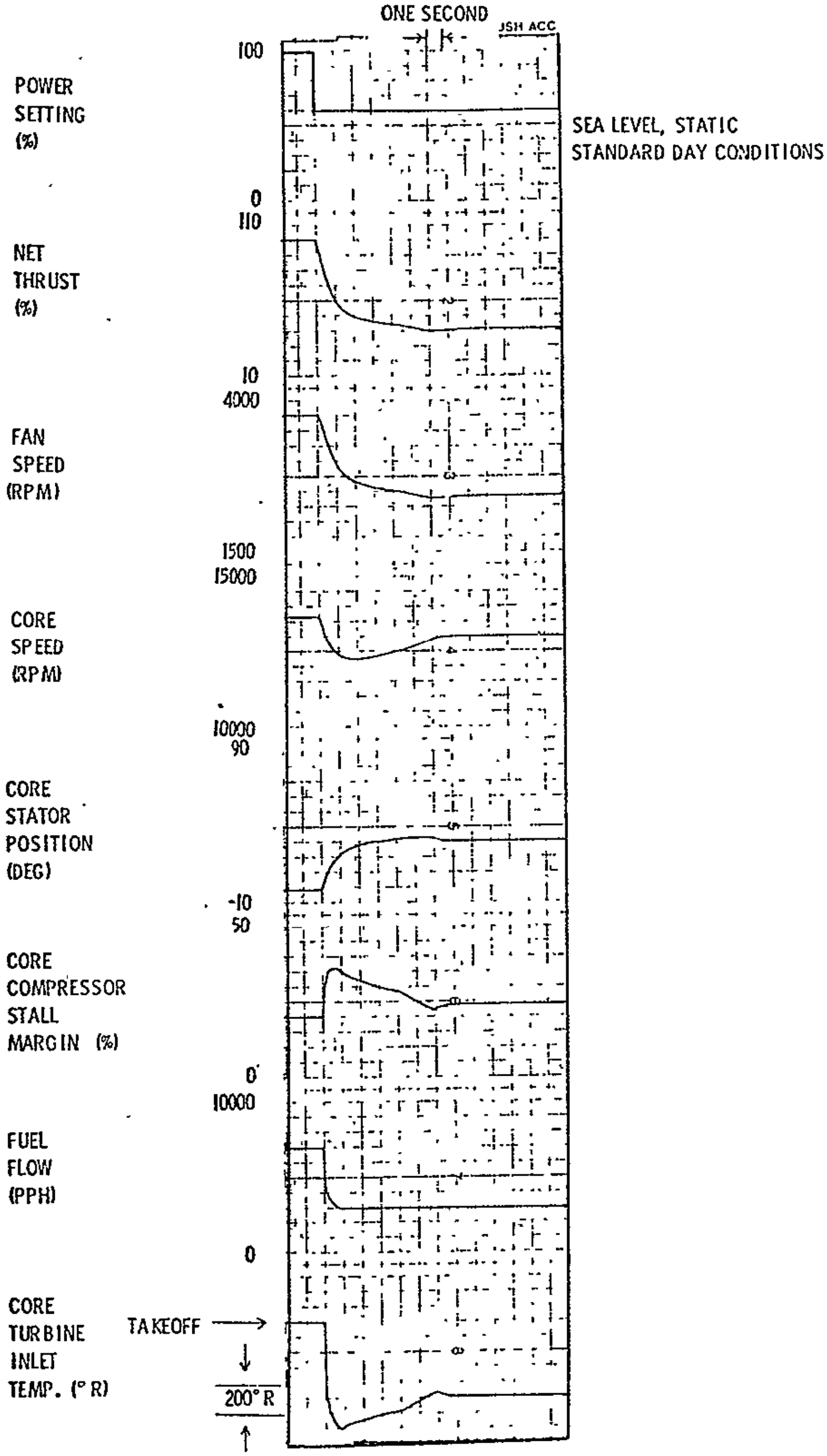


Figure 33. QCSEE OTW Throttle Chop to 62% Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation.

ORIGINAL PAGE IS
OF POOR QUALITY

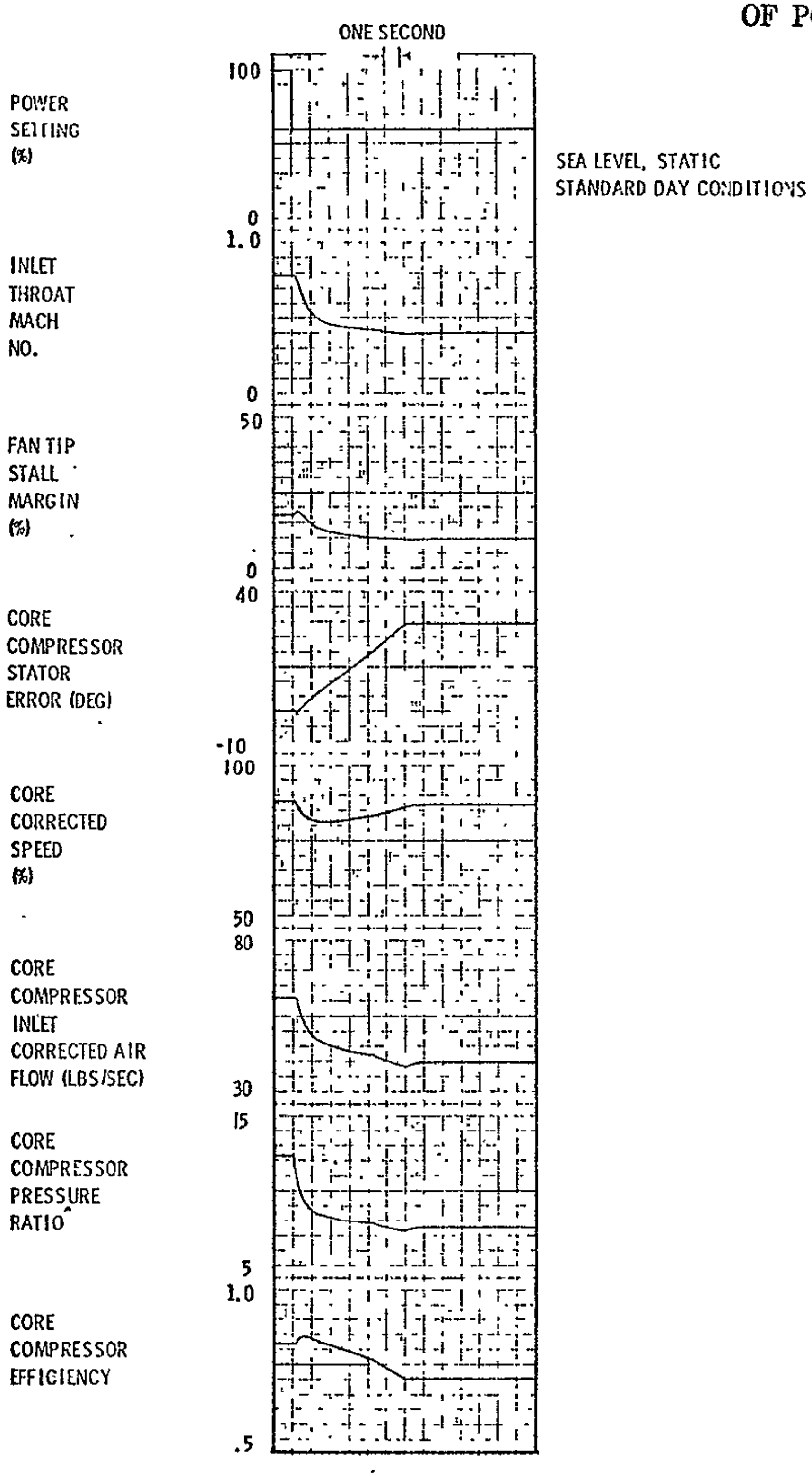


Figure 33. QCSEE OTW Throttle Chop to 62% Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation (Concluded).

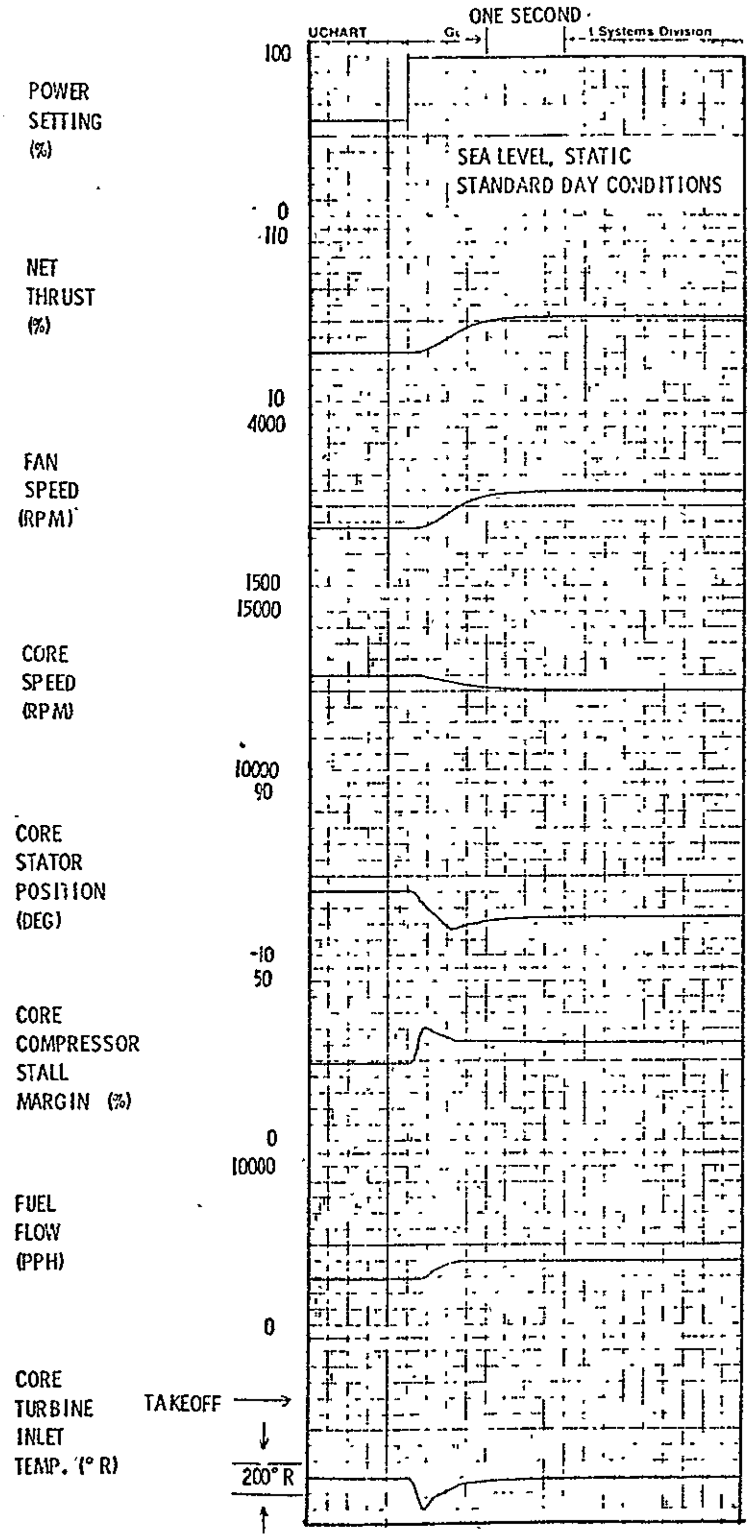


Figure 34. QCSEE OTW Throttle Burst to Takeoff Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation.

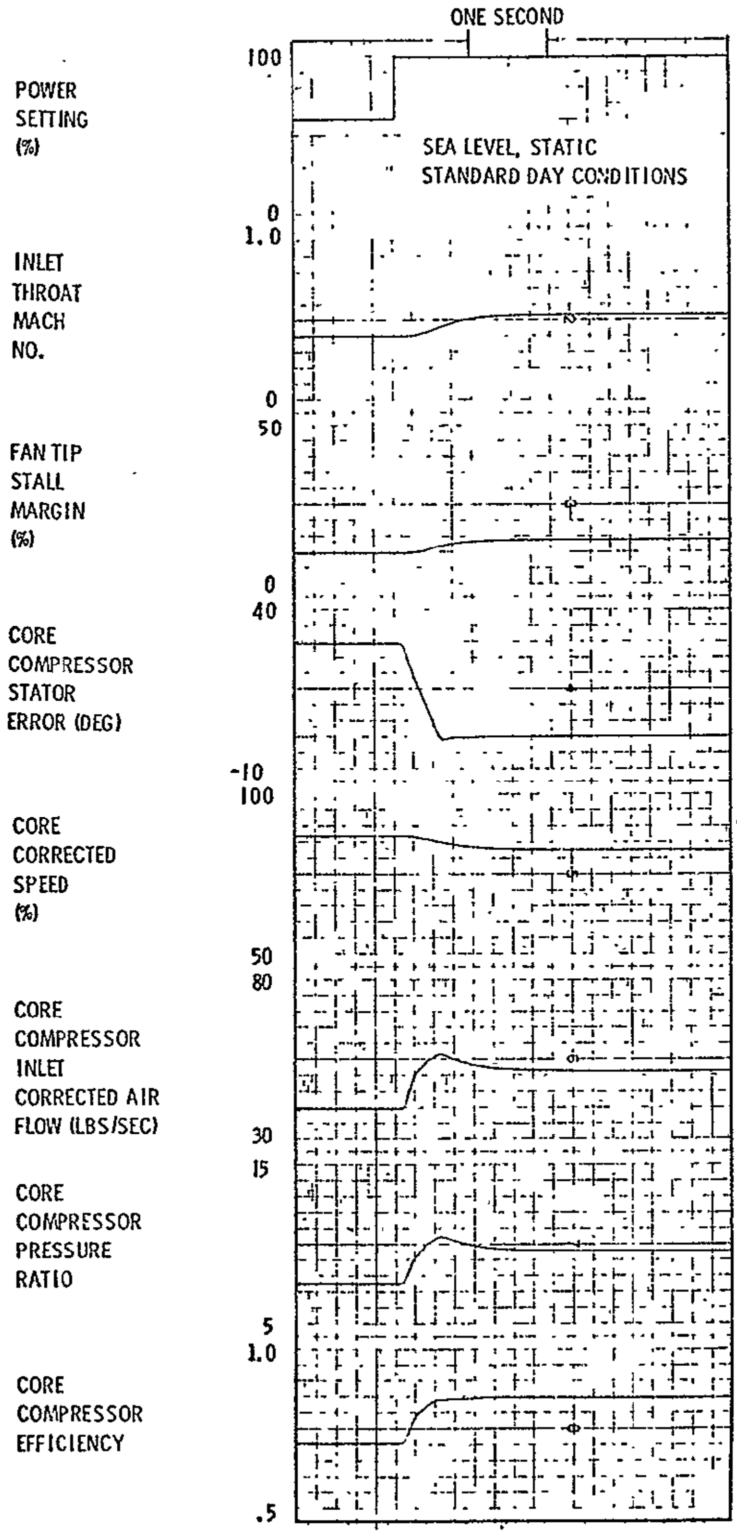


Figure 34. QCSEE OTW Throttle Burst to Takeoff Power Setting Using Bipolar Pulse Fail-Fixed Servovalve with No Deadzone Compensation (Concluded).

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

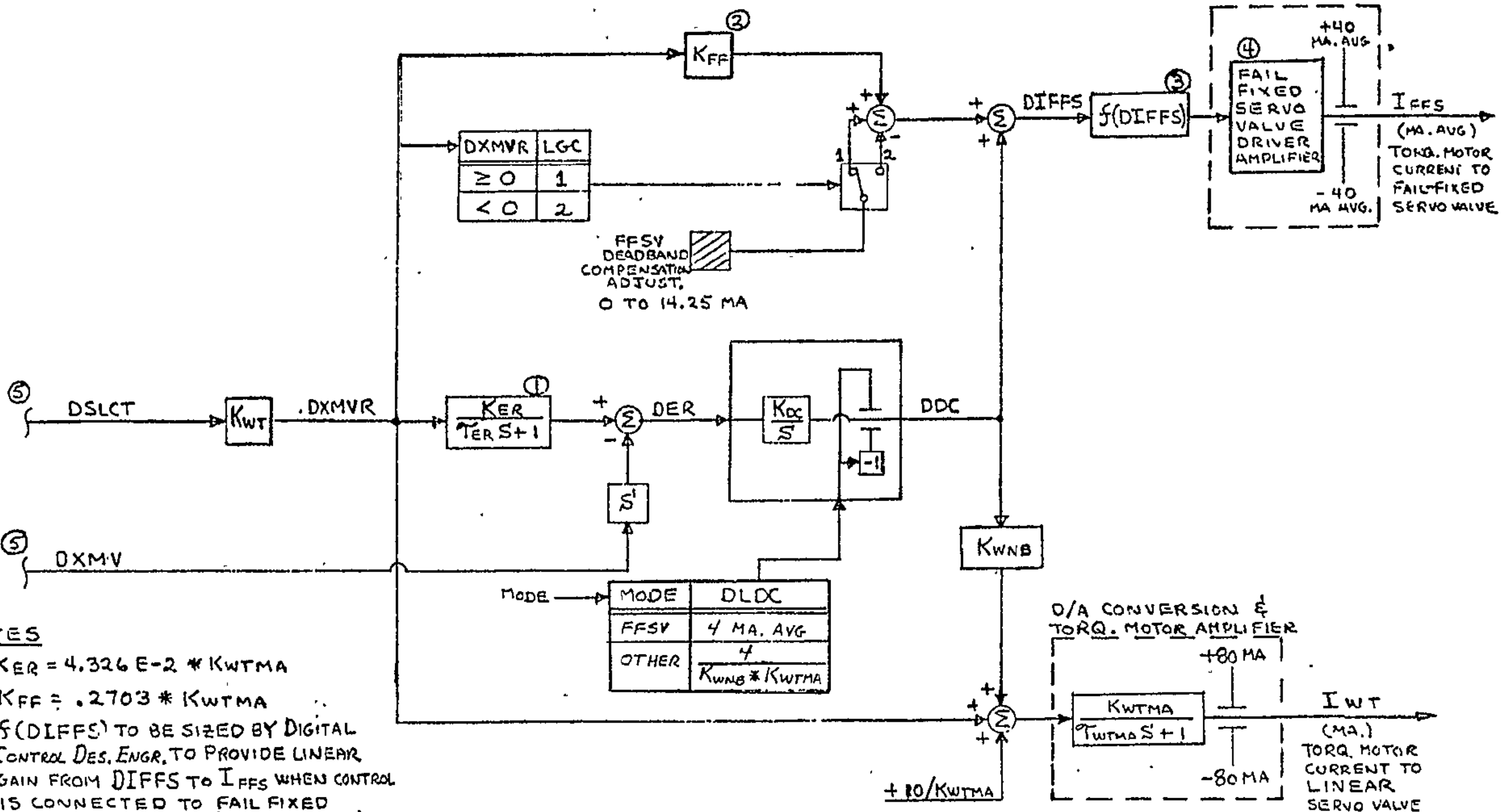
$$\left[\frac{KER}{T_{ER}S + 1}\right] * DXMVR - [S] * DXMV$$

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.



NOTES

1. $K_{ER} = 4.326\,E{-2} * K_{WTMA}$
2. $K_{FF} = .2703 * K_{WTMA}$
3. f(DIFFS) TO BE SIZED BY DIGITAL CONTROL DES. ENGR. TO PROVIDE LINEAR GAIN FROM DIFFS TO I_{FFS} WHEN CONTROL IS CONNECTED TO FAIL FIXED SERVO VALVE (WET & PRESSURIZED)
4. LAG TIME CONSTANT (T_{FFSMA}) OF FFSV DRIVER AMP. SHALL BE ≤ .01 SEC.
5. SEE FIGURE 30

Figure 35. QCSEE OTW Servovalve Fuel Control Block Diagram.

ORIGINAL PAGE IS OF POOR QUALITY

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 McDonnel 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 evalute 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.

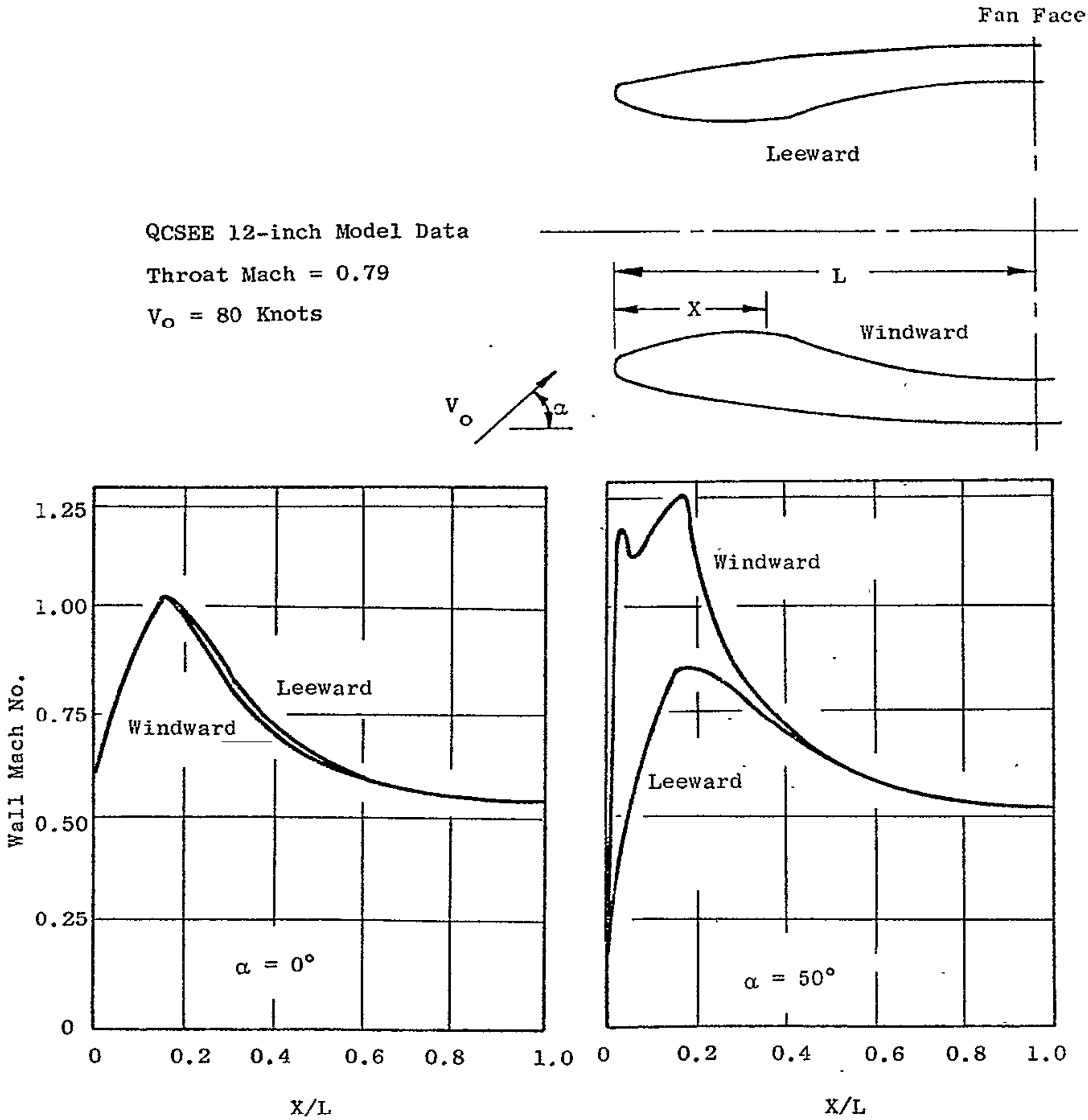


Figure 36. Inlet Pressure Sensing Data.

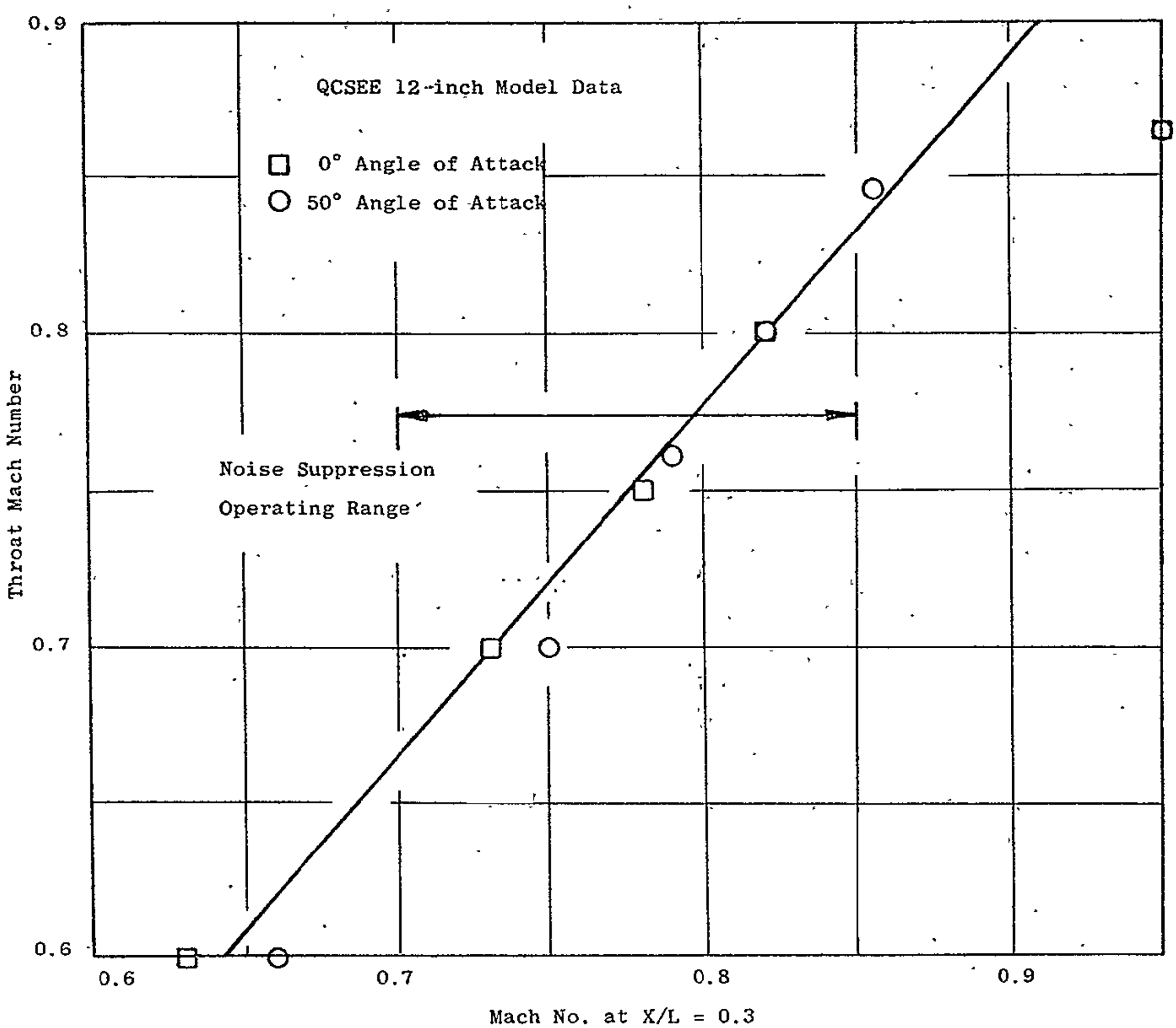


Figure 37. Inlet Mach Number Correlation Data.

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 ATS100-277A 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.

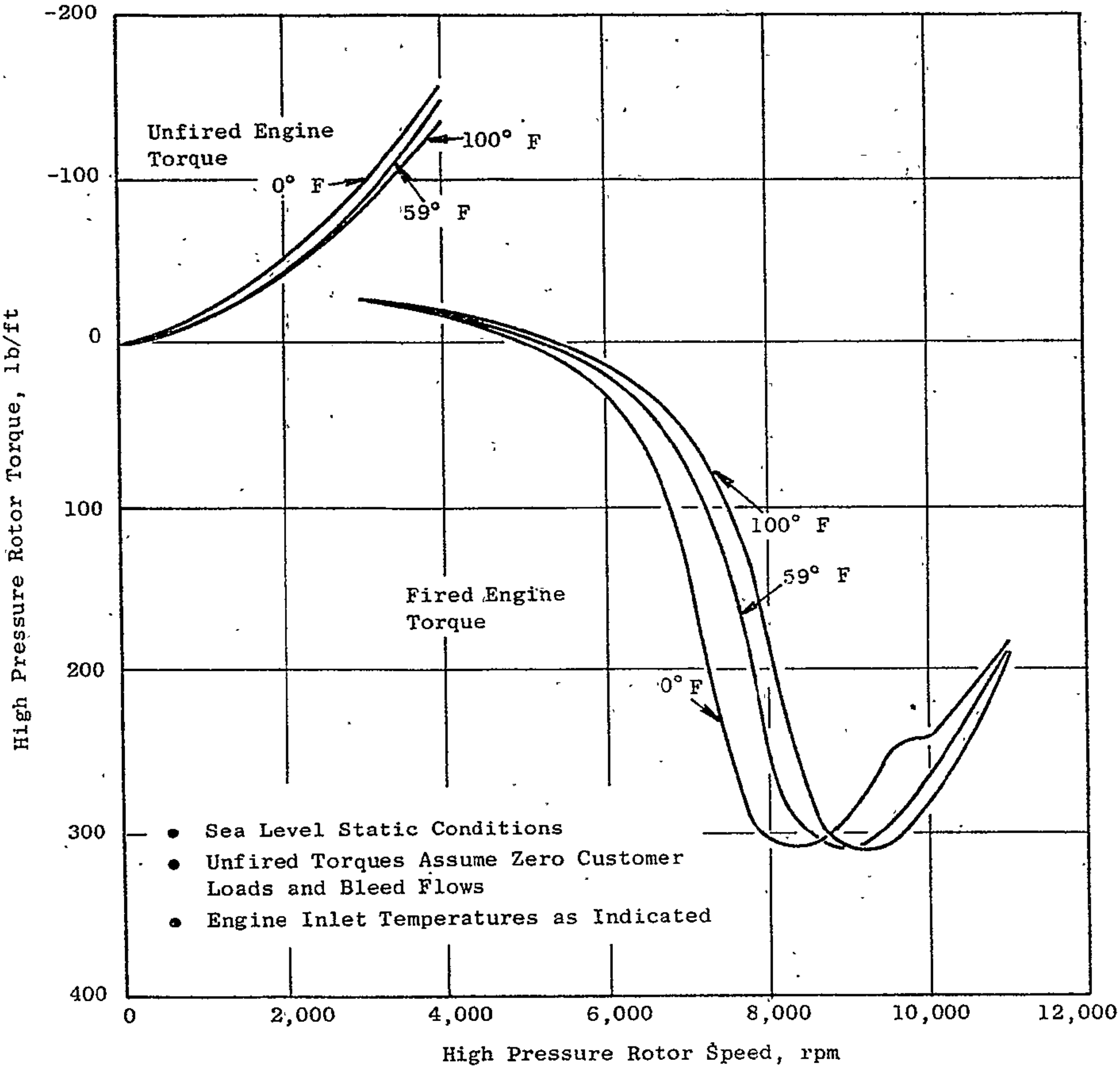


Figure 38. Estimated QCSEE Engine Torques.

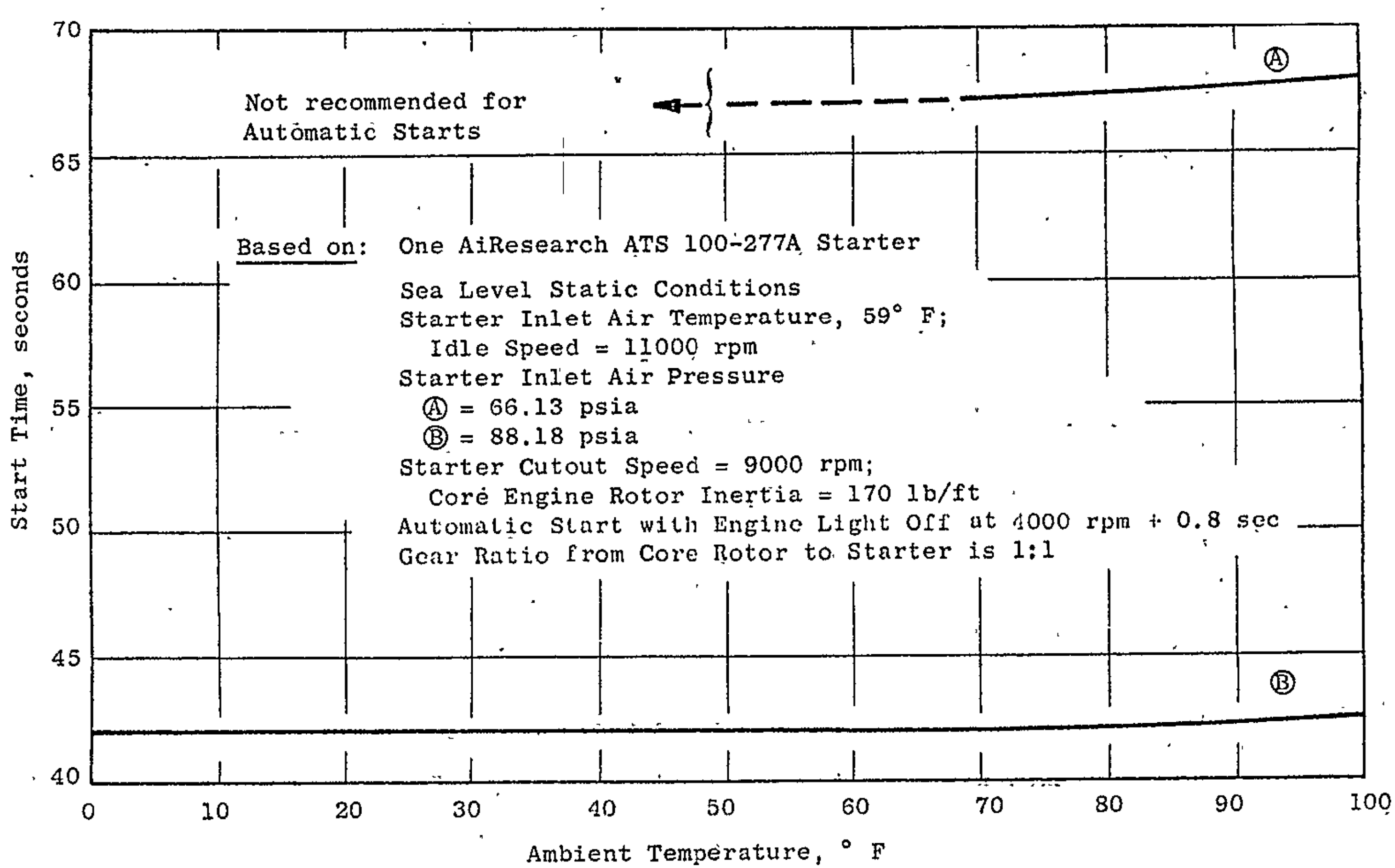


Figure 39. QCSEE Start Time Study.

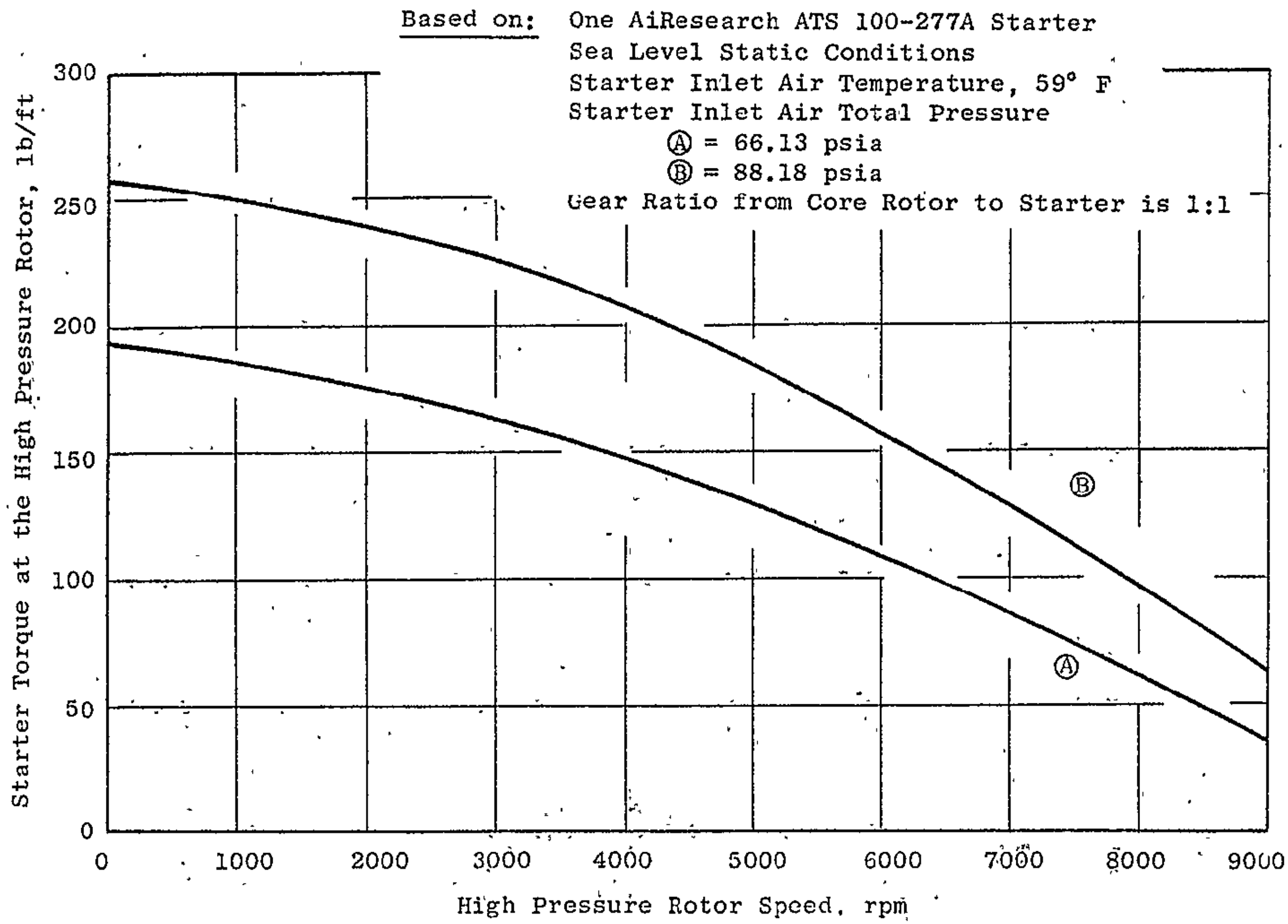


Figure 40. Expected Starter Torque for QCSEE Development Engine.

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 even to 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.

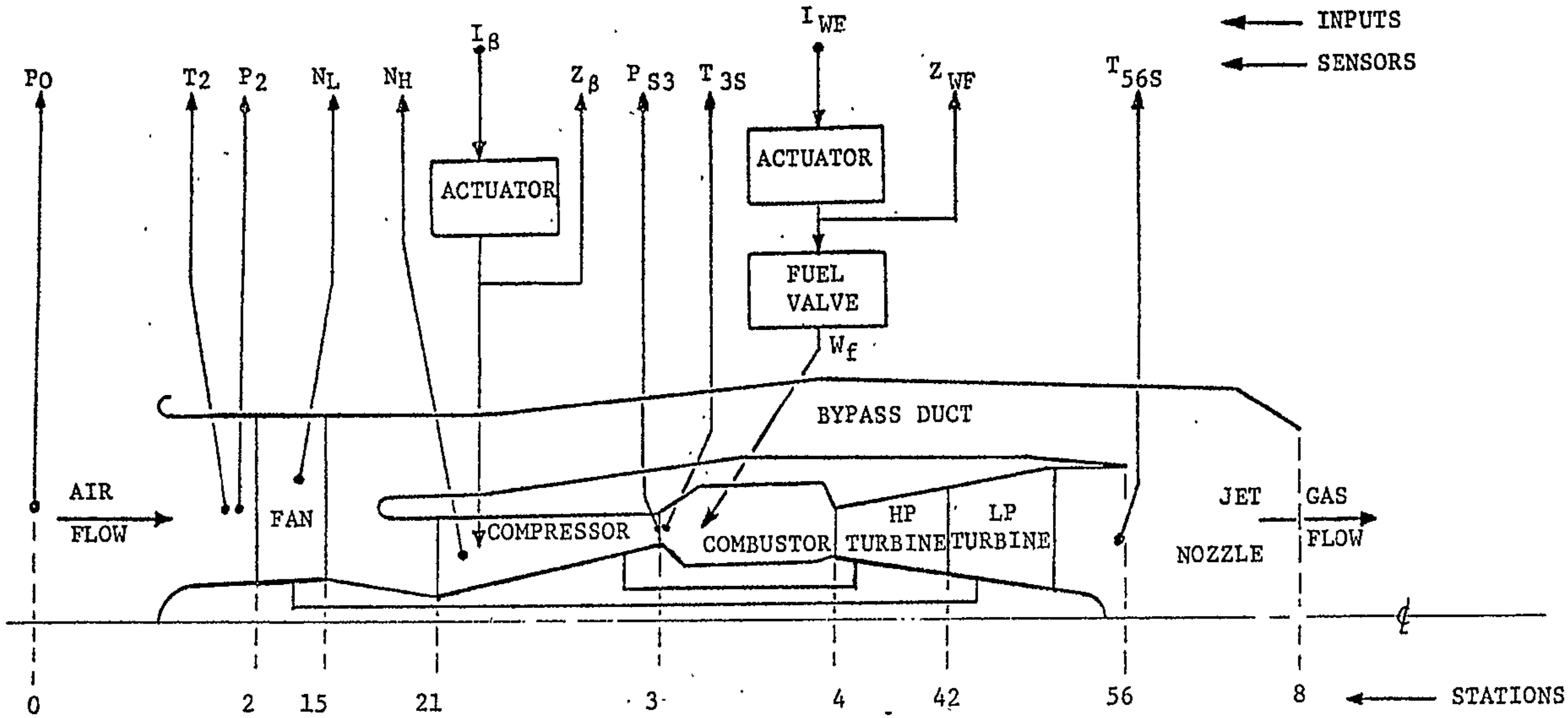


Figure 41. QCSEE Engine Schematic - Stations, Inputs, and Sensors.

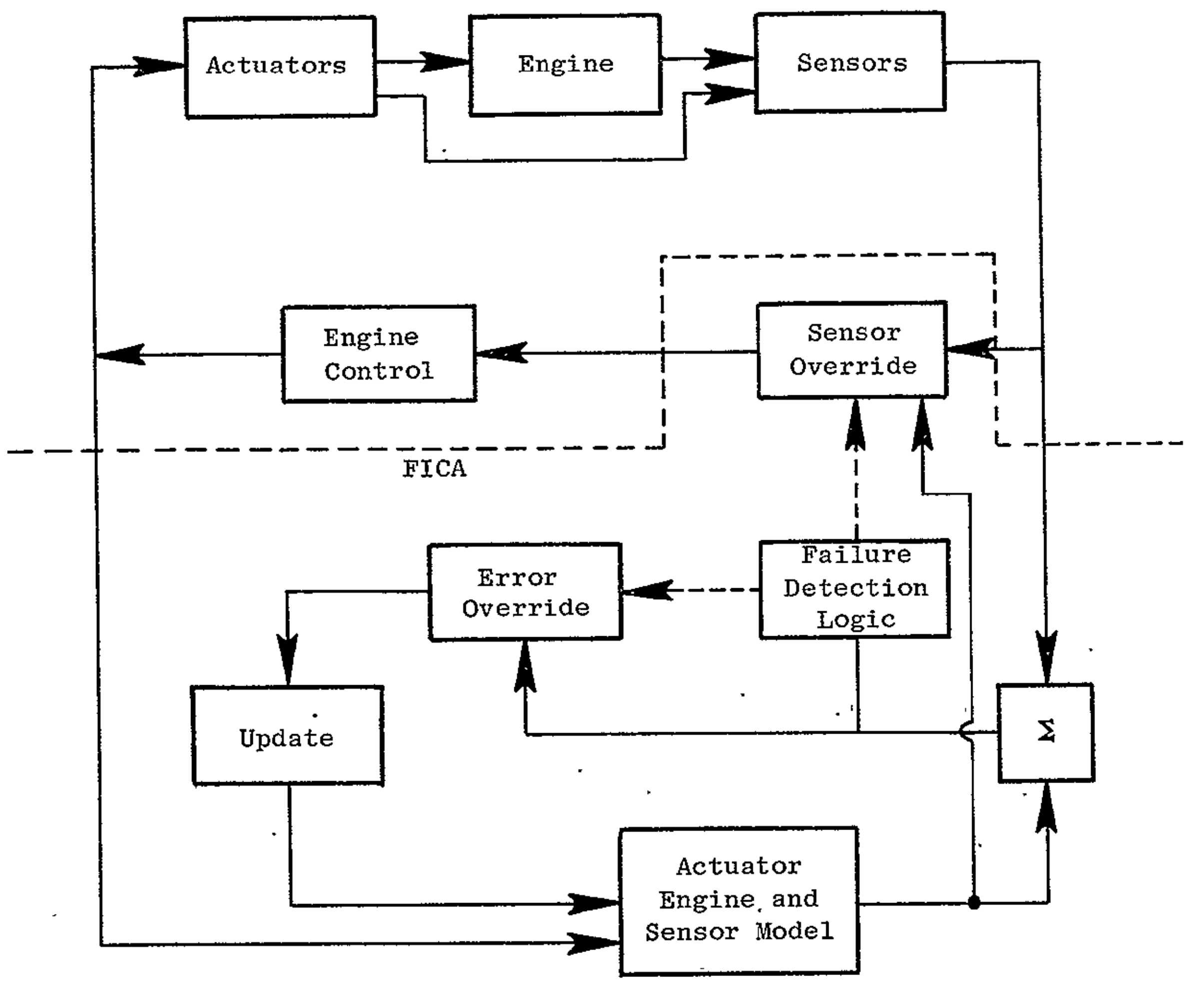


Figure 42. Block Diagram of the FICA Strategy.

C-2

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 inidicating 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:

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

and the temperature rise across the fan is:

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

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

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

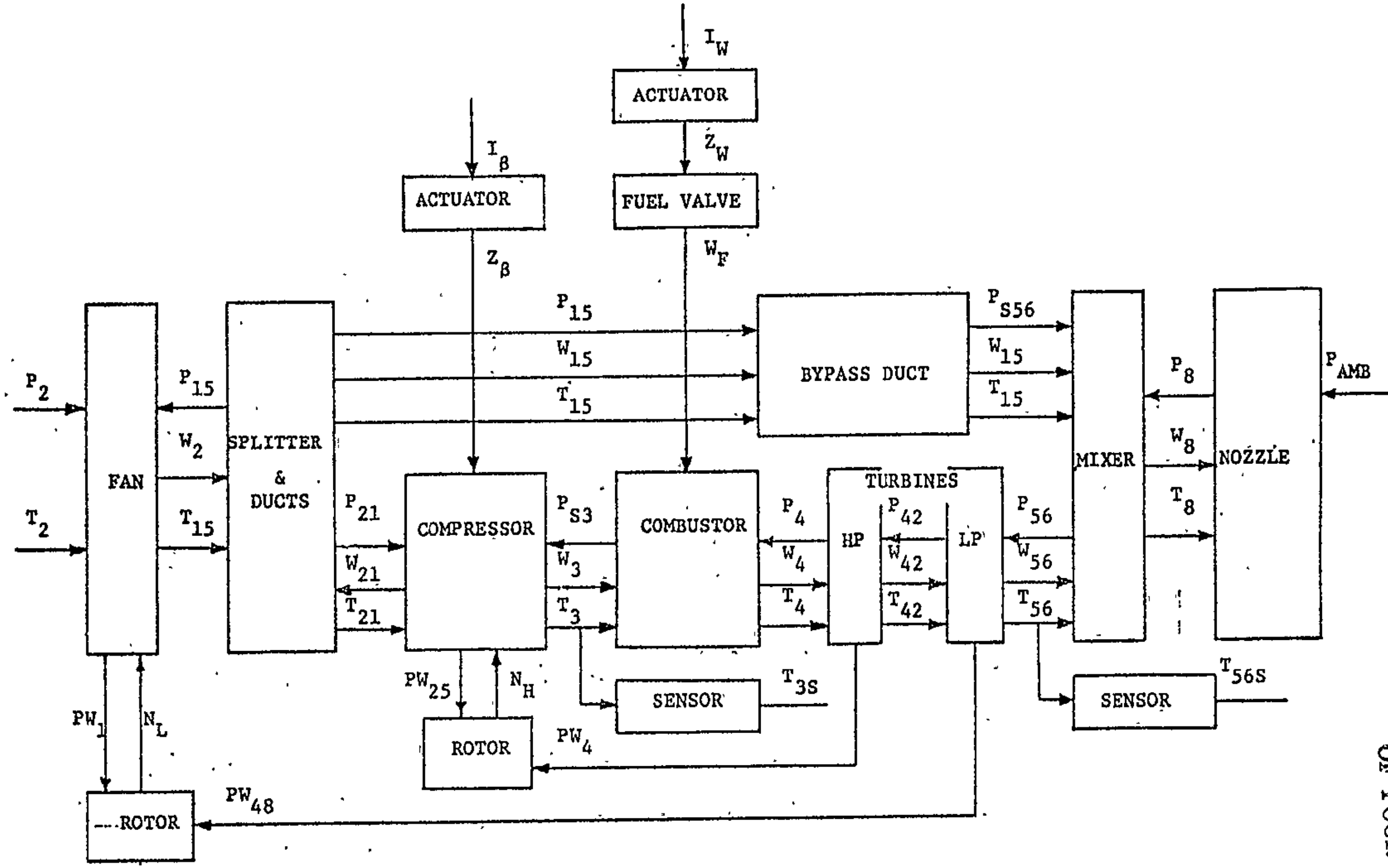


Figure 43. Block Diagram of Engine Model Computation.

ORIGINAL PAGE IS OF POOR QUALITY

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

The high pressure compressor air flow is:

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

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

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

The combustor inlet air flow is:

$$W_3 = C_W \cdot W_{21} \tag{7}$$

where C_W is a constant.

The combustor temperature rise depends on fuel air ratio:

$$T_4 = T_3 + f_c\ (W_F/W_3) \tag{8}$$

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

$$W_4 = W_3 + W_F \tag{9}$$

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

$$P_4 = C_{TN} \cdot W_4 \cdot \sqrt{T_4} \tag{10}$$

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

$$P_{S3} = C_{BL} \cdot P_4 \tag{11}$$

The fuel flow is a function of the metering valve position

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

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

$$W_{15} = W_2 - W_{21} \tag{13}$$

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.

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

$$W_{56} = W_{21} + W_f \tag{15}$$

The stagnation at the turbine discharge is

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

The inter turbine pressure and temperature are

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

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

The low pressure turbine exit temperature is

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

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

$$W_8 = W_2 + W_f \tag{20}$$

The gas temperature leaving the mixer is

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

The nozzle pressure is

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

The mixer inlet static pressure is

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

The fan power is

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

and the compressor power is

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

The high and low pressure turbine powers are

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

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

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.

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

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

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

$$\dot{Z}_W = C_W \cdot I_W \tag{30}$$

$$\dot{Z}_W = C_B \cdot I_B \tag{31}$$

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

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

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

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:

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

$$y_n = g(x_n, u_n) + \varepsilon_n' \tag{35}$$

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

u_n = input to the engine

y_n = measured output

ε' is the measurement noise with $E(\varepsilon_n') = 0$ and

$$E(\varepsilon' \, \varepsilon'^T) = R_2'$$

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

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

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

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 $(0,R_,)$

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_u, between the states of the engine and the model.

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

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

For small errors:

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

$$y_n - \hat{y}_n = C\, e_n + e_n \tag{41}$$

where $e_n - e_n' + e_n''$ is Gaussian (O,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

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

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

$$P_o = E(e_o e_o^T)$$

where

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

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

$$R_y = R_2 + C P_n C^T \tag{45}$$

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

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

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

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

$$\left|y_{i,n} - y_{i,n}\right| > K_i R_{yii} \quad \text{Failure} \tag{48}$$

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. Initally, 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 failues 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 optimumn 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	P_{S3} Failed	N_L & P_{S3} Failed	N_H & P_{S3} 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_{S3} Sensor Failure.

Optimum Closed Loop		Optimum No Failure Feedback Matrix With P_{S3} Failed	Primary Engine Variables
No Failure	P_{S3} 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 detecton 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 explantion 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 transiet 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	P_{S3} Failed	Z_W Failed	N_L & P_{S3} Failed	N_H & P_{S3} Failed	N_L, P_{S3} & 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

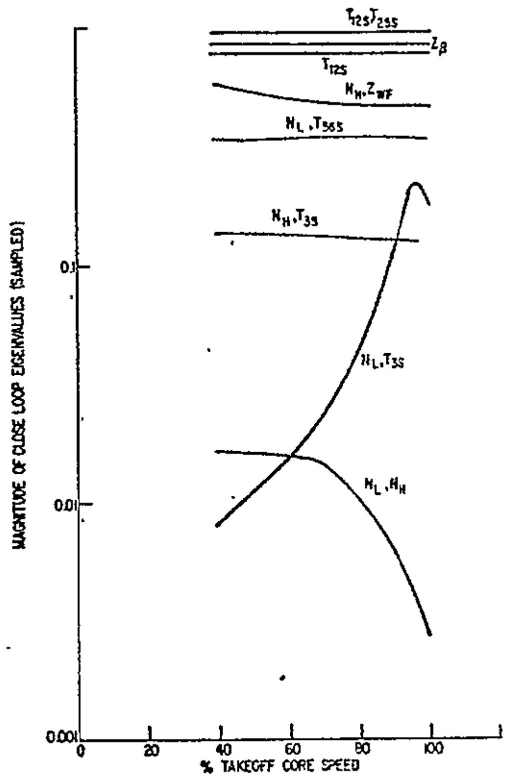


Figure 44. Closed Loop Eigenvalue Variations.

ORIGINAL PAGE IS
OF POOR QUALITY

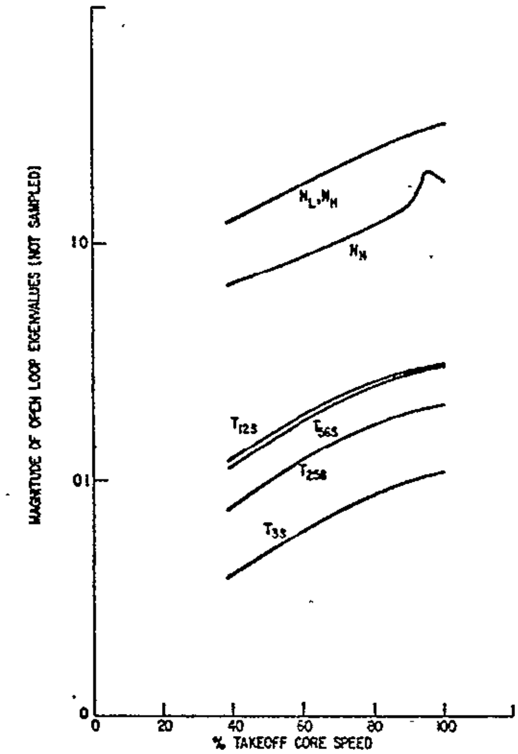


Figure 45. Open Loop Eigenvalue
Variations.

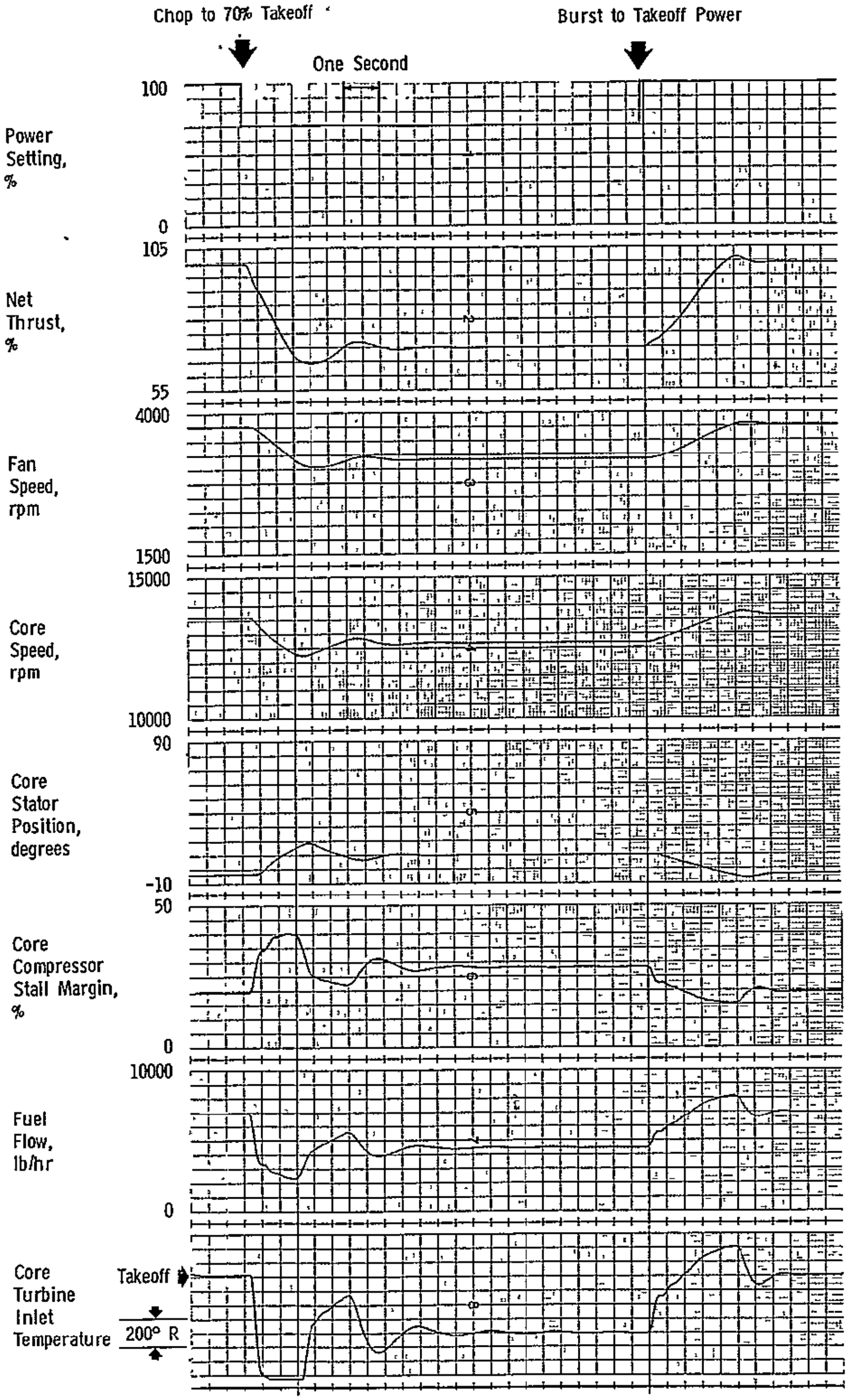


Figure 46. Computer Trace with All Sensors Functioning.

ORIGINAL PAGE IS
OF POOR QUALITY

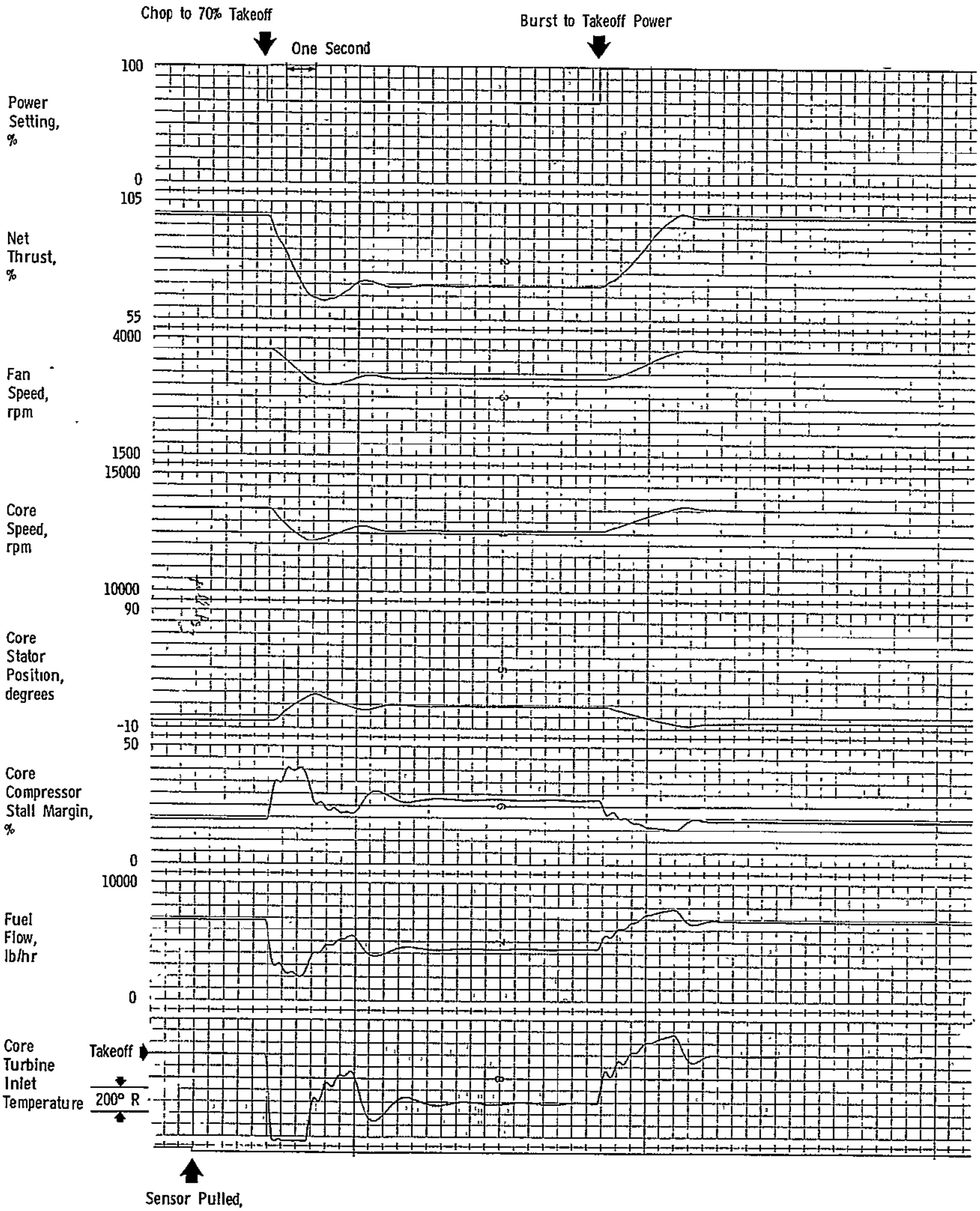


Figure 47. Computer Trace with PS3 Sensor Pulled.

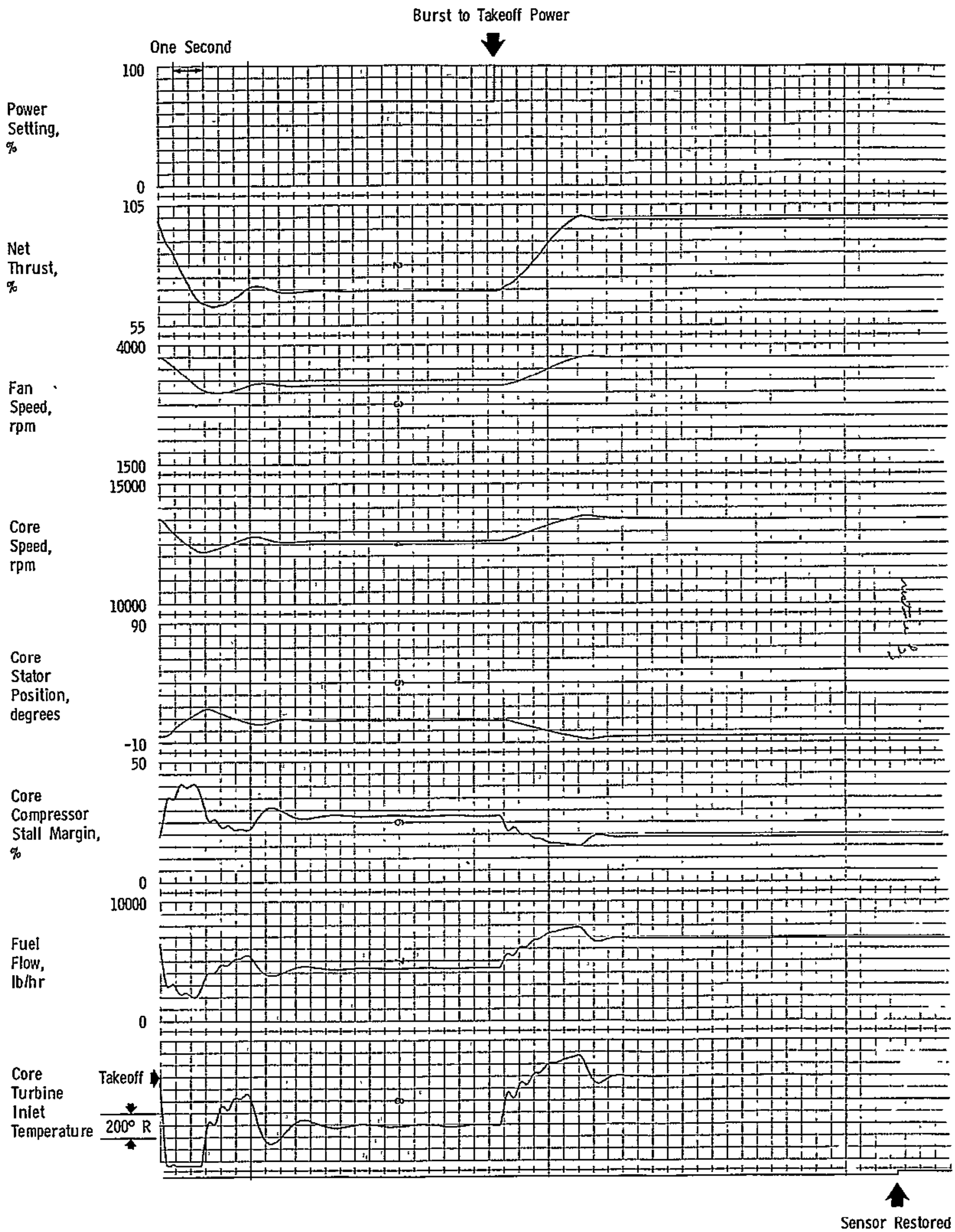


Figure 47. Computer Trace with PS3 Sensor Pulled (Concluded).

ORIGINAL PAGE IS
OF POOR QUALITY

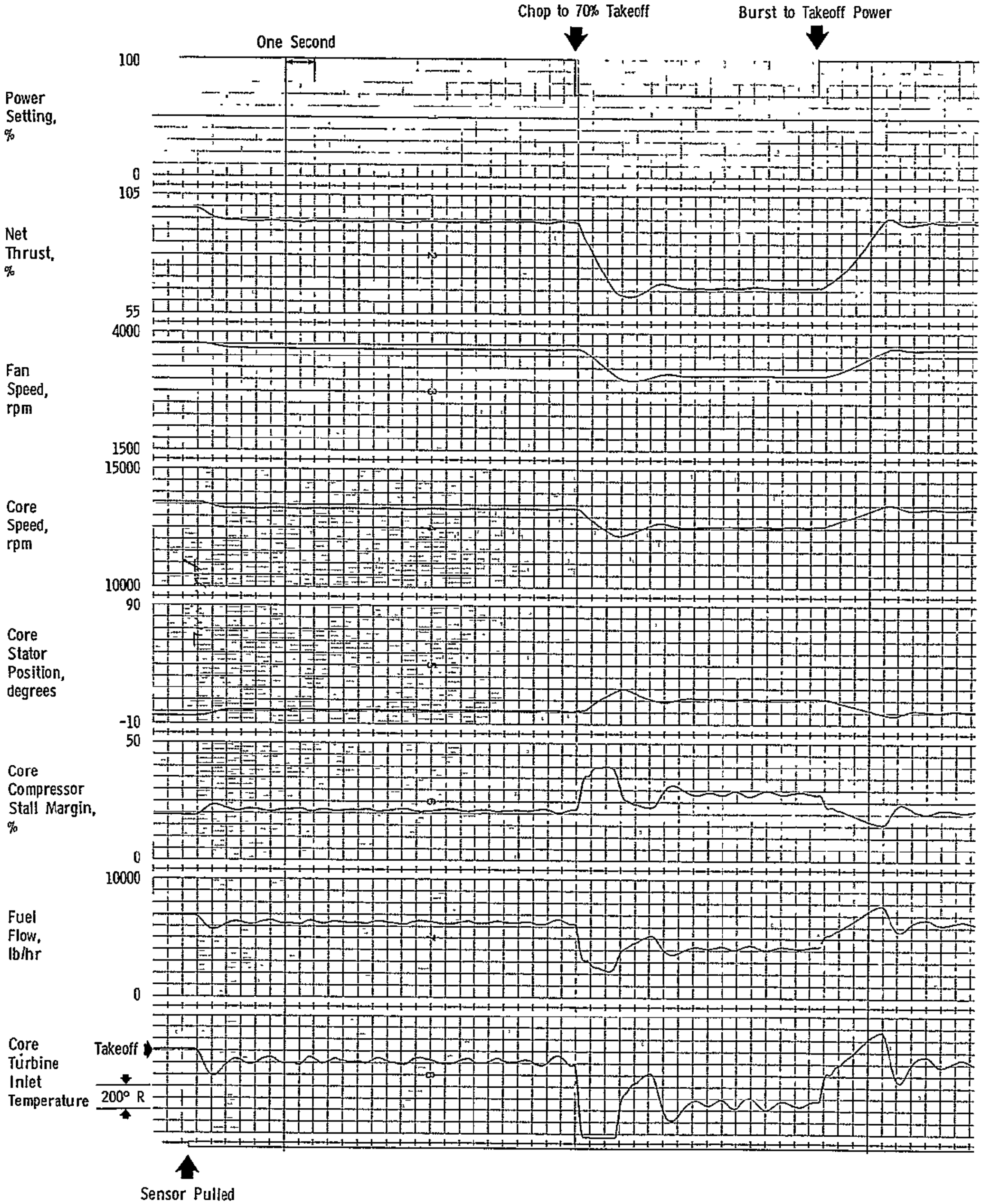


Figure 48. Computer Trace with XNL Sensor Pulled.

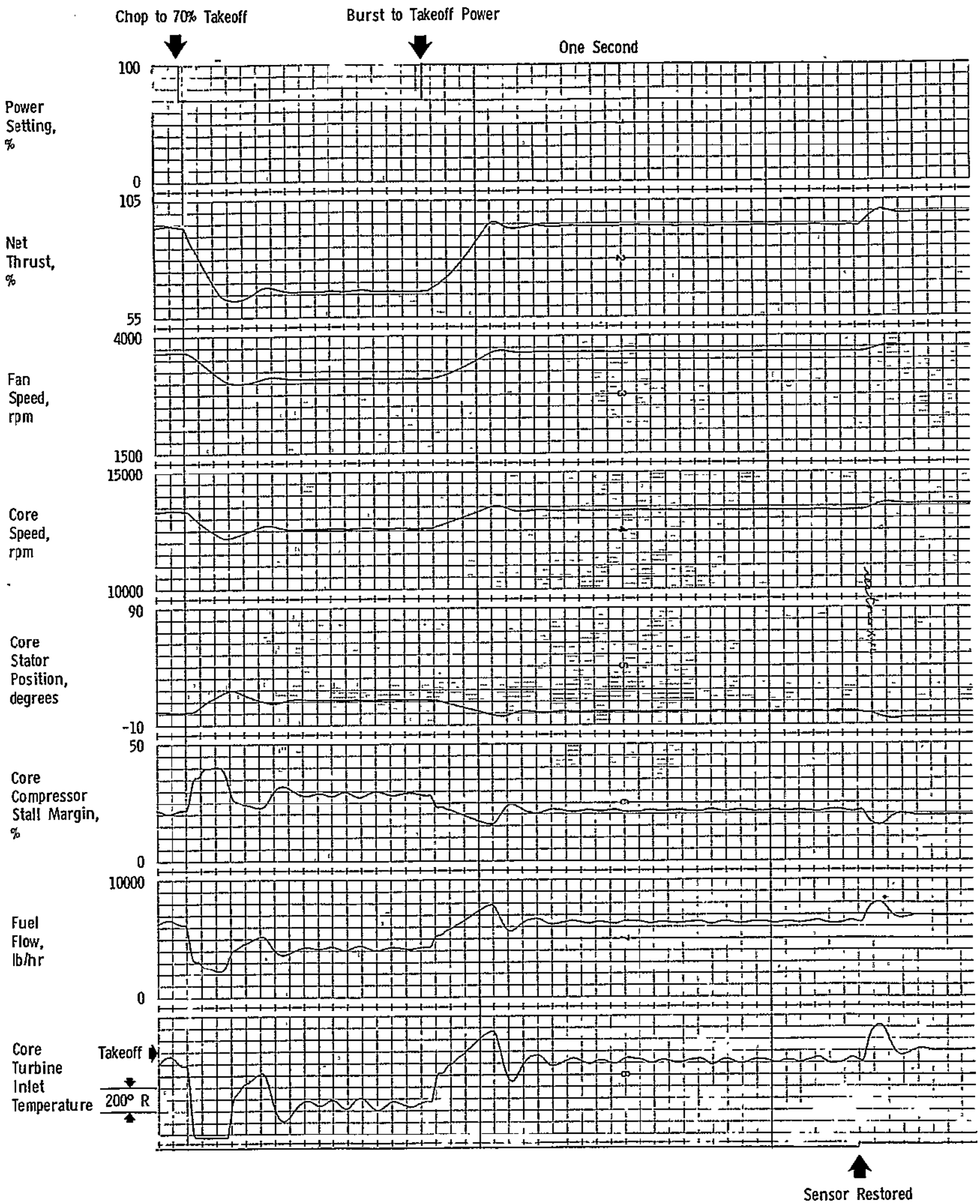


Figure 48. Computer Trace with XNL Sensor Pulled (Concluded).

ORIGINAL PAGE IS
OF POOR QUALITY

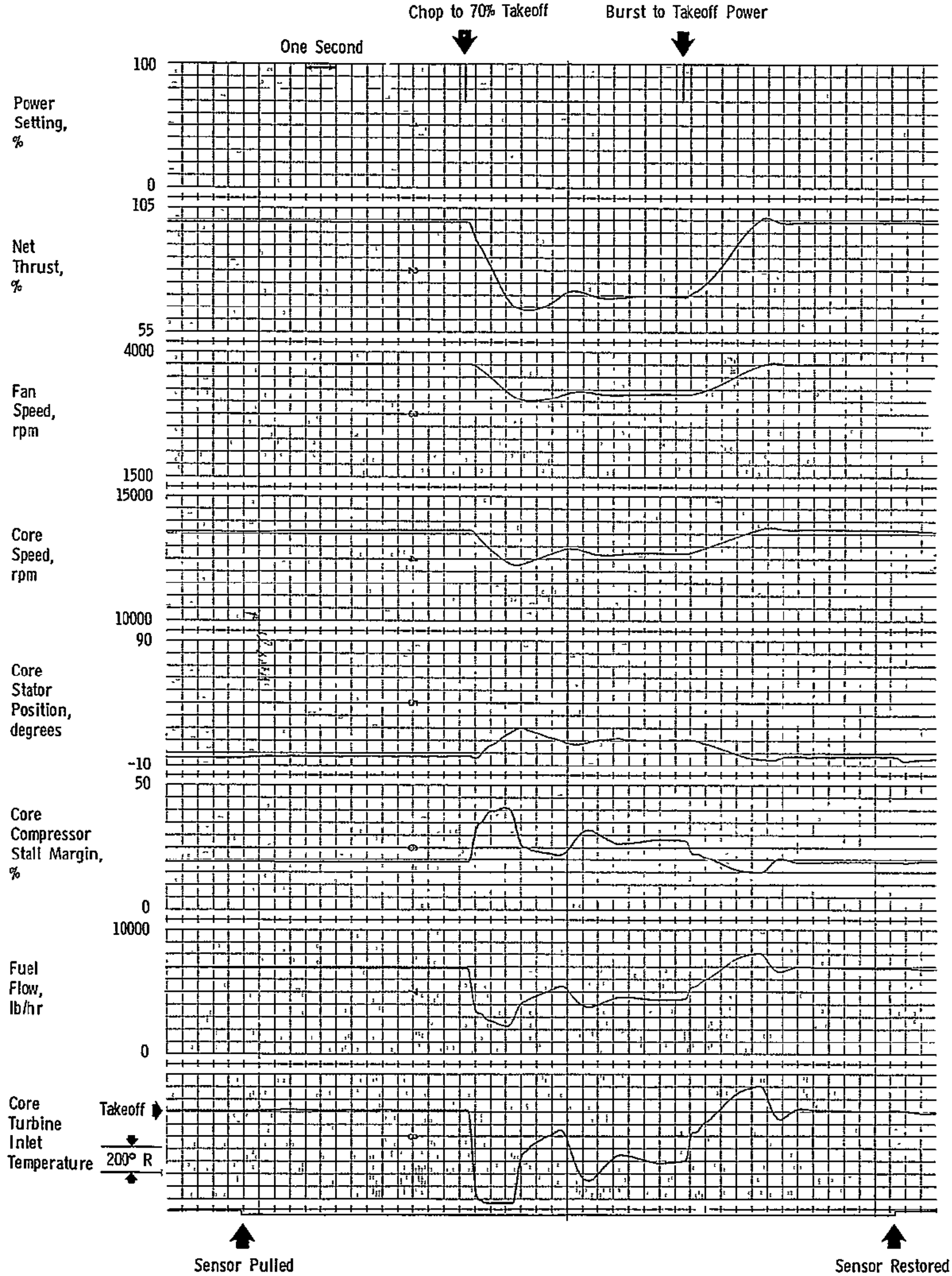


Figure 49. Computer Trace with XNH Sensor Pulled.

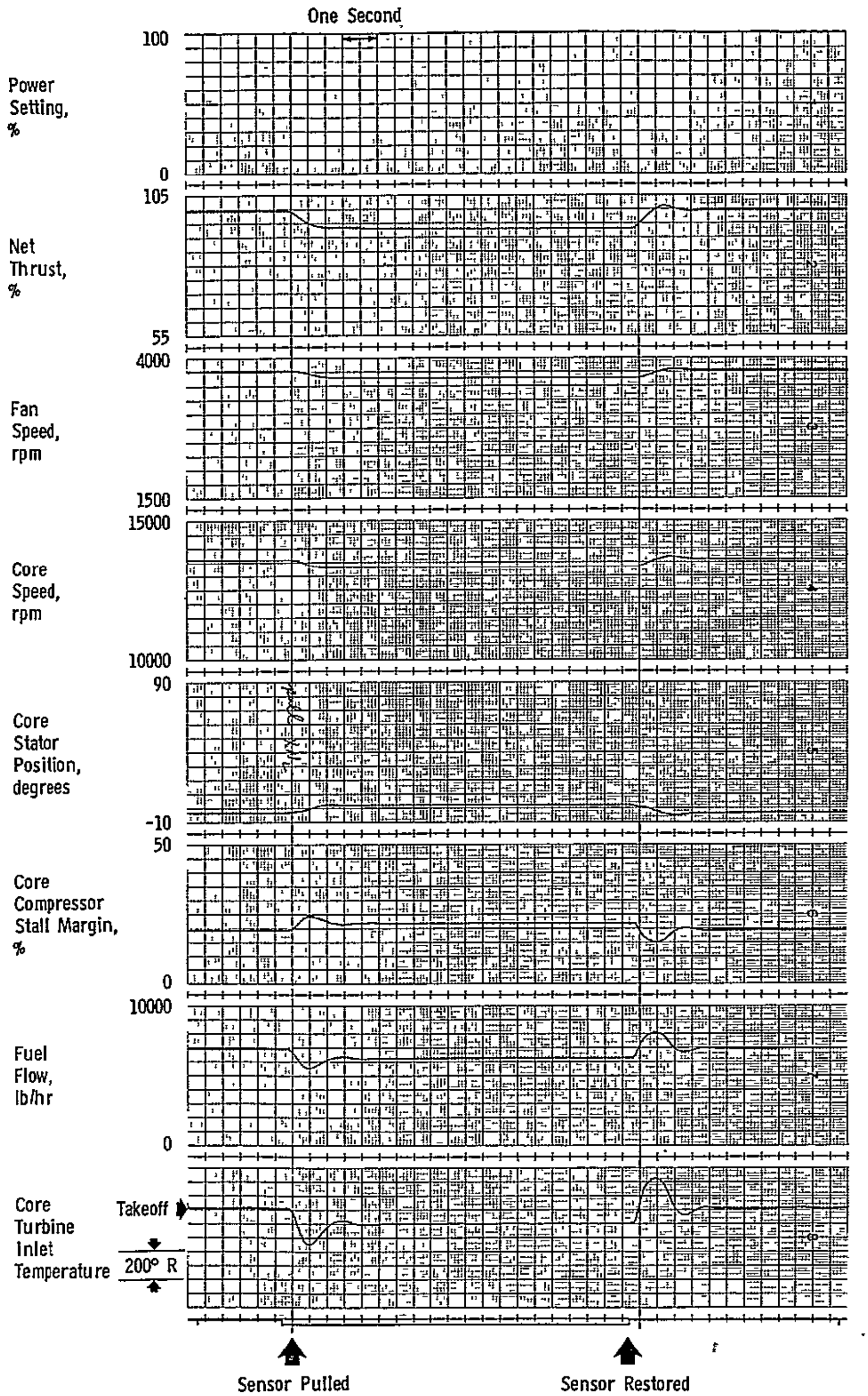


Figure 50. Computer Trace with XNL Sensor Pulled and with 16-Bit Control Computer Simulated.

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.

ORIGINAL PAGE IS
OF POOR QUALITY

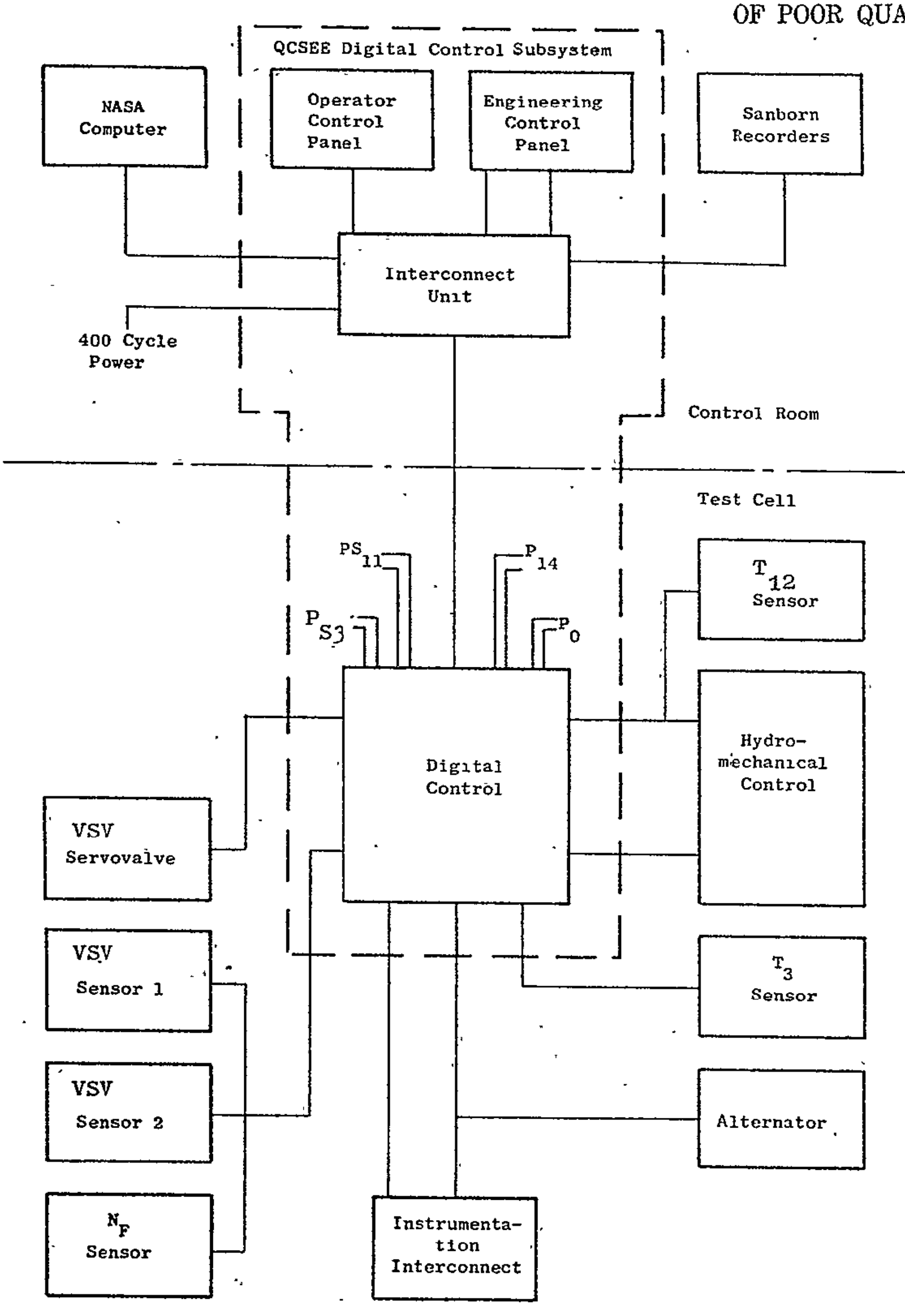


Figure 51. A Block Diagram of Digital Control System.

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

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

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 tansmit 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
A. Engine and Control Inputs	A. Torque Motors
1. Alternator - Power and Core Speed Sensing	1. WFTMC - Fuel Control
2. Primary LP Turbine Speed Signal	2. VSVTMC - Core Stator Vane Control
3. Secondary LP Turbine Speed Signal	3. ESTMC - Emergency Shutdown
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	
B. Instrumentation Inputs (0-10V)	B. LVDT Drives
1. Spare	1. MVP
2. Fuel Temperature - ° F	2. VSV 1
3. Fuel Manifold Pressure - psia	3. VSV 2
4. Exhaust Gas Temperature - ° F	4. PLA
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	
C. Operator Inputs	C. Other Inputs
Multiplex Digital Signals	1. T12 Sensor Excitation
Ability to Receive Any Number	2. LPT Speed Indication
	3. Multiplex Digital Data Link Transmit any number of data words

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME 2

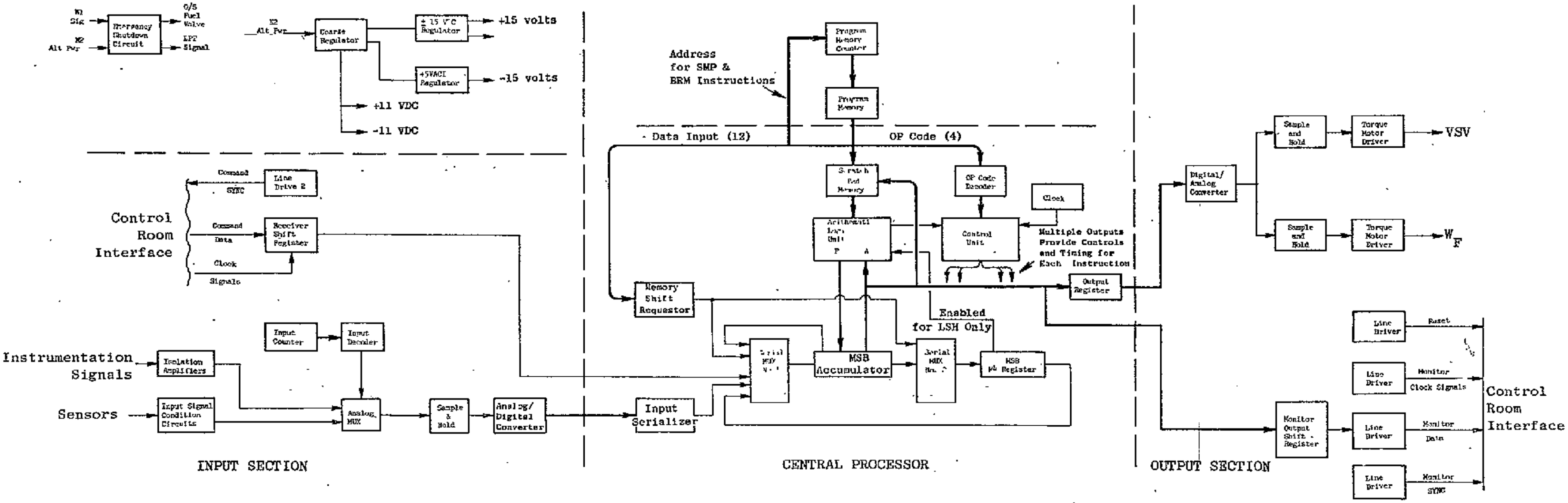


Figure 52. Digital Control Block Diagram.

PRECEDING PAGE BLANK NOT FILMED

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 compromised 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.

PRECEDING PAGE BLANK NOT FILMED.

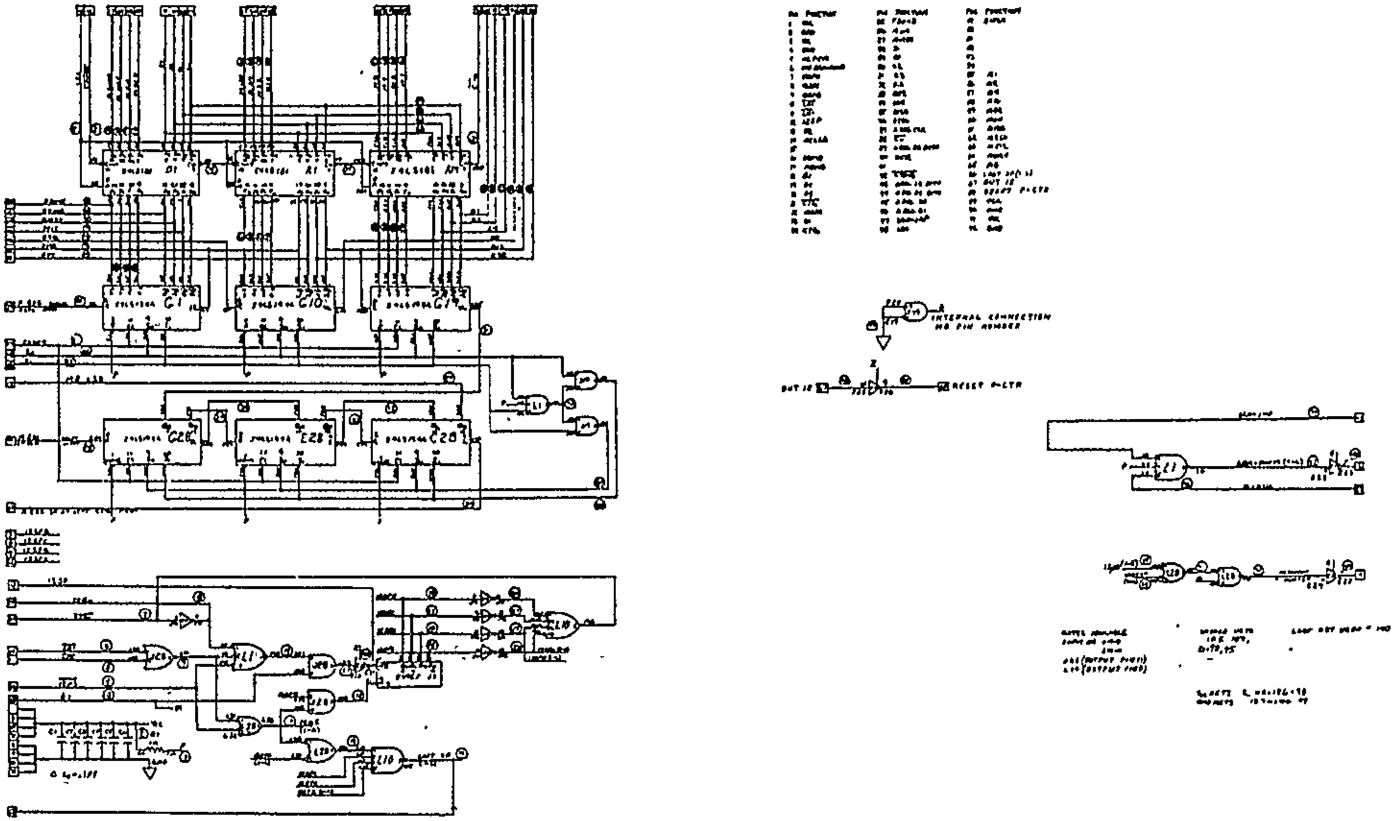


Figure 53. QCSEE Digital Control Arithmetic Elements.

ORIGINAL PAGE IS
OF POOR QUALITY

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	$F = \overline{A}$	$F = \overline{A}$
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	$F = A\overline{B}$ minus 1	$F = A+\overline{B}$	L	L	H	L	$F = \overline{A}+B$	$F = \overline{A}B$
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 $(A+\overline{B})$	F = A plus $A\overline{B}$	L	H	L	L	$F = \overline{A+B}$	$F = \overline{AB}$
L	H	L	H	F = AB plus $(A+\overline{B})$	F = (A+B) plus $A\overline{B}$	L	H	L	H	$F = \overline{B}$	$F = \overline{B}$
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	$F = A+\overline{B}$	$F = A\overline{B}$ minus 1	L	H	H	H	$F = A+\overline{B}$	$F = A\overline{B}$
H	L	L	L	F = A plus (A+B)	F = A plus AB	H	L	L	L	$F = \overline{A}B$	$F = \overline{A}+B$
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	$F = A\overline{B}$ plus (A+B)	$F = (A+\overline{B})$ plus AB	H	L	H	L	F = B	F = B
H	L	H	H	F = A+B	F = AB 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	$F = A\overline{B}$	$F = A+\overline{B}$
H	H	H	L	$F = A\overline{B}$ 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 24μs 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 require to ensure that 24μs 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 Ø - 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 Ø 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.

<u>ADD</u> - 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 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 12μs 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 instrution 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 substraction 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.

ORIGINAL PAGE IS
OF POOR QUALITY

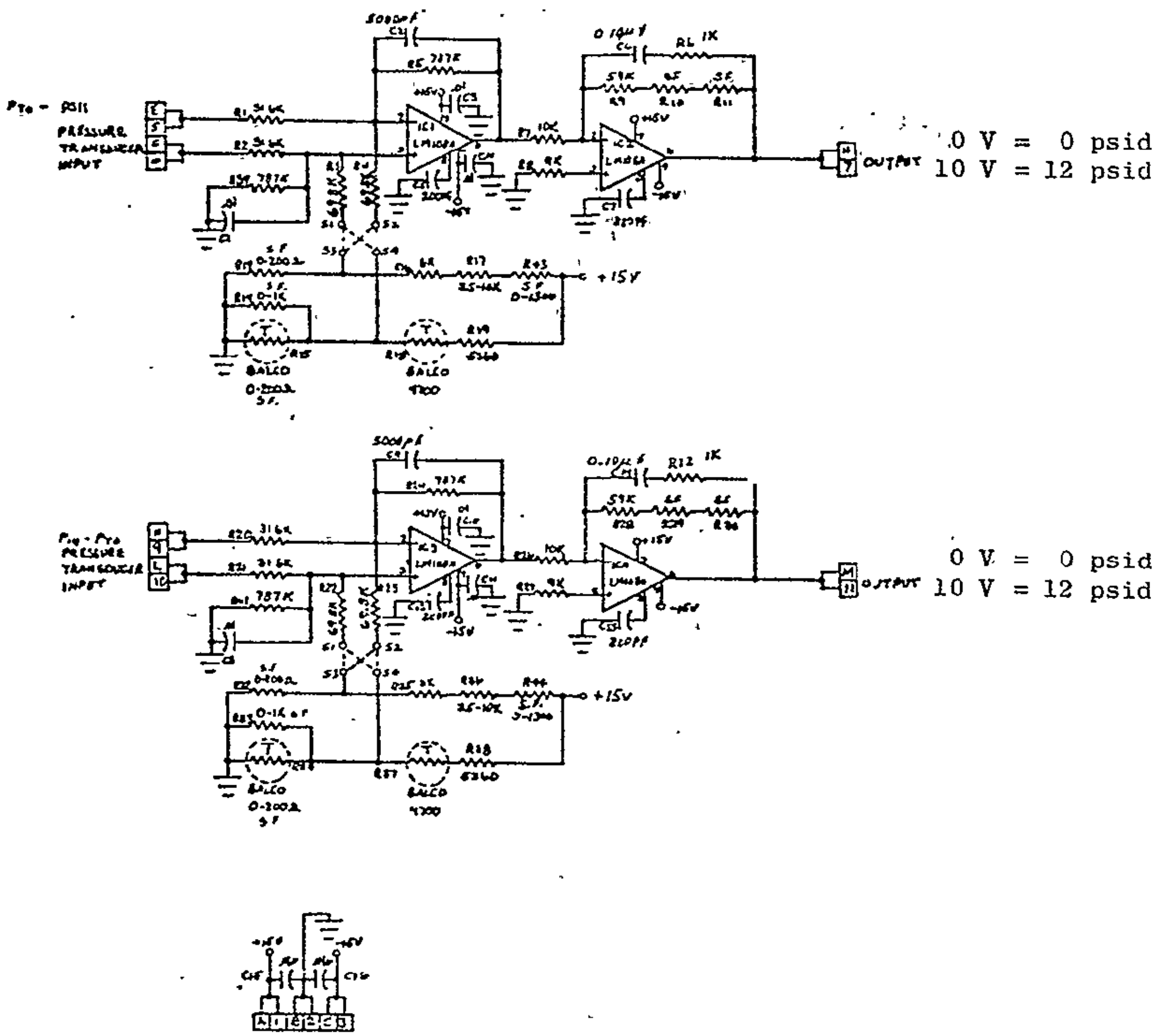


Figure 54. Typical Analog Circuit.

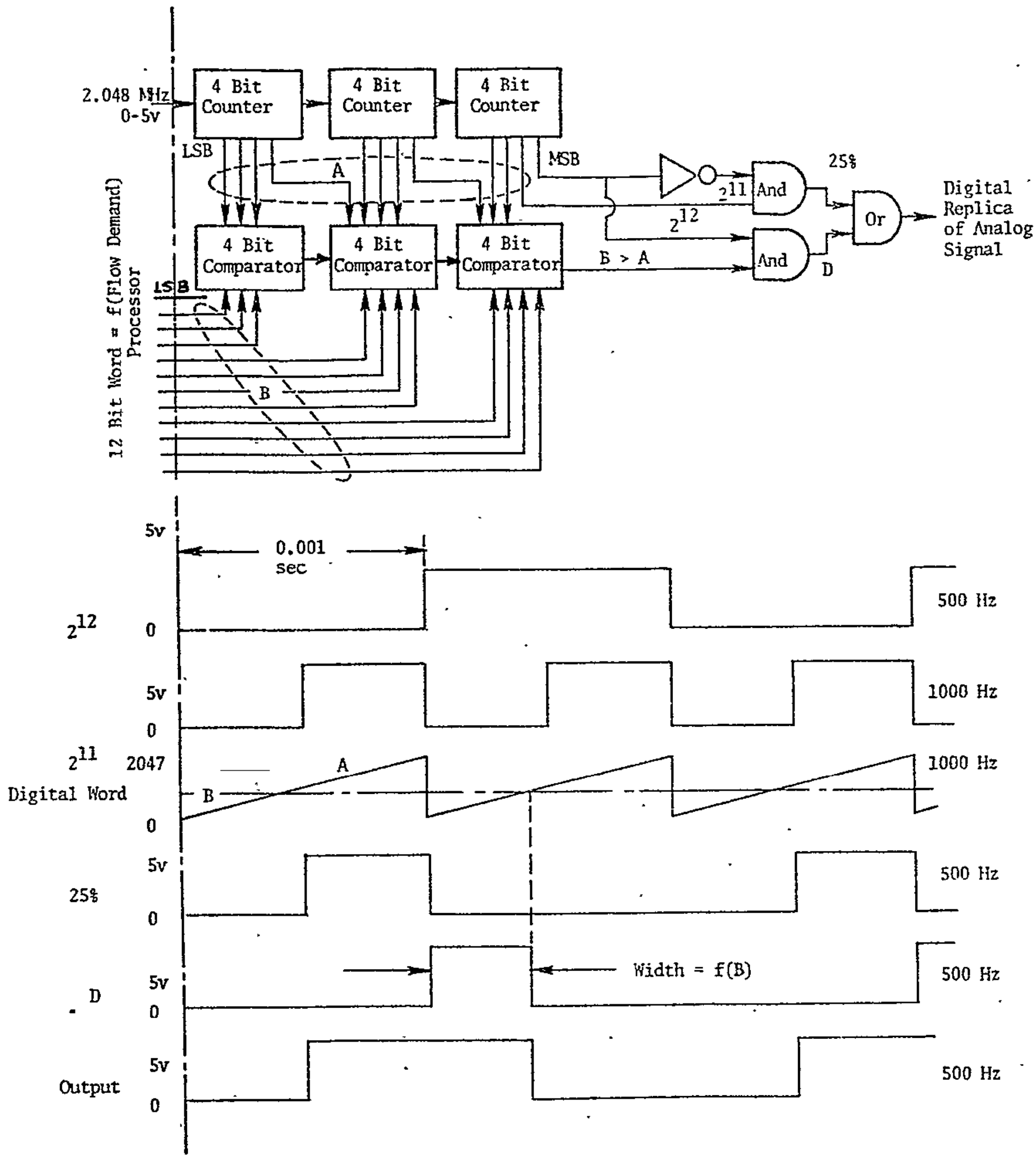


Figure 55. Digital Driver Amplifier for Fail-Fixed Servovalve.

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

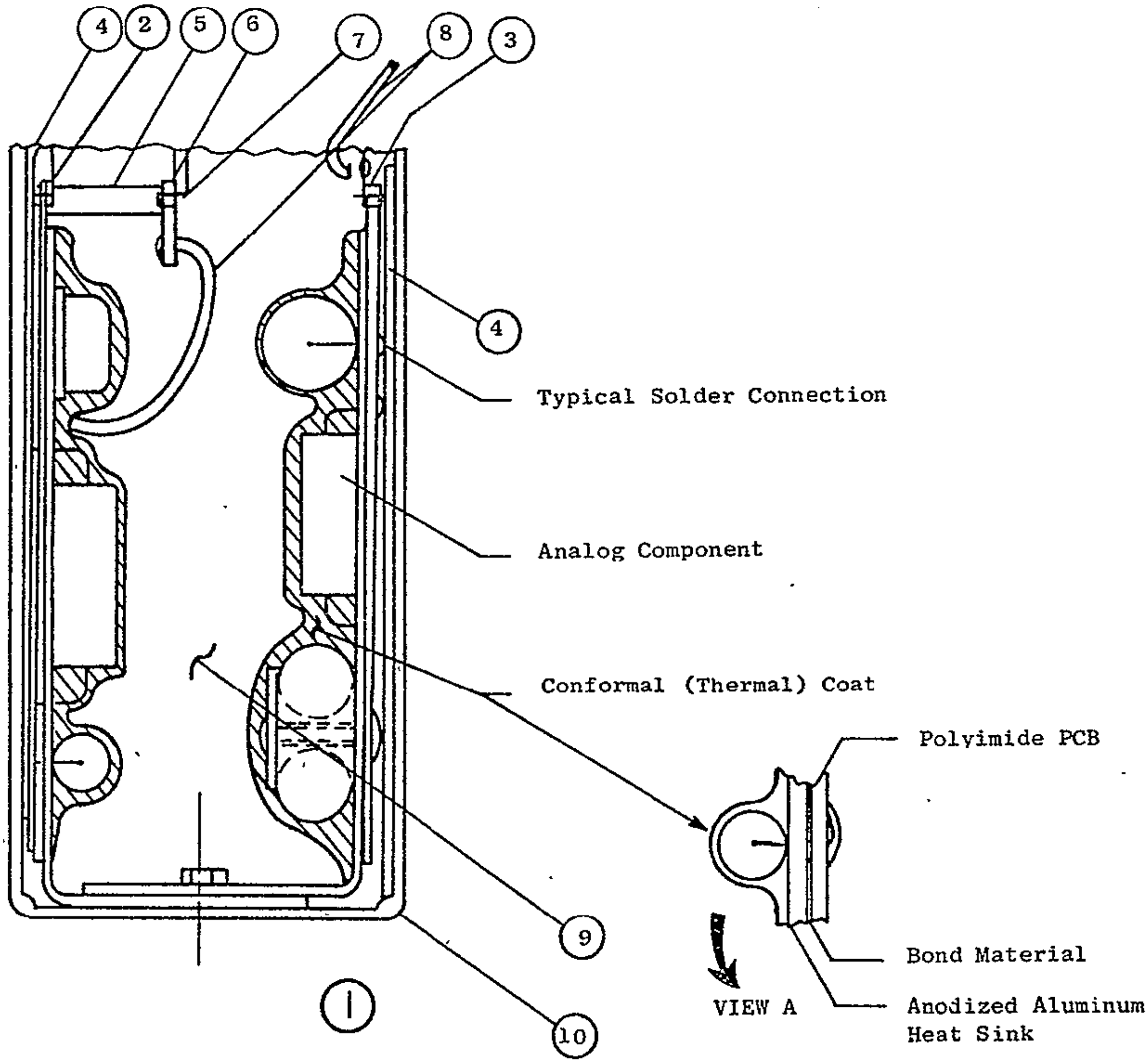
An analog module consists of electrical analog components mounted to printed circuit boards (PCB's). A typical analog module requires two PCB's. All QCSEE analog PCB's utilizes a 2 oz., double-sided copper, 0.079-cm (0.031-in.)-thick polyimide boards bonded to an anodized heat sink made from aluminum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

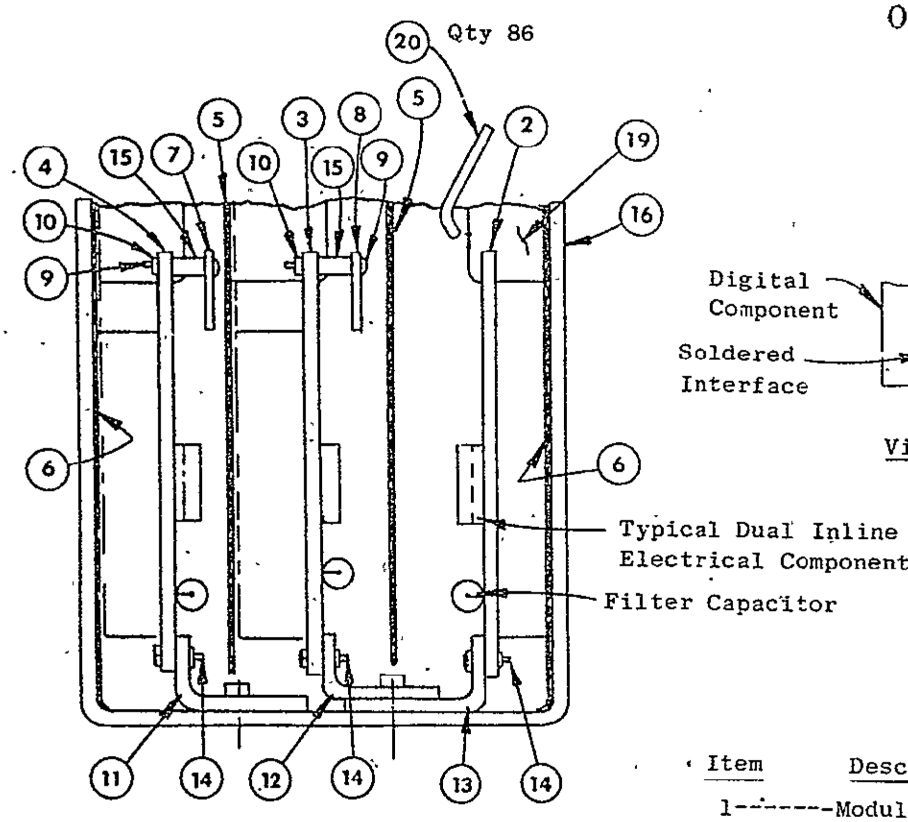


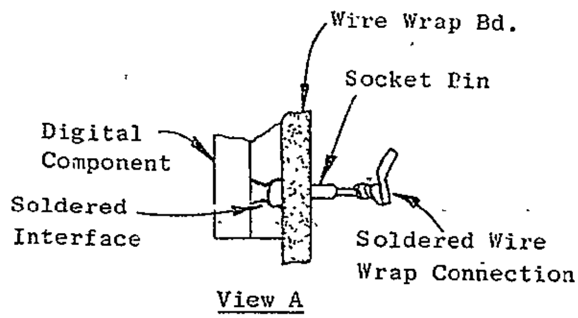
Item

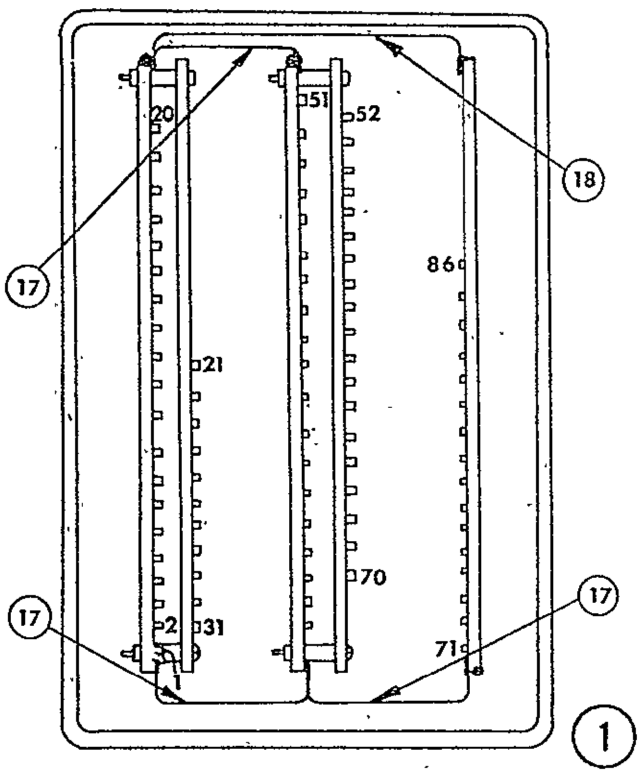
1------------------------ Typical Module Assembly
2------------------------ Printed Wiring Bd. Assy.
3------------------------ Printed Wiring Bd. Assy.
4------------------------ Insulator (Electrical)
5------------------------ Satellite Bd. Spacer
6------------------------ Satellite Bd.
7------------------------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

Figure 56. Typical Analog Module.

ORIGINAL PAGE IS
OF POOR QUALITY







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.

ORIGINAL PAGE IS
OF POOR QUALITY

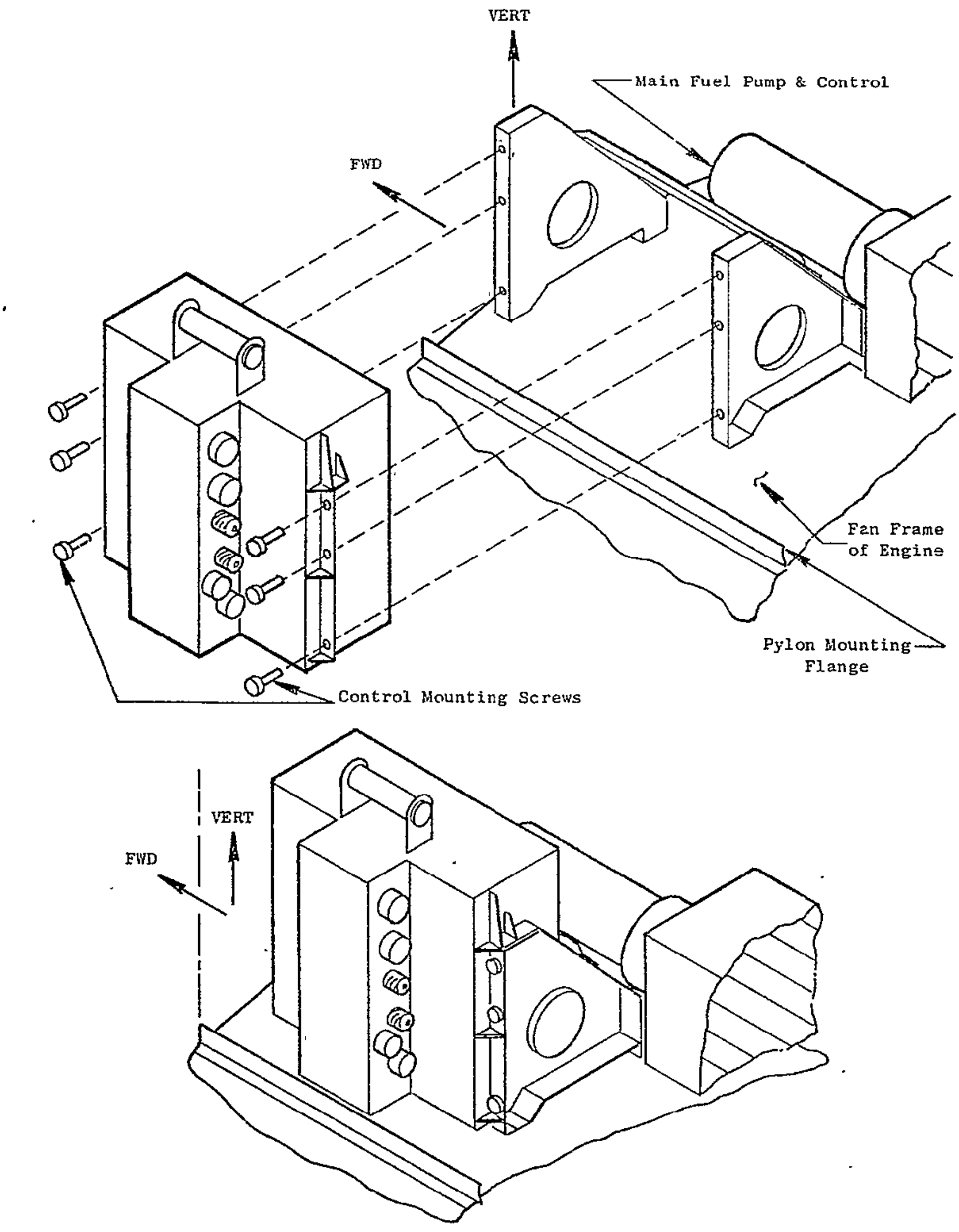


Figure 58. Digital Control Installation.

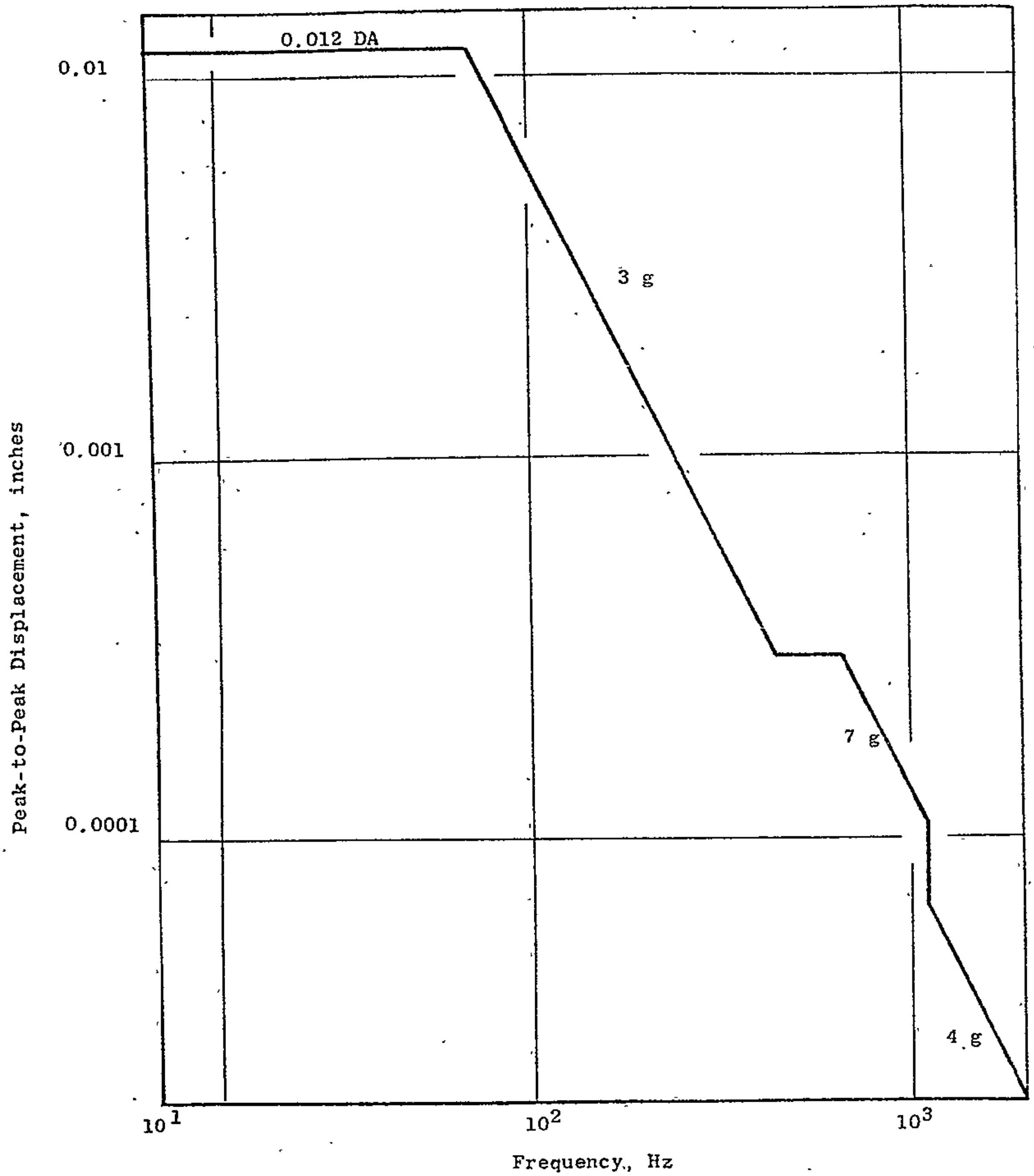


Figure 59. Vibration Testing.

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 airscoop 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.

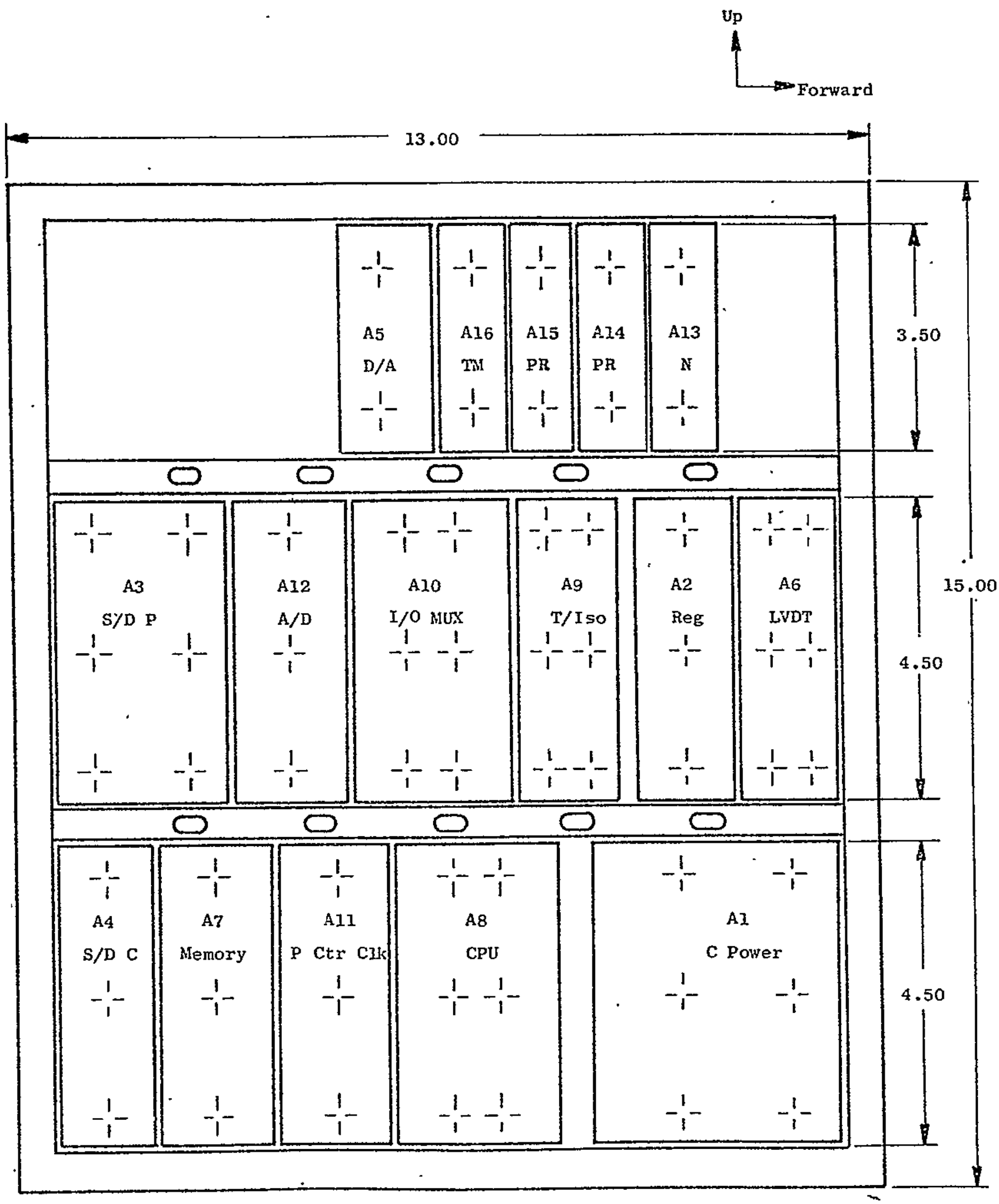
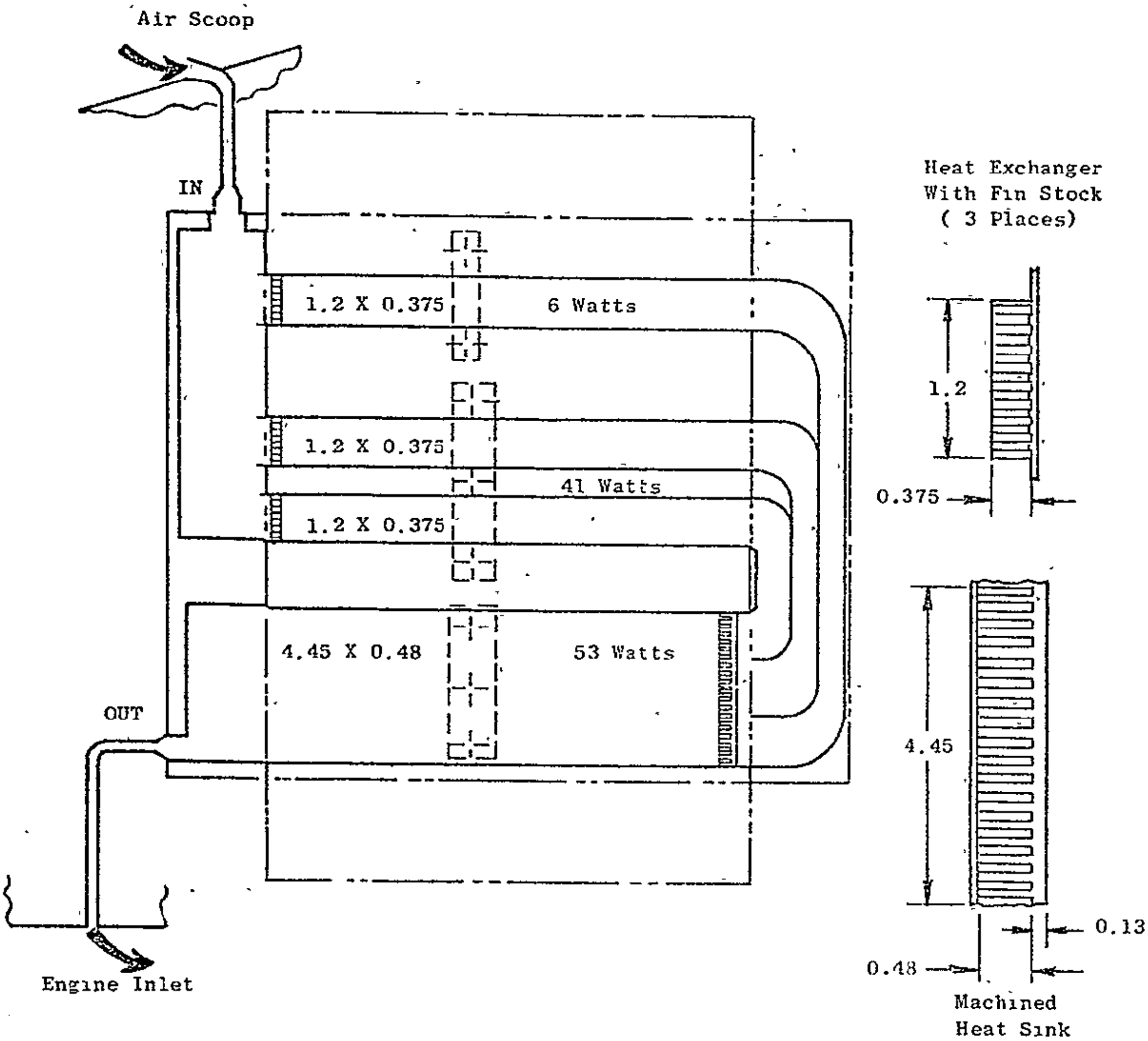


Figure 60. Module Arrangement Digital Control.

ORIGINAL PAGE IS
OF POOR QUALITY



Minimum Pressure Drop..........0.288 psid
Minimum Flow Rate..............0.026 lbm/sec
Estimated Maximum ΔT...........43° 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 Ø 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.

Line No	Mnemonic	Comment	Min Value	Max Value
	(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 Ø	Subtract zero (stored in Ø)		
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		

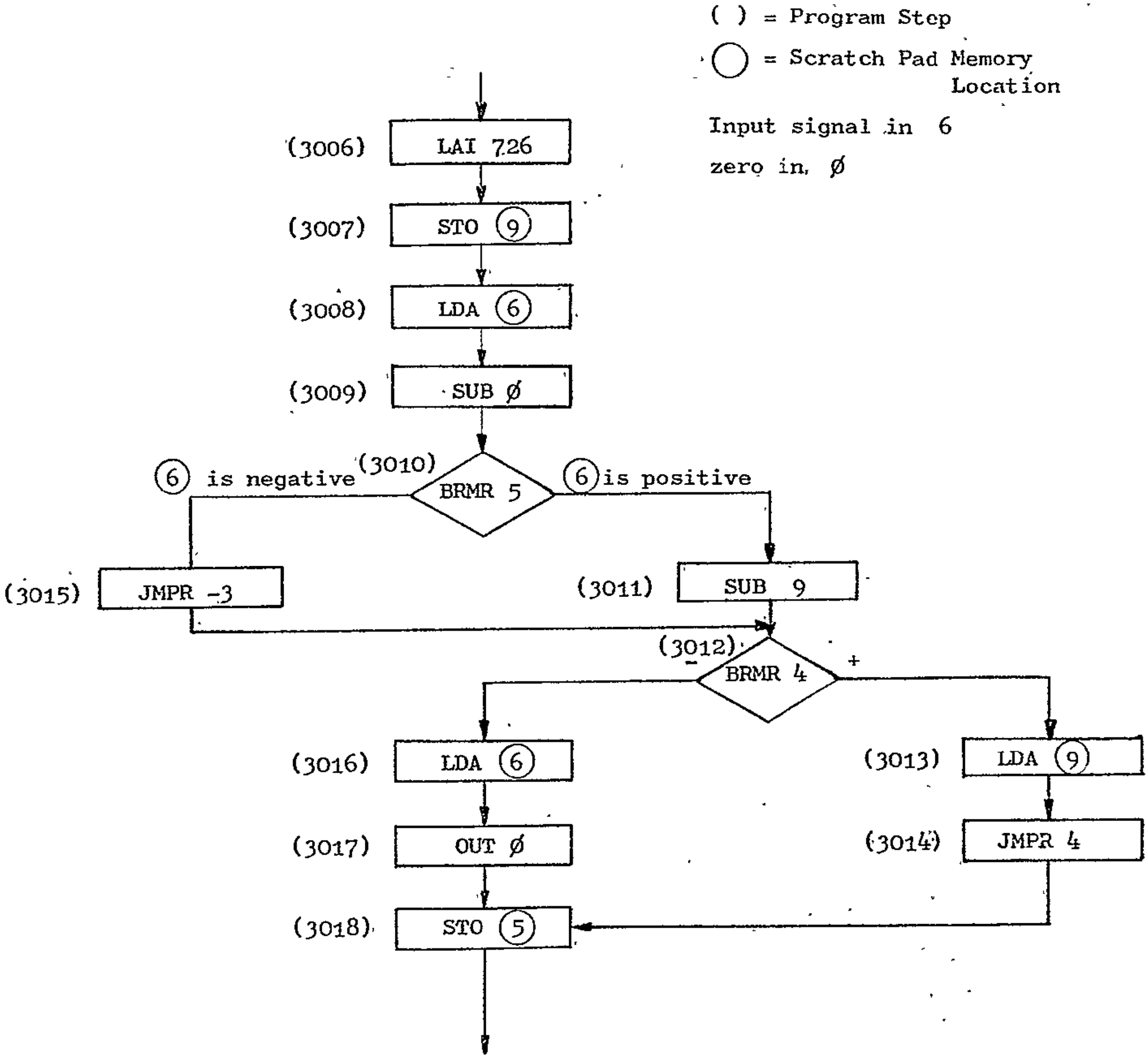
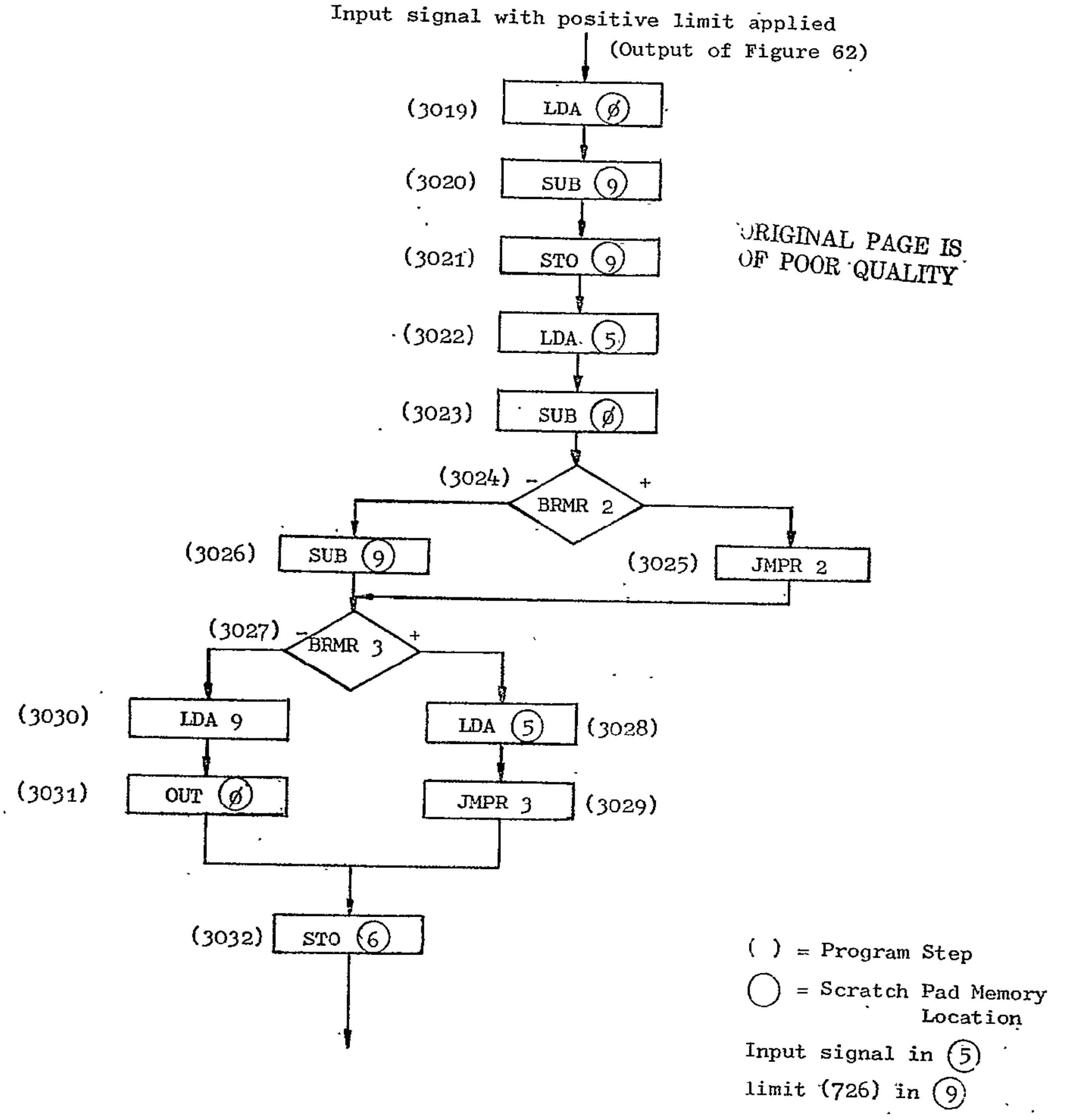


Figure 62. Flow Chart of Positive Limit Check in Fuel Flow Channel.



ORIGINAL PAGE IS OF POOR QUALITY

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

Line No	Mnemonic	Comment	Min Value	Max Value
	(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 Ø	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 Ø	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 Ø	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 Ø	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:

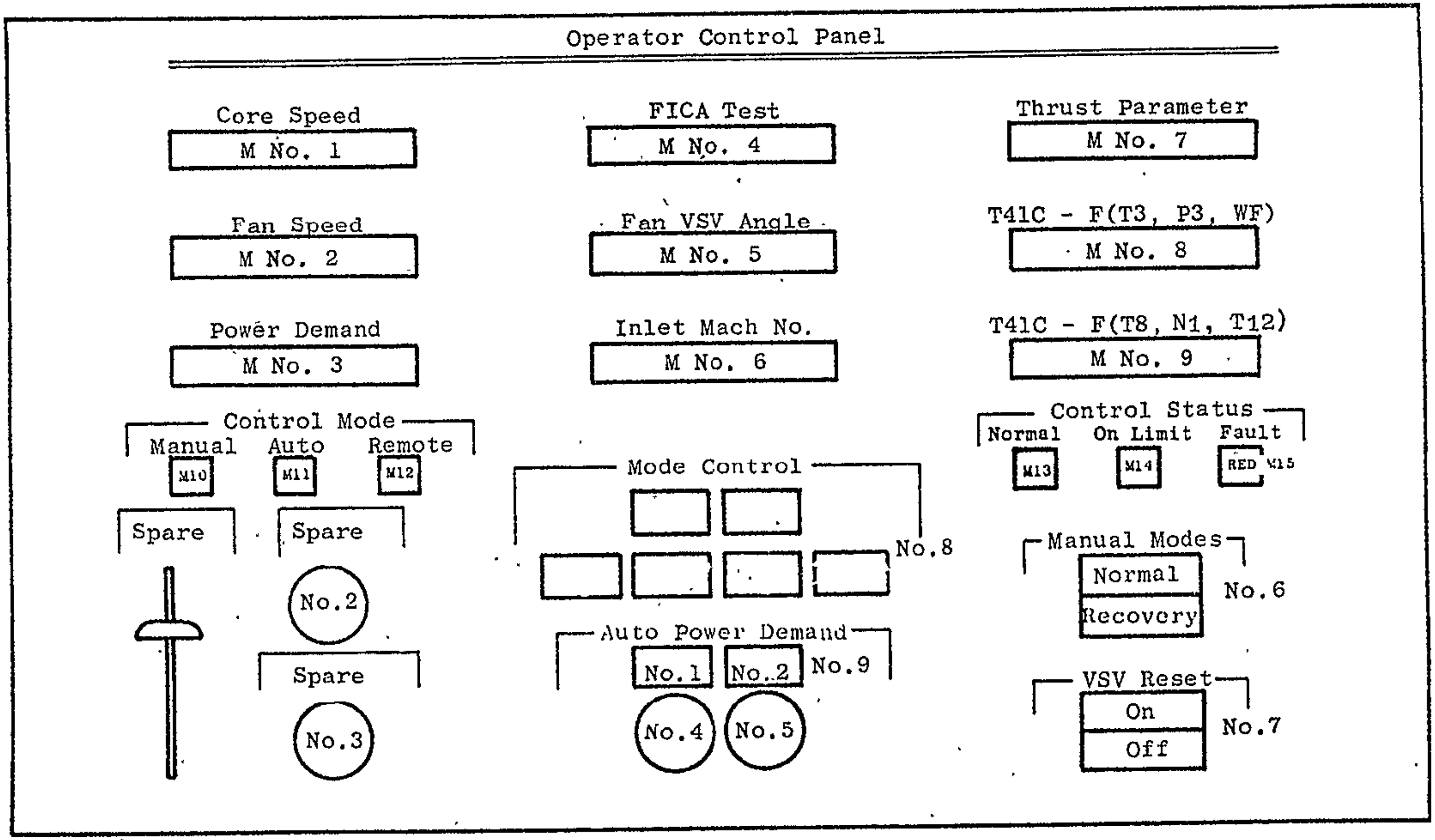


Figure 64. Operator Control Panel.

- 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 pushbuttons 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 x $10^3 m^3$/sec (42.8 gpm) at 107.2° C (225° F)	2.7 x $10^{-3} m^3$/sec (42.8 gpm) at 107.2° C)225° F)
Rated ΔP at Rated Flow	2.76 x $10^5 N/m^2$ (40 psi) min.	≈6.65 x $10^6 N/m^2$ (≈964 psia)
Rated Inlet Pressure at Rated flow and Speed	3.45 x $10^5 N/m^2$ (50 psia)	6.21 x $10^5 N/m^2$ (90 psia)
Power Loss at Rated Speed	1.49 x 10^3 W (2 hp) max.	Overall Efficiency = 0.72 at Design Point

ORIGINAL PAGE IS
OF POOR QUALITY

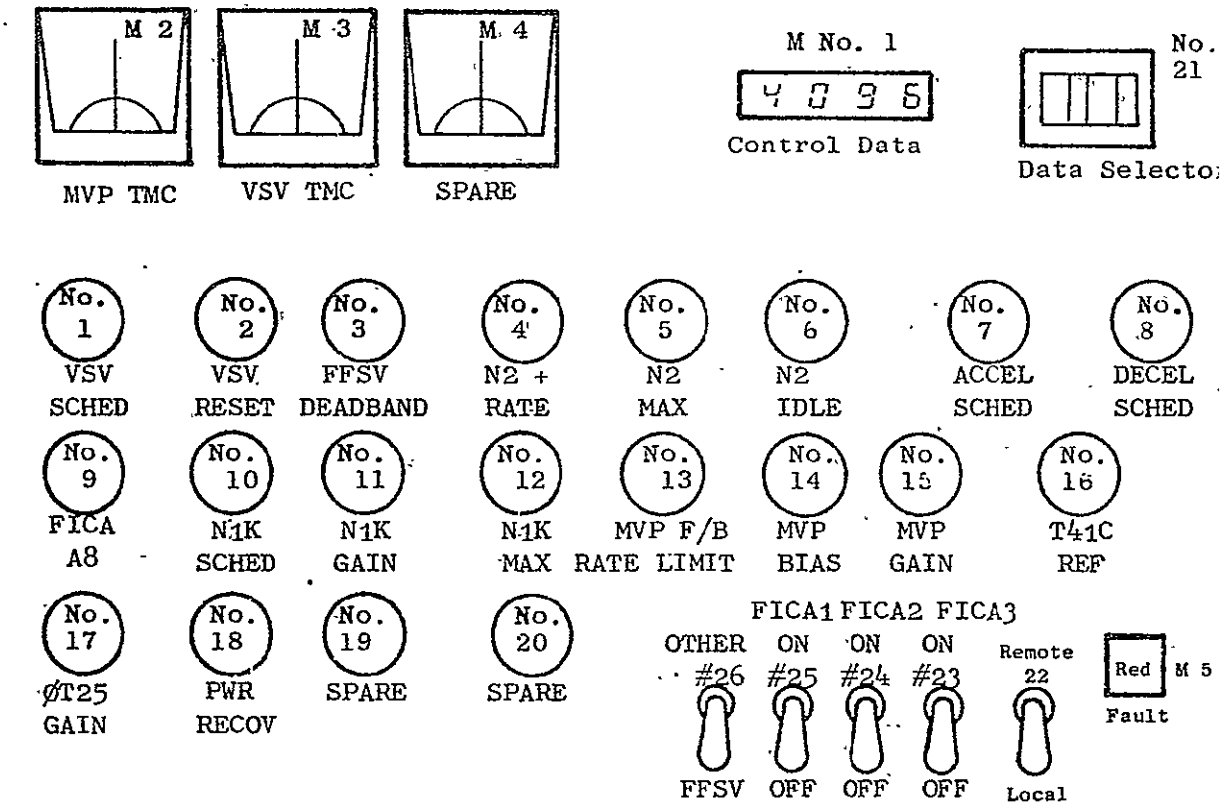


Figure 65. Engineering Control Panel.

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 handlilng 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.

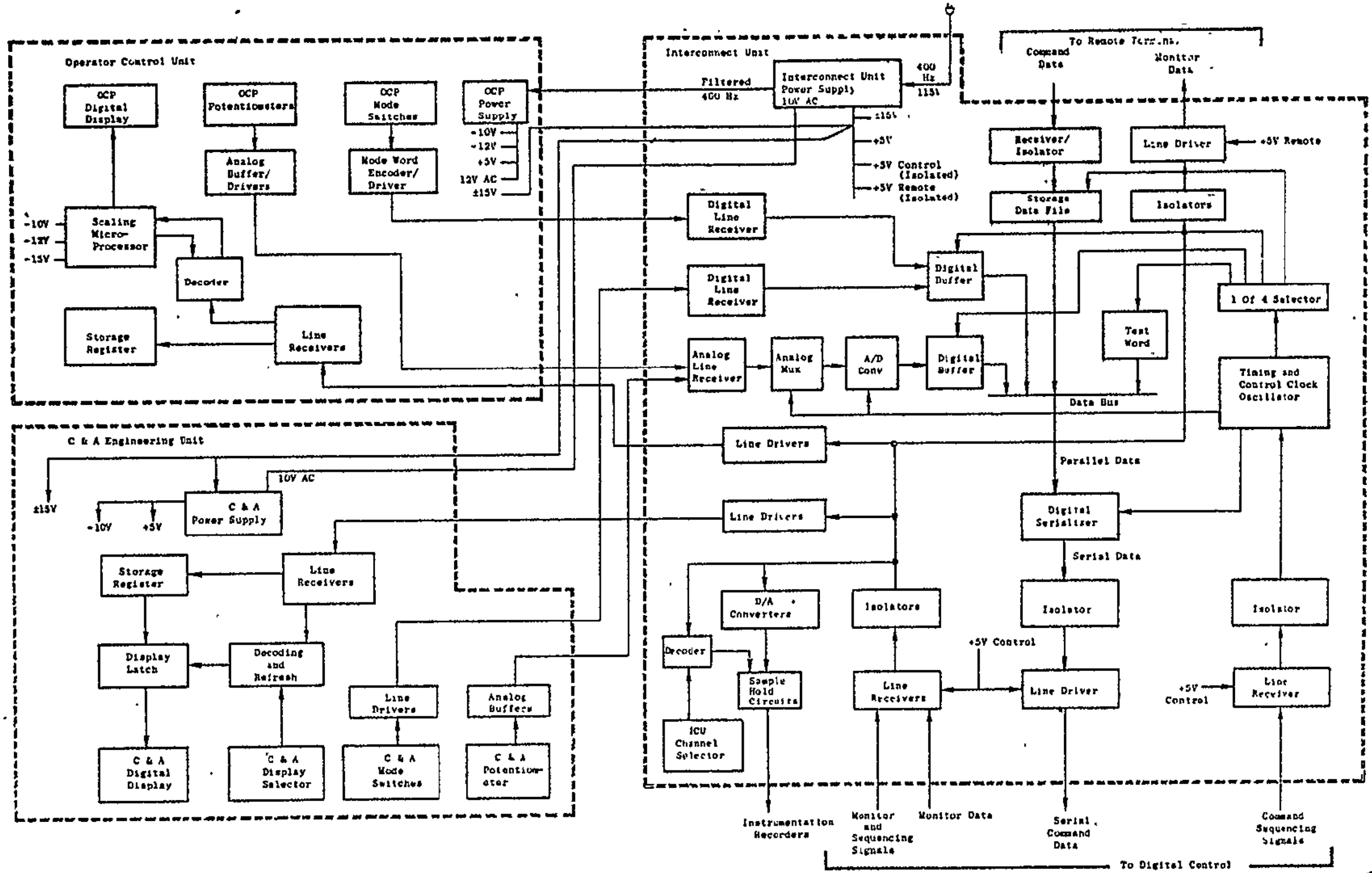


Figure 66. Off-Engine Block Diagram.

ORIGINAL PAGE IS OF POOR QUALITY

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 Geneal 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 digitial 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:

Inputs	Outputs
• 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 direcction, 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

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME 1

FOLDOUT FRAME 2

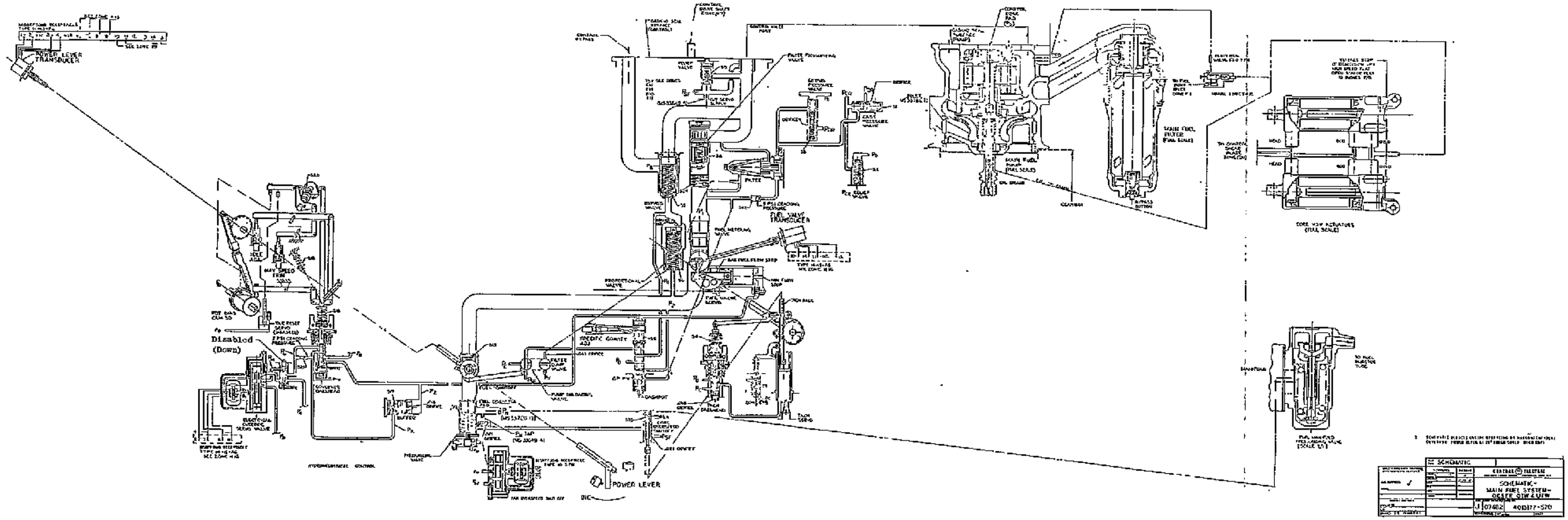


Figure 67. Hydromechanical Control Schematic.

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/m^2 (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 electrohydraulic servovalve physically mounted to the control but functionally isolated from it. This valve is described in Sectin 9.0.

- Emergency Fuel Shutoff - An electrical-to-hydromechanical 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.

PRECEDING PAGE BLANK NOT FILMED

- 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.

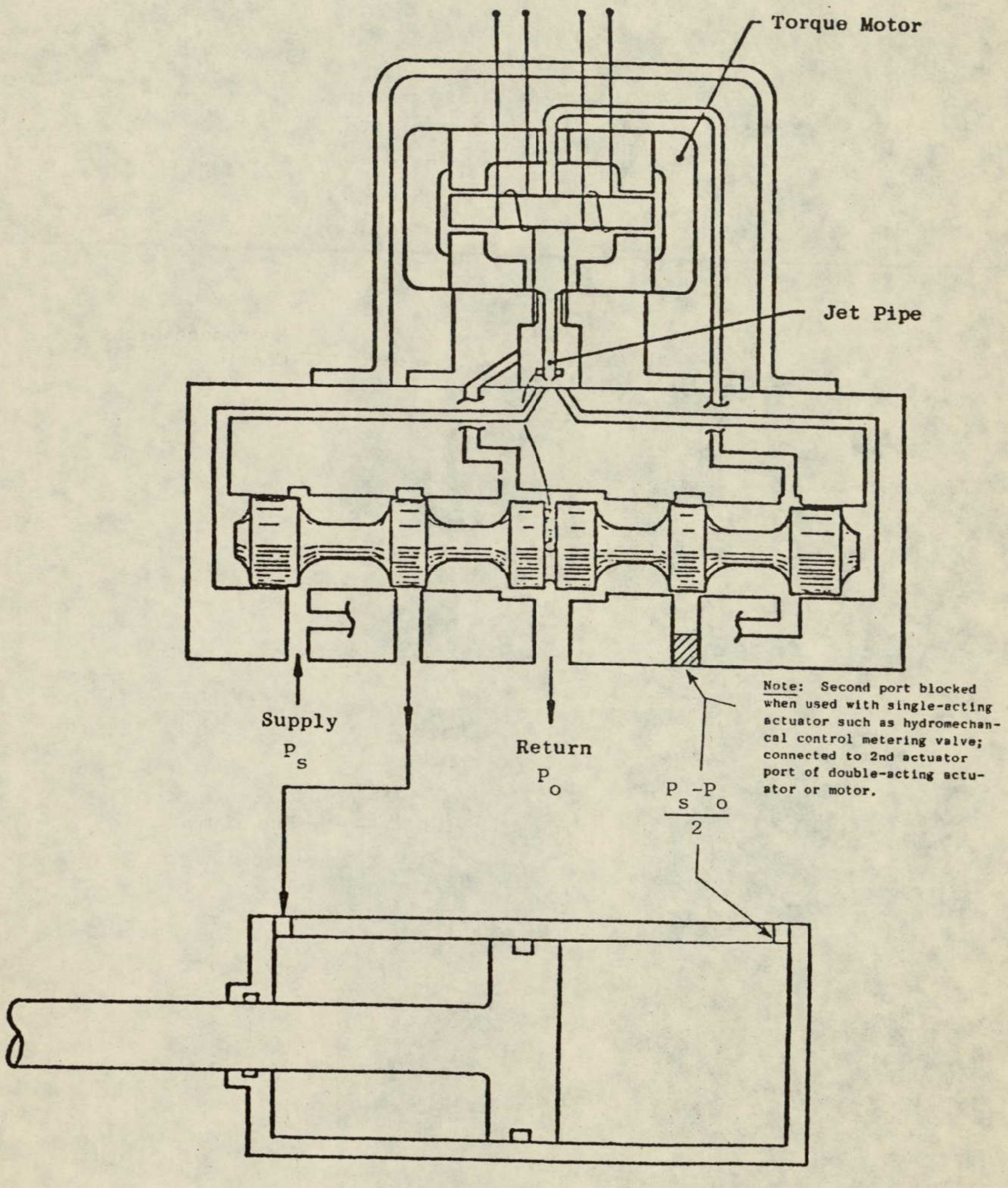


Figure 68. Fail-Fixed Servovalve.

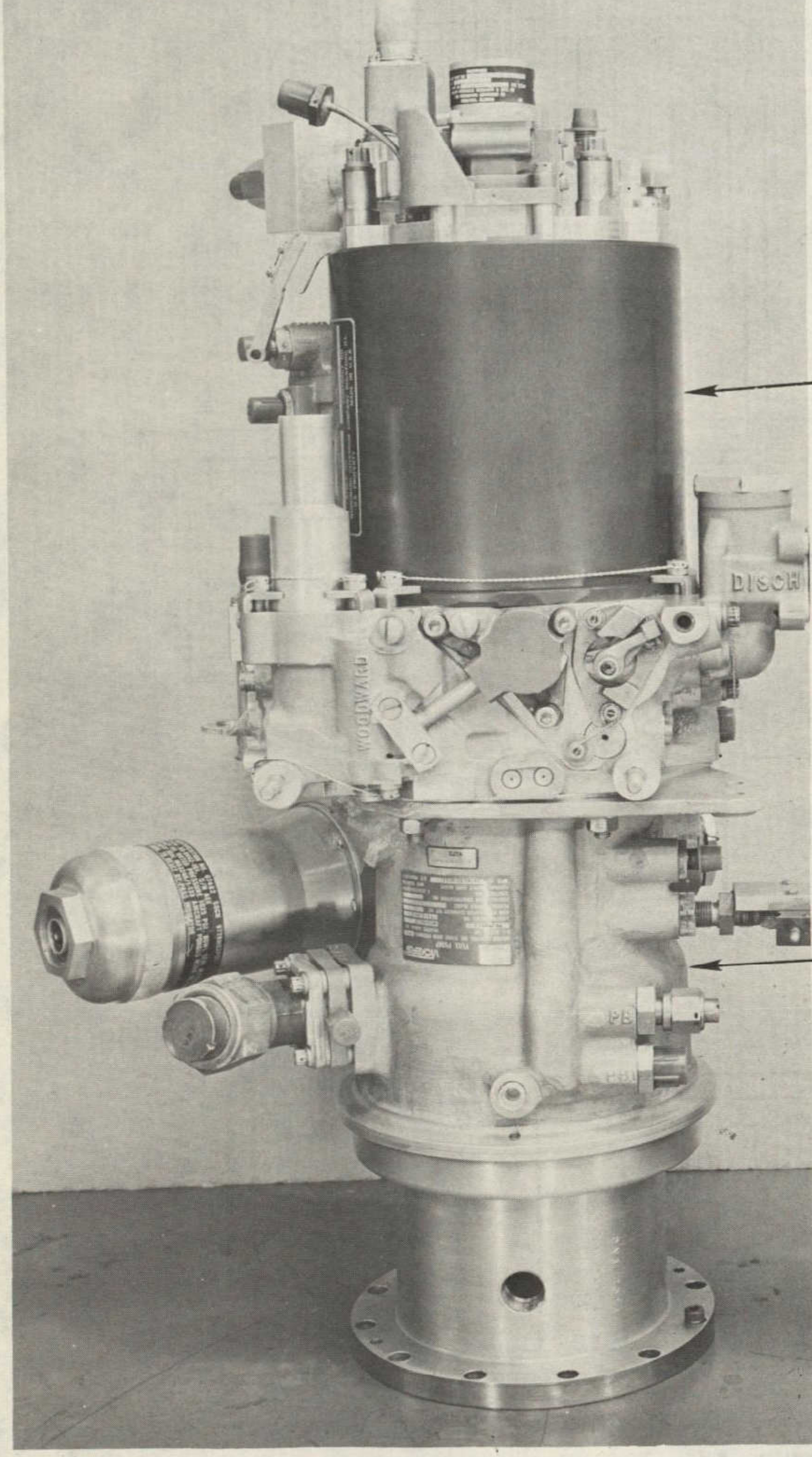


Figure 69. Hydromechanical Control and Fuel Pump.

ORIGINAL PAGE IS
OF POOR QUALITY

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.

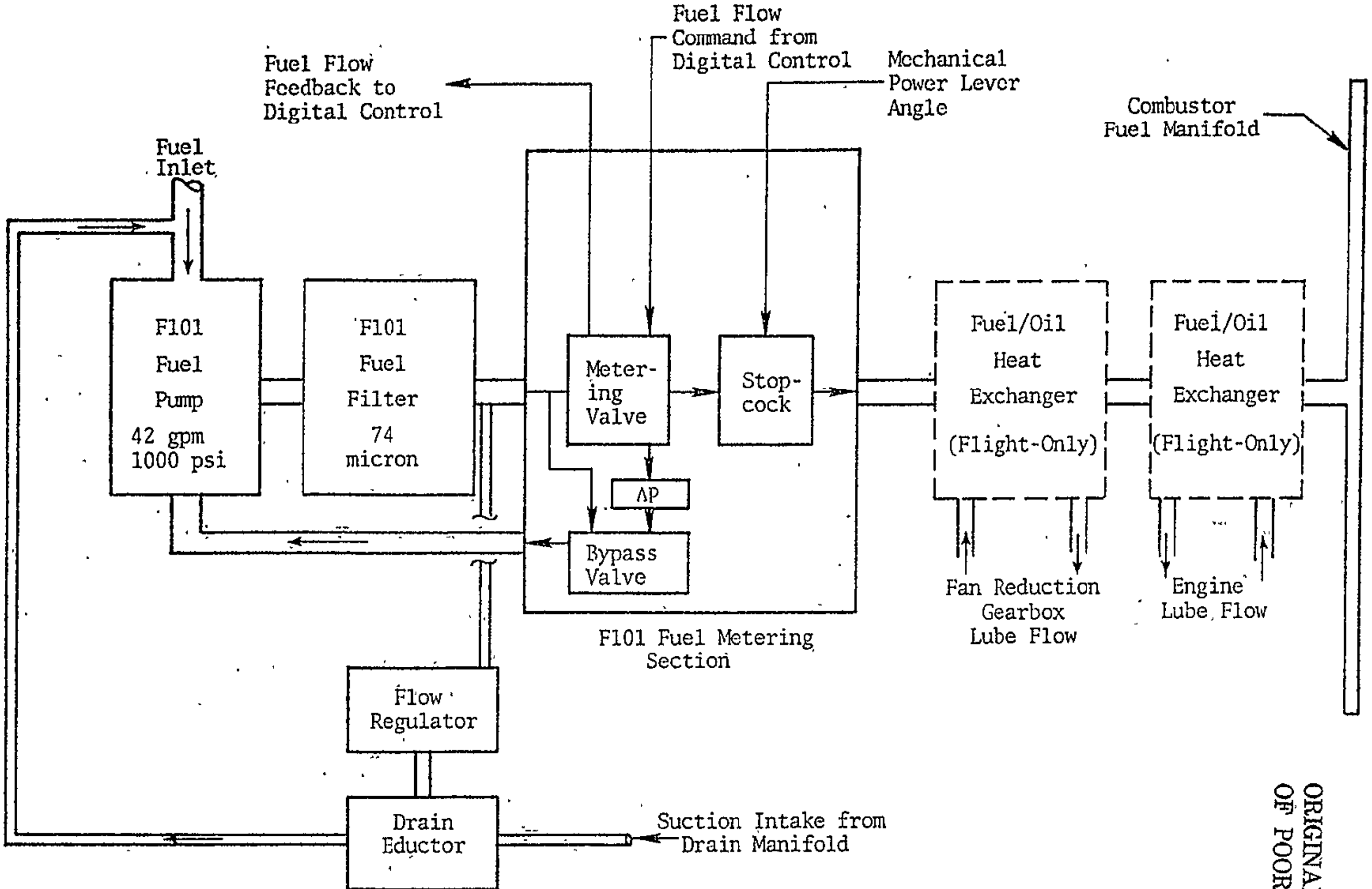


Figure 70. Fuel Delivery System.

ORIGINAL PAGE IS OF POOR QUALITY

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 pupmping 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 cm (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.

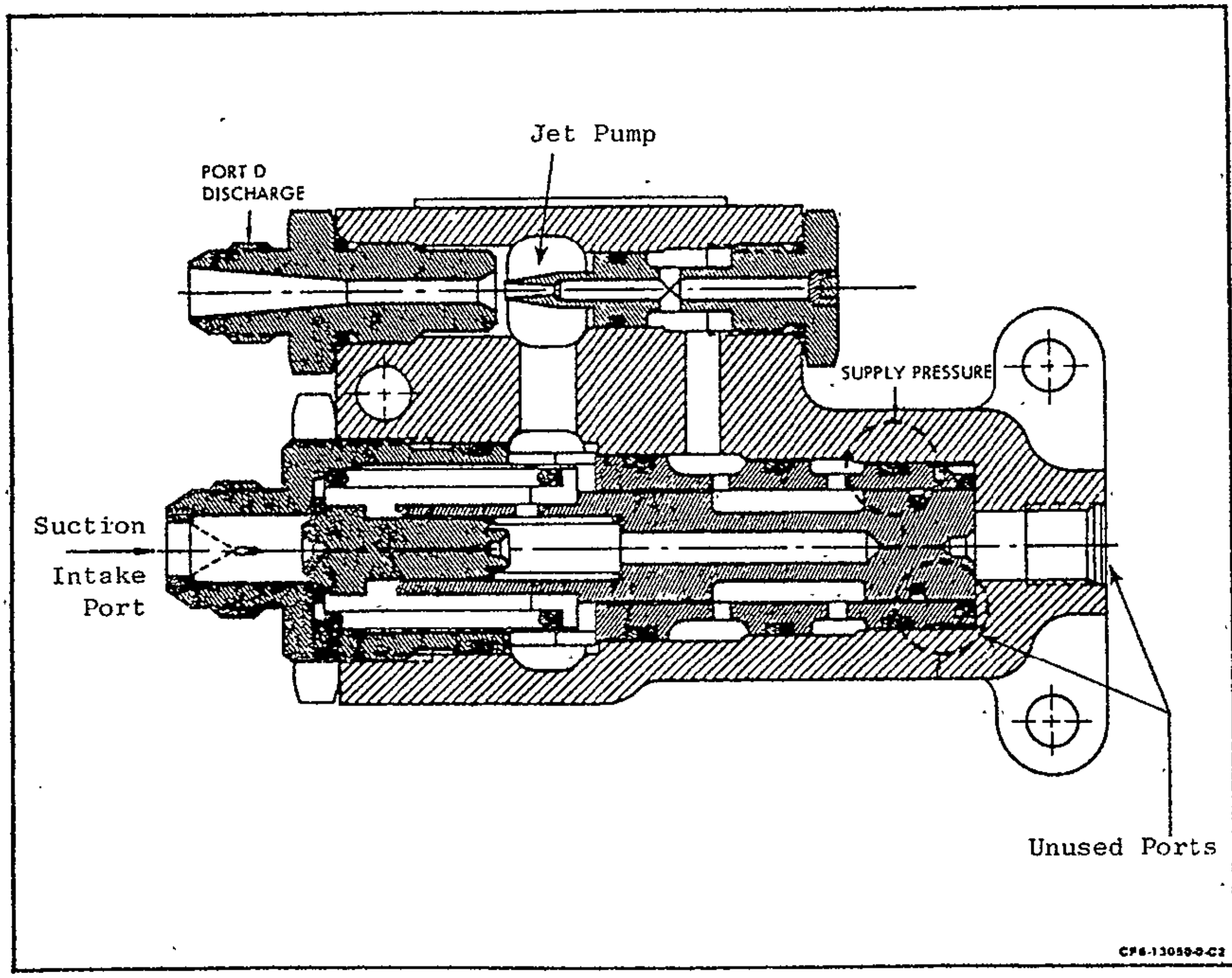


Figure 71. Drain Eductor Cross Section.

ORIGINAL PAGE IS
OF POOR QUALITY

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 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 continously 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.

ORIGINAL PAGE IS
OF POOR QUALITY

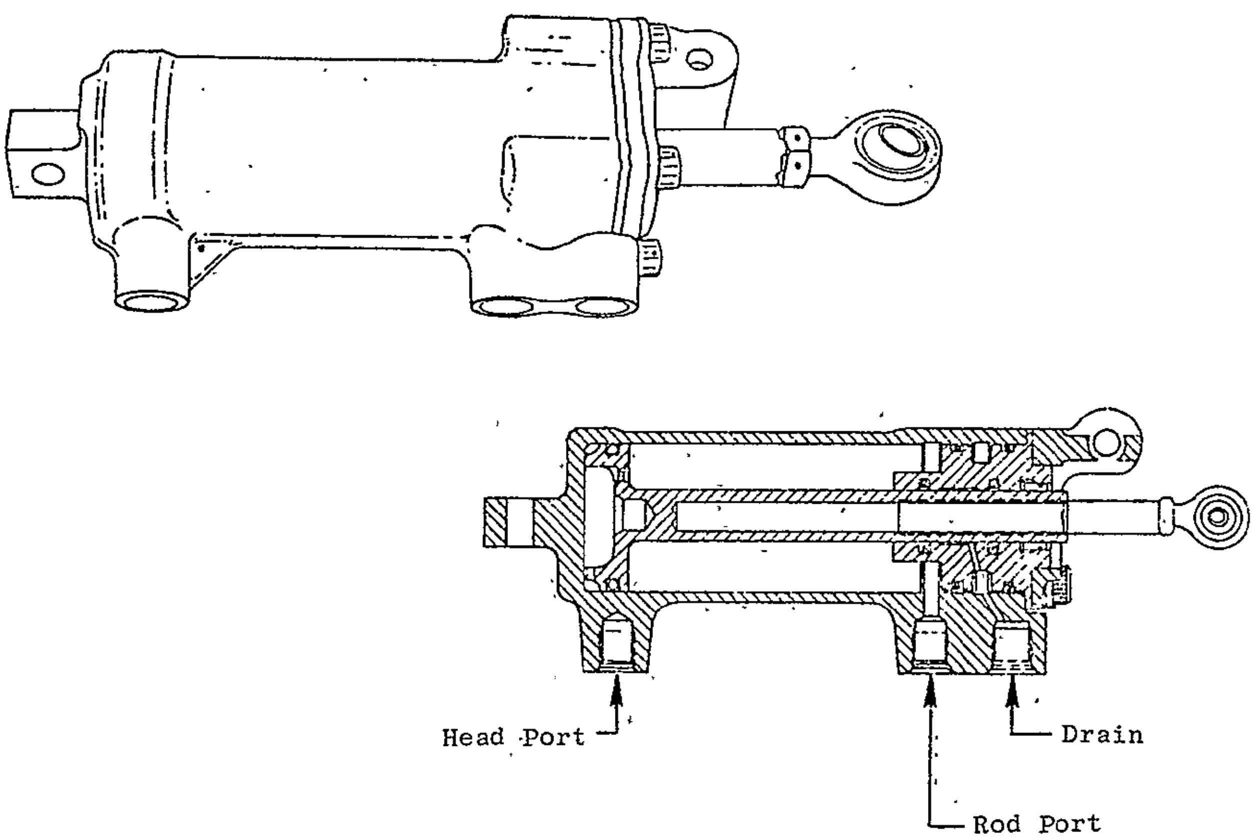


Figure 72. Core Stator Actuator.

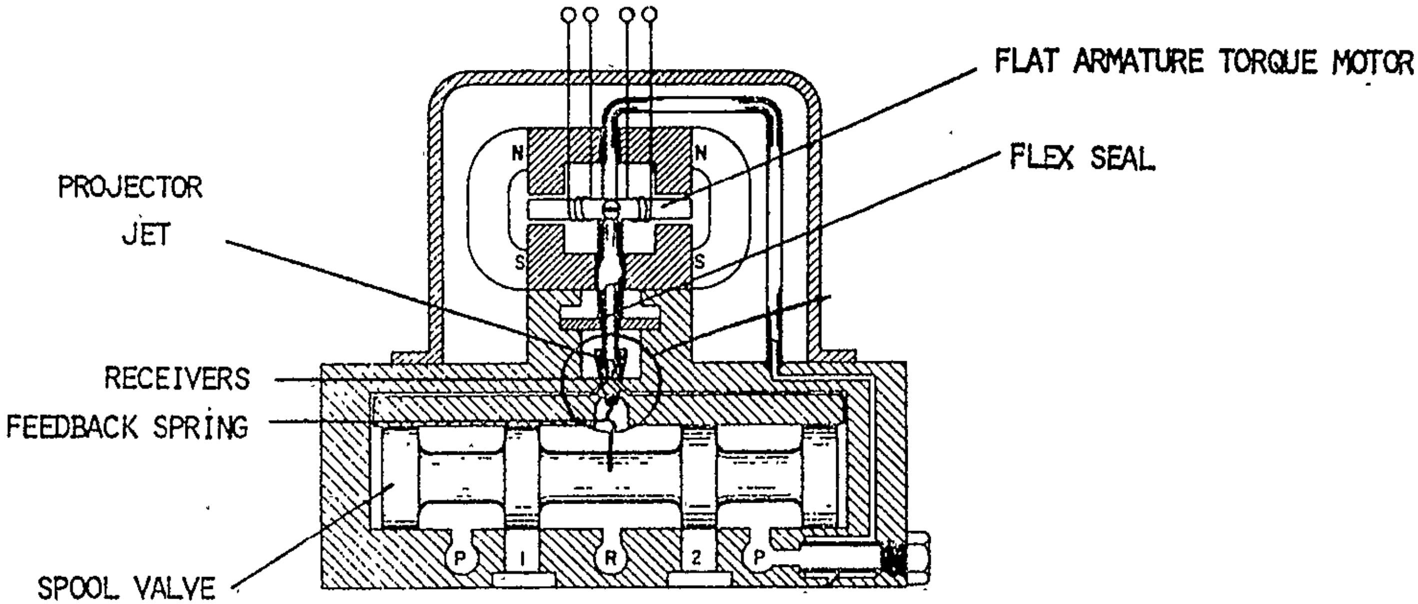


Figure 73. Electrohydraulic Servovalve.

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

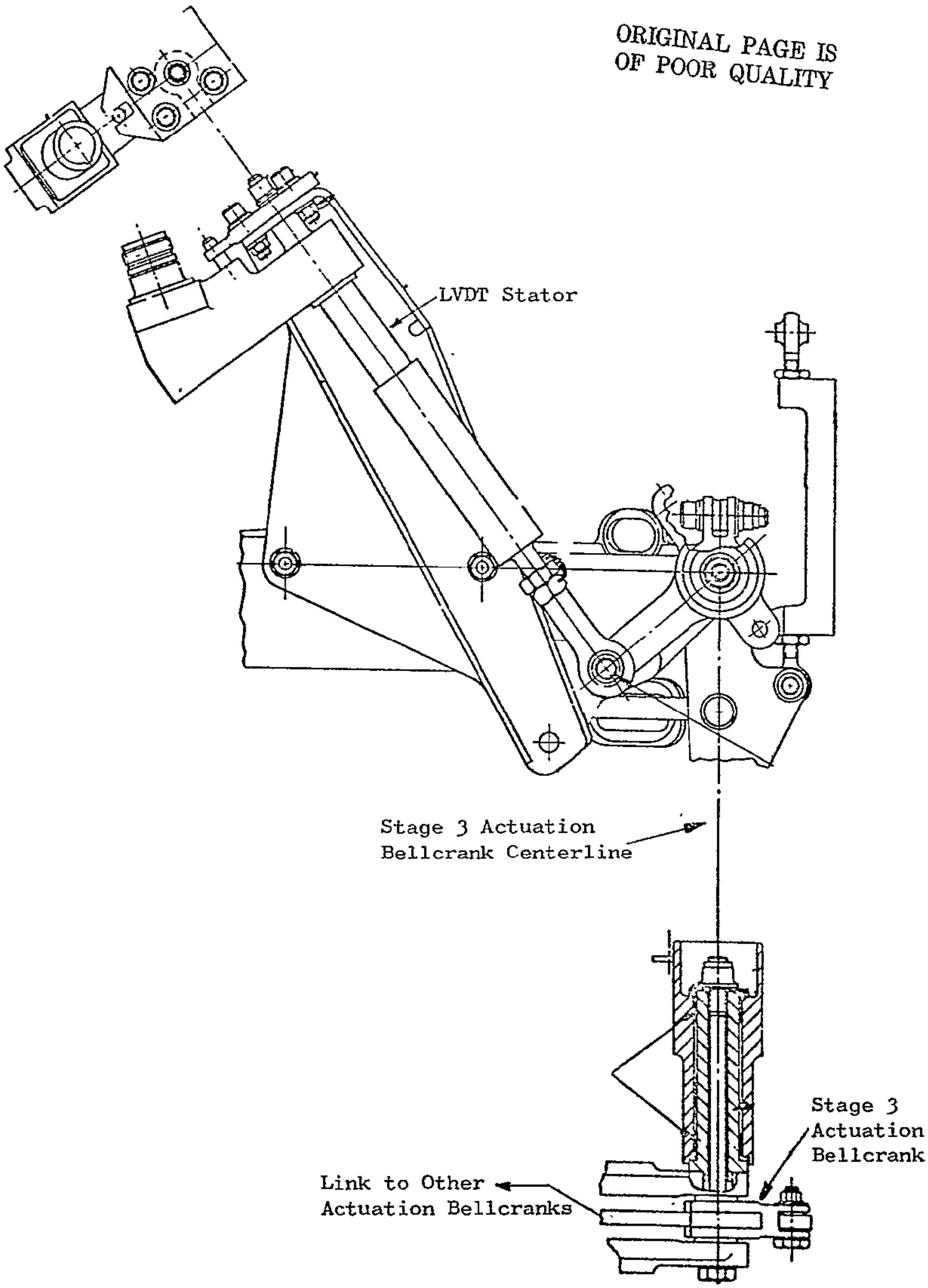


Figure 74. Core Stator Feedback LVDT.

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

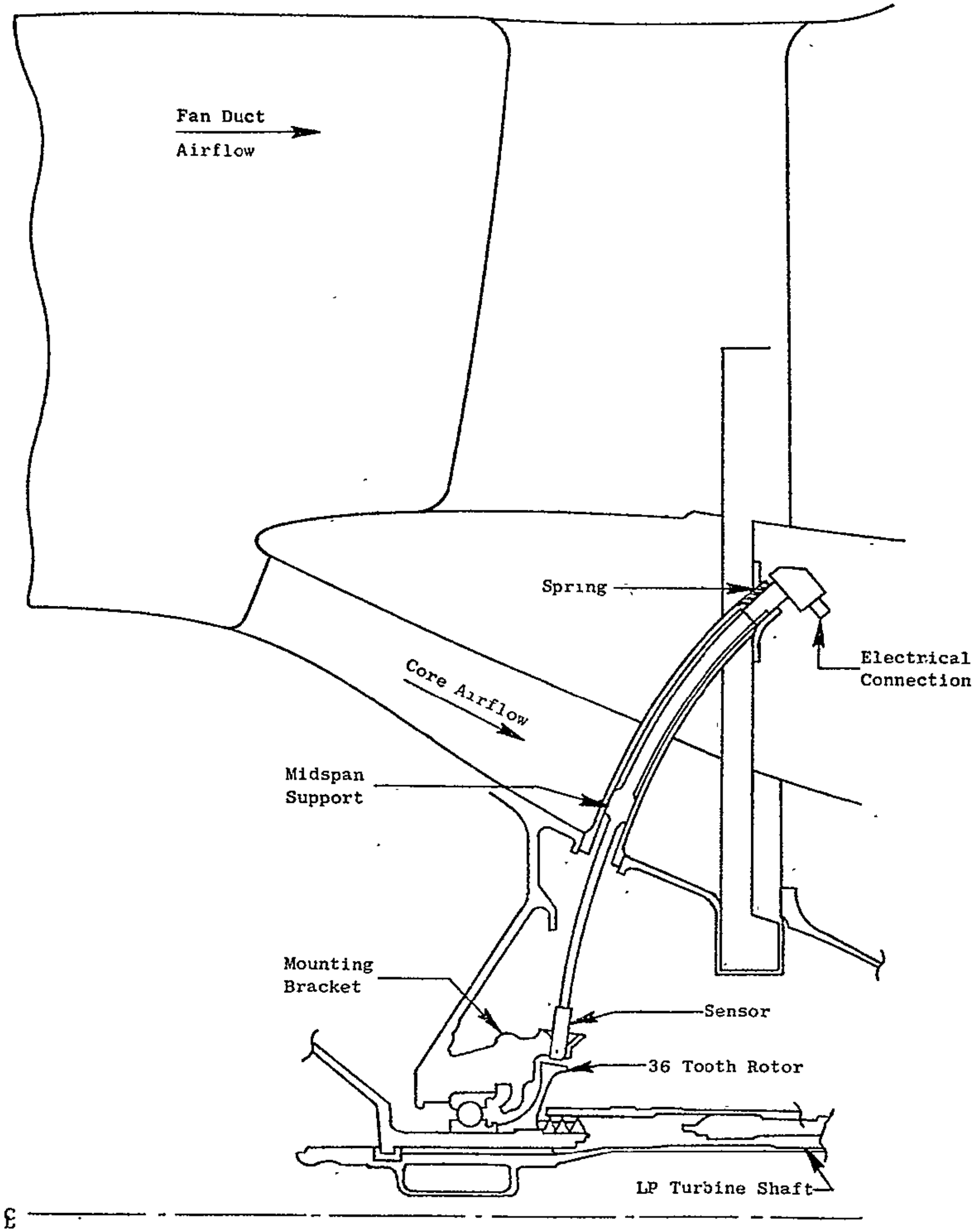


Figure 75. Low Pressure Turbine Speed Sensor.

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 proportinal 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 configuation.

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 airsteam 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.

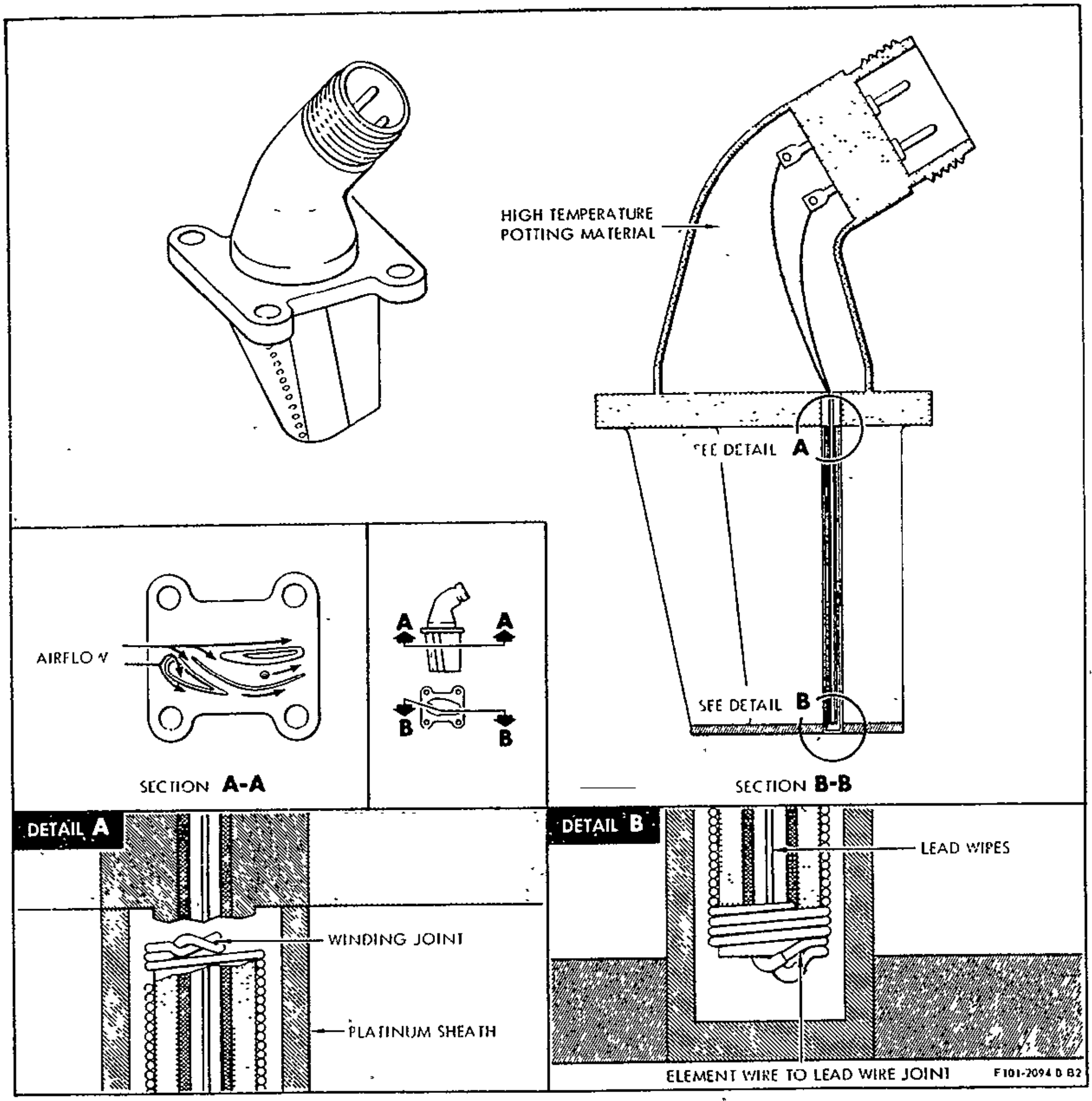


Figure 76. Fan Inlet Temperature (T12) Sensor.

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:

C-3

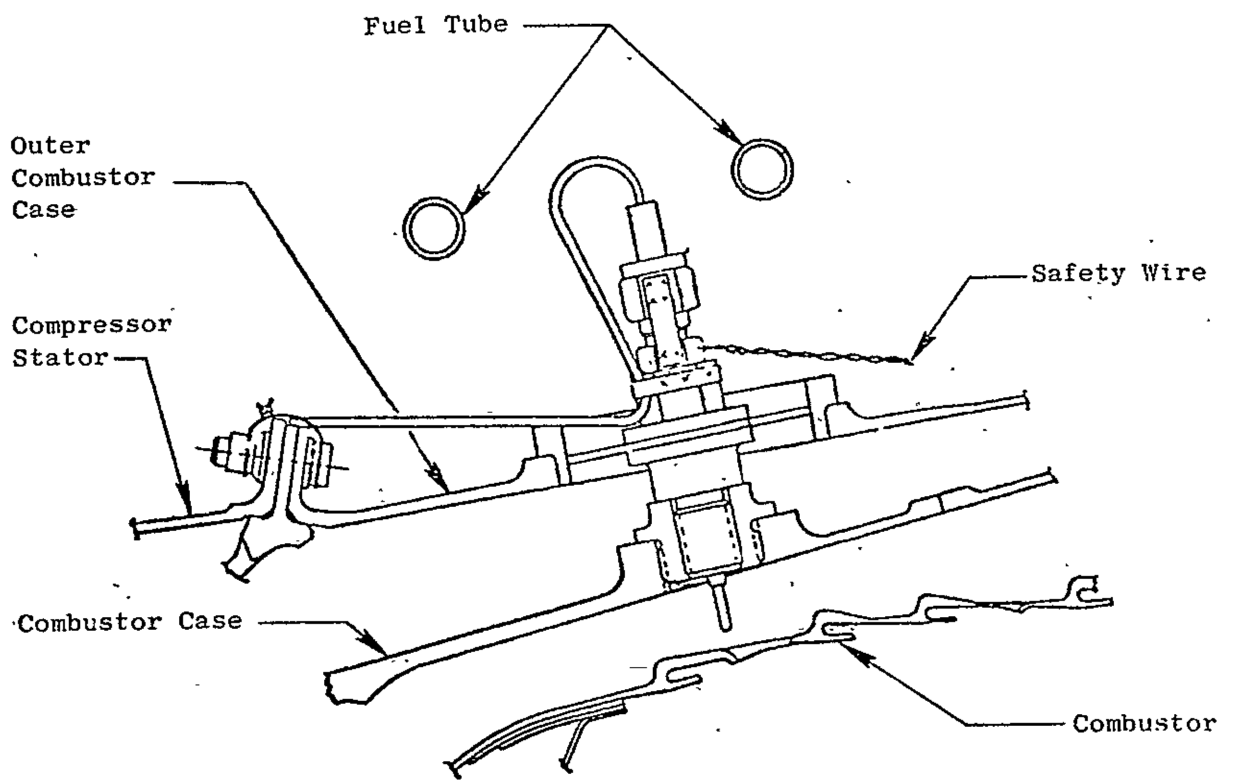


Figure 77. Compressor Discharge Temperature (T3) Sensor.

ORIGINAL PAGE IS
OF POOR QUALITY

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 reatined 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.

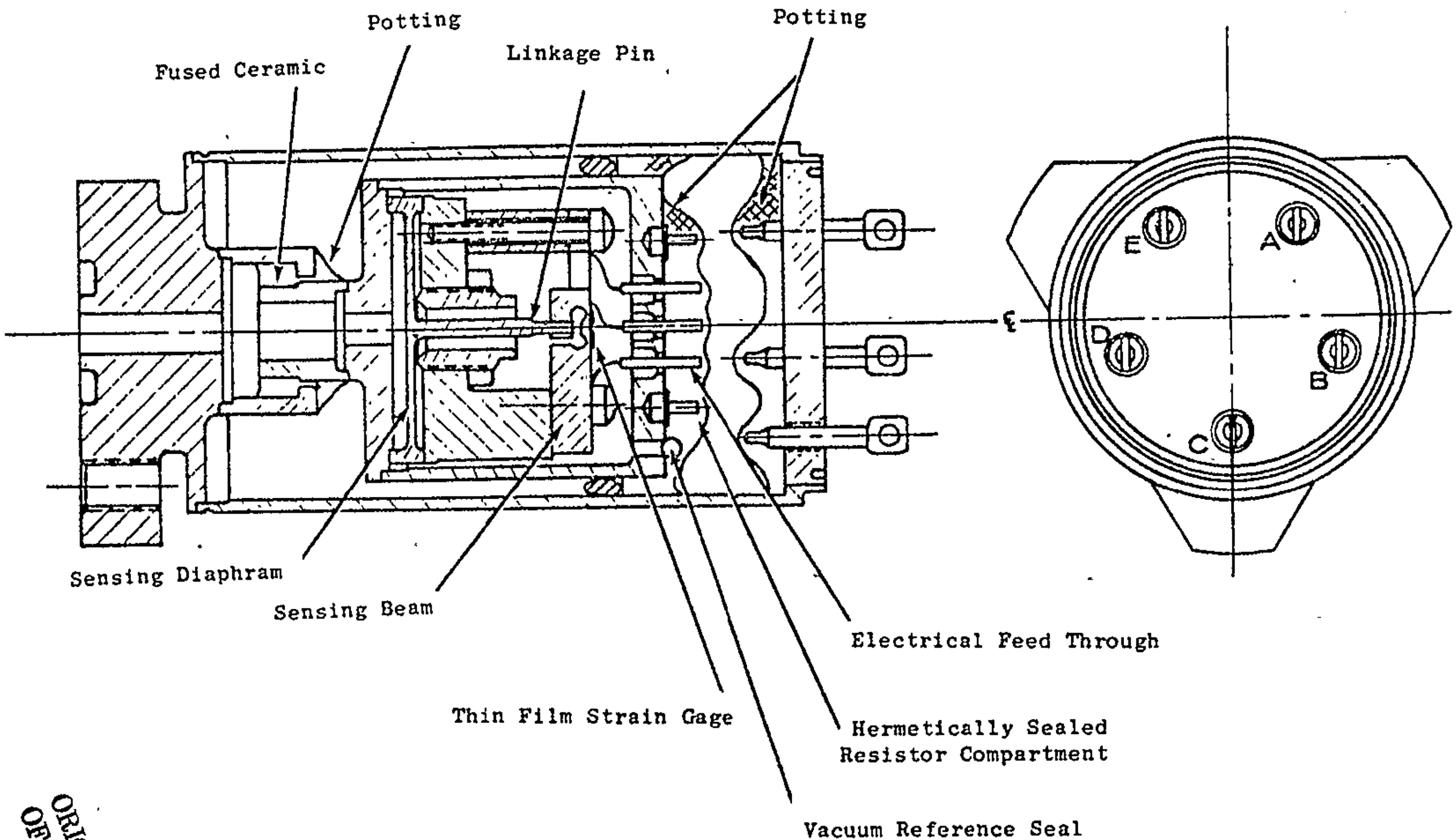


Figure 78. Pressure Transducer.

ORIGINAL PAGE IS
OF POOR QUALITY

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:

Winding	Maximum Open Circuit Voltage (volts rms)	Maximum Short Circuit Current (amperes rms)
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

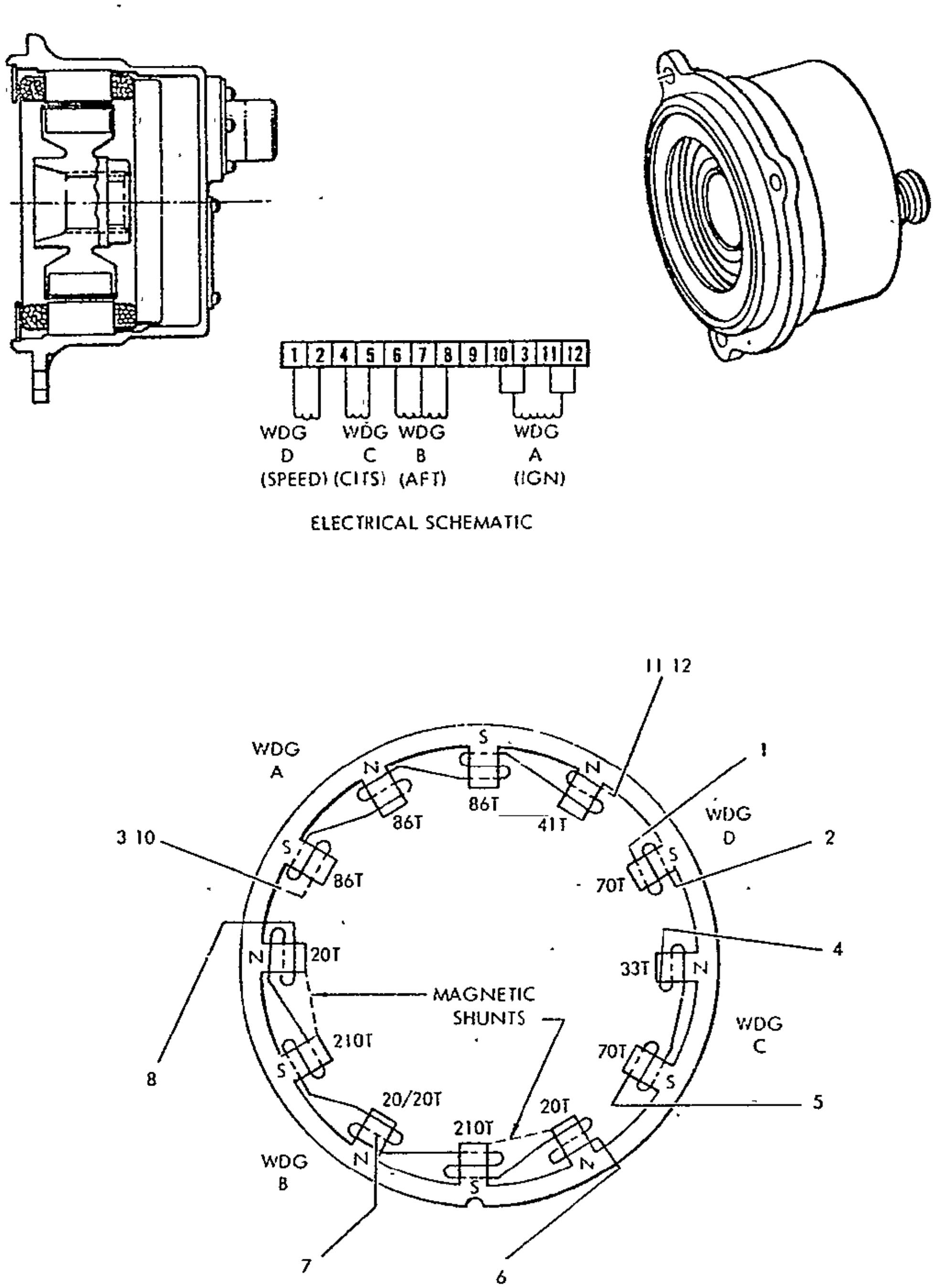


Figure 79. Control Alternator.

ORIGINAL PAGE IS OF POOR QUALITY

the engine. Interconnecting cables are made up with wires combined in shielded, twisted pairs to minimize electromagnetic interface. 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.

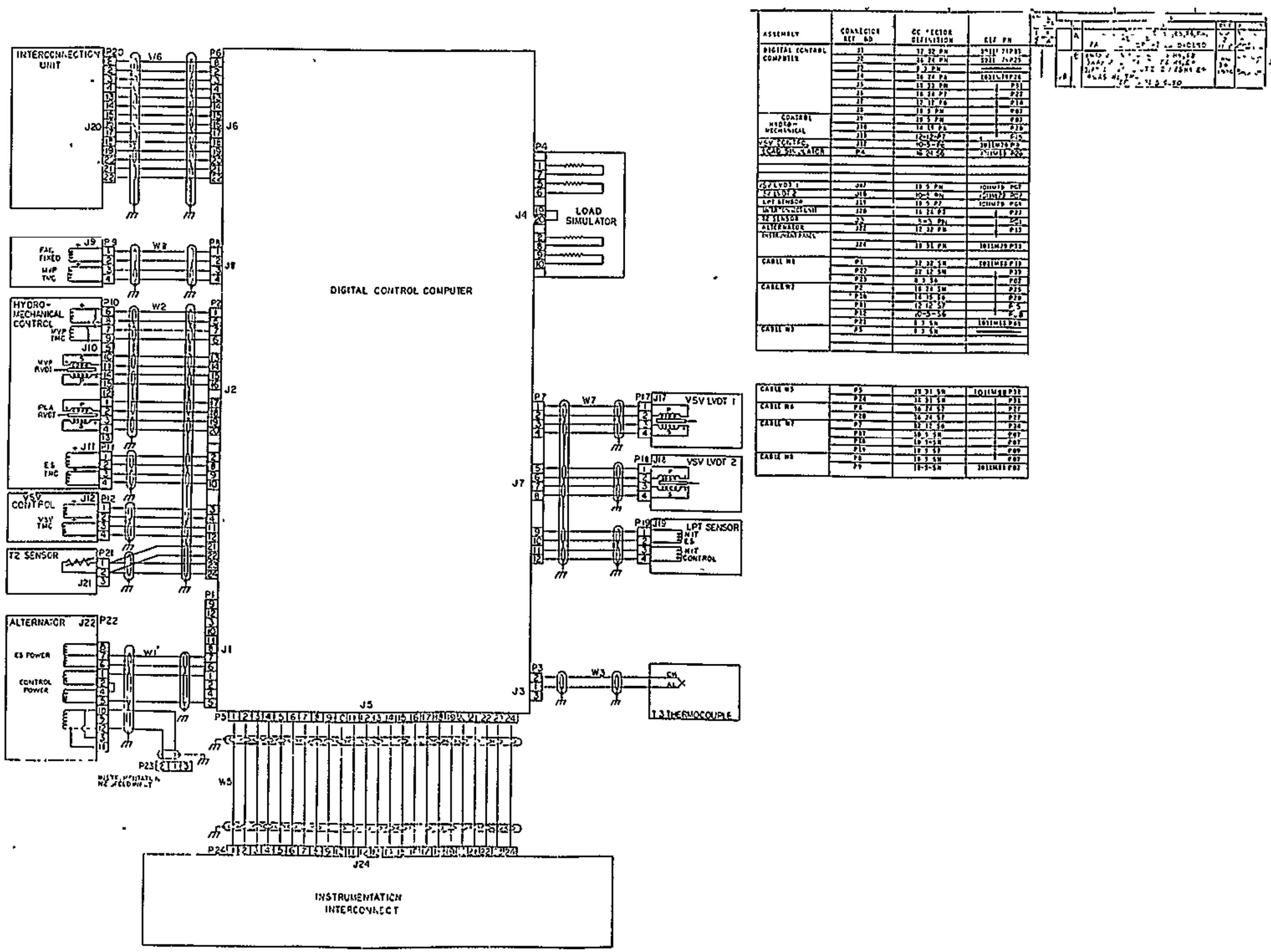


Figure 80. Electrical Interconnections.

ORIGINAL PAGE IS
OF POOR QUALITY

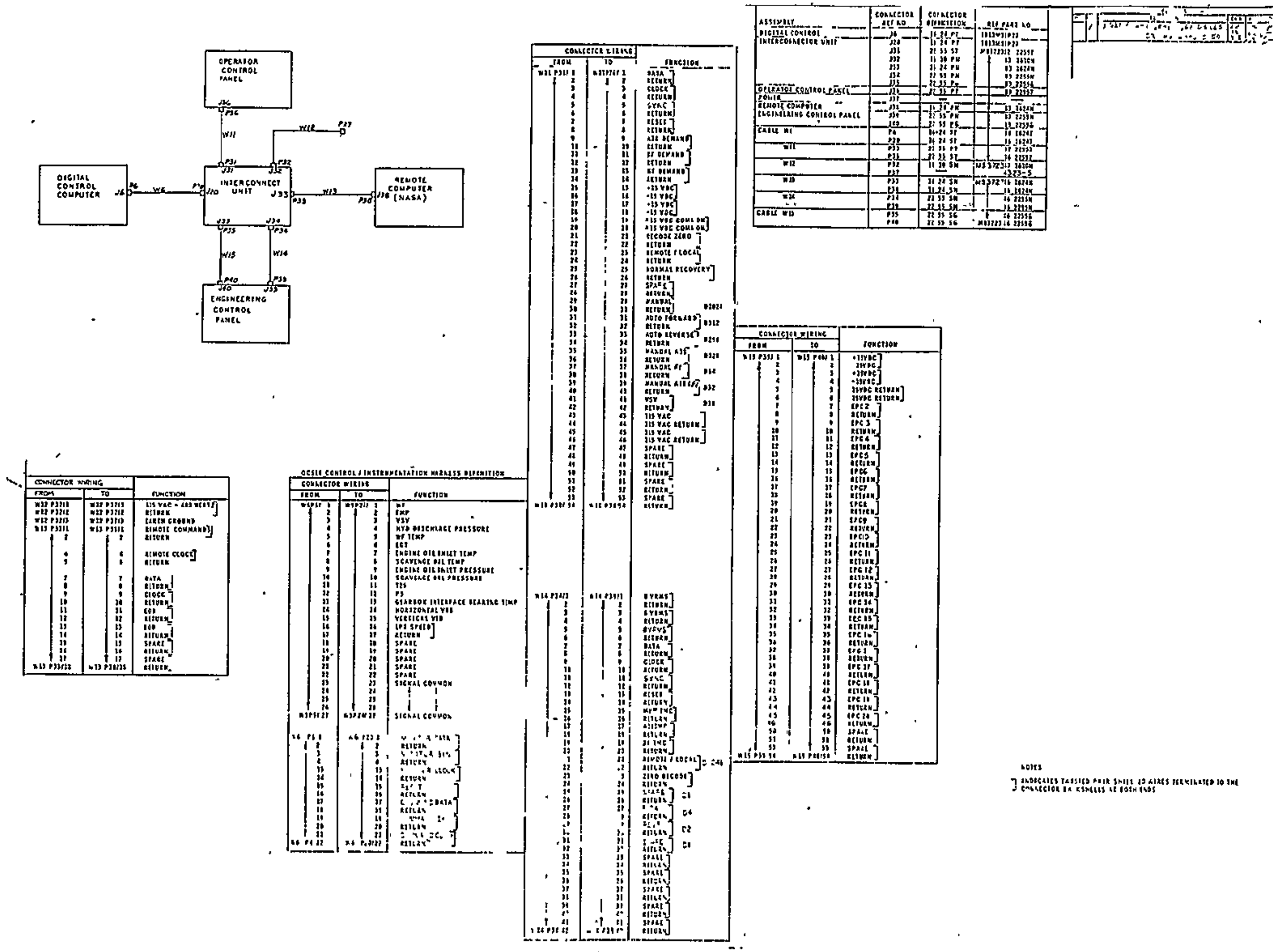


Figure 80. Electrical Interconnections (Concluded).

ORIGINAL PAGE IS OF POOR QUALITY

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	---
Eductor Flow Regulator	3.0	3.0
Fuel System Total	70.2	45.4
Digital Control and Mounting Hardware	51.6	26.0
Altenator	3.5	4.5
LPT Speed Sensor	1.1	1.1
T12 Sensor	0.5	0.5
T3 Sensor	1.0	1.0
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 Tmperature
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.

ORIGINAL PAGE IS
OF POOR QUALITY

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, N1 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 N1 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 <u>$\Delta P/P$ is sensed</u> causing WF to decrease to min. WF.	Decel to below idle.

ORIGINAL PAGE IS
OF POOR QUALITY

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

Failure	Control System Effects	Engine Effects
E. Digital Control Failures (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 prefault 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. Hydromechanical Control System Failures		
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.

ORIGINAL PAGE IS OF POOR QUALITY

Failure	Control System Effects	Engine Effects
F. Hydromechanical Control System Failures (Cont'd)		
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 prefault position.	Probably no effect if one coil fails. If both fail, WF remains at prefault 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.	Depends on prefault conditions as follows: Steady State - WF remaining at prefault level. Can be reduced by backup governor in response to PLA. WF Increase - Increase continues until backup governor interferes. PLA control with backup governor still available. WF Decrease - Decrease continues to min. WF engine decels to below idle.
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
F. <u>Hydromechanical Control System Failures</u> (Cont'd)		
10. VSV servovalve spool stuck.	Servovalve won't respond to input changes, remains at condition existing when spool stuck.	Depends on prefault conditions as follows: <u>Steady State</u> - VSV remain at prefault position. If at high power setting, compressor stall likely when power setting reduced. <u>VSV Opening</u> - Opening continues. Compressor stall likely. <u>VSV Closing</u> - Closing continues, thrust is reduced.
11. VSV servovalve jet plugged.	Servovalve tends to stay at prefault conditions.	Same as F.10.

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX C

DIGITAL CONTROL PROCESSOR
SOFTWARE

1. Instruction Repertoire

Mnemonic	Excecution Time (Microseconds)	Operation
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).

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

Mnemonic	Execution Time (Microseconds)	Operation
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.

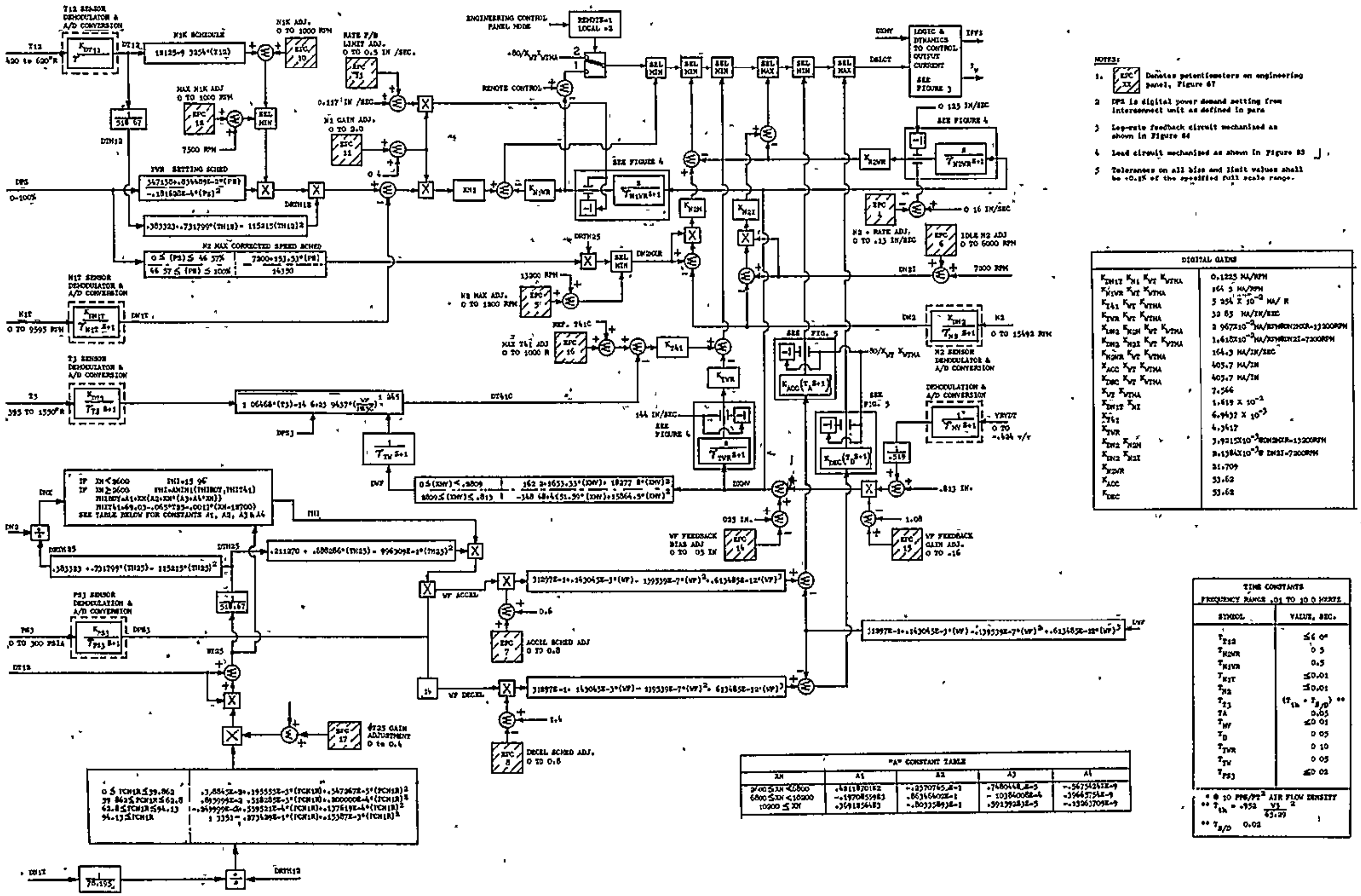
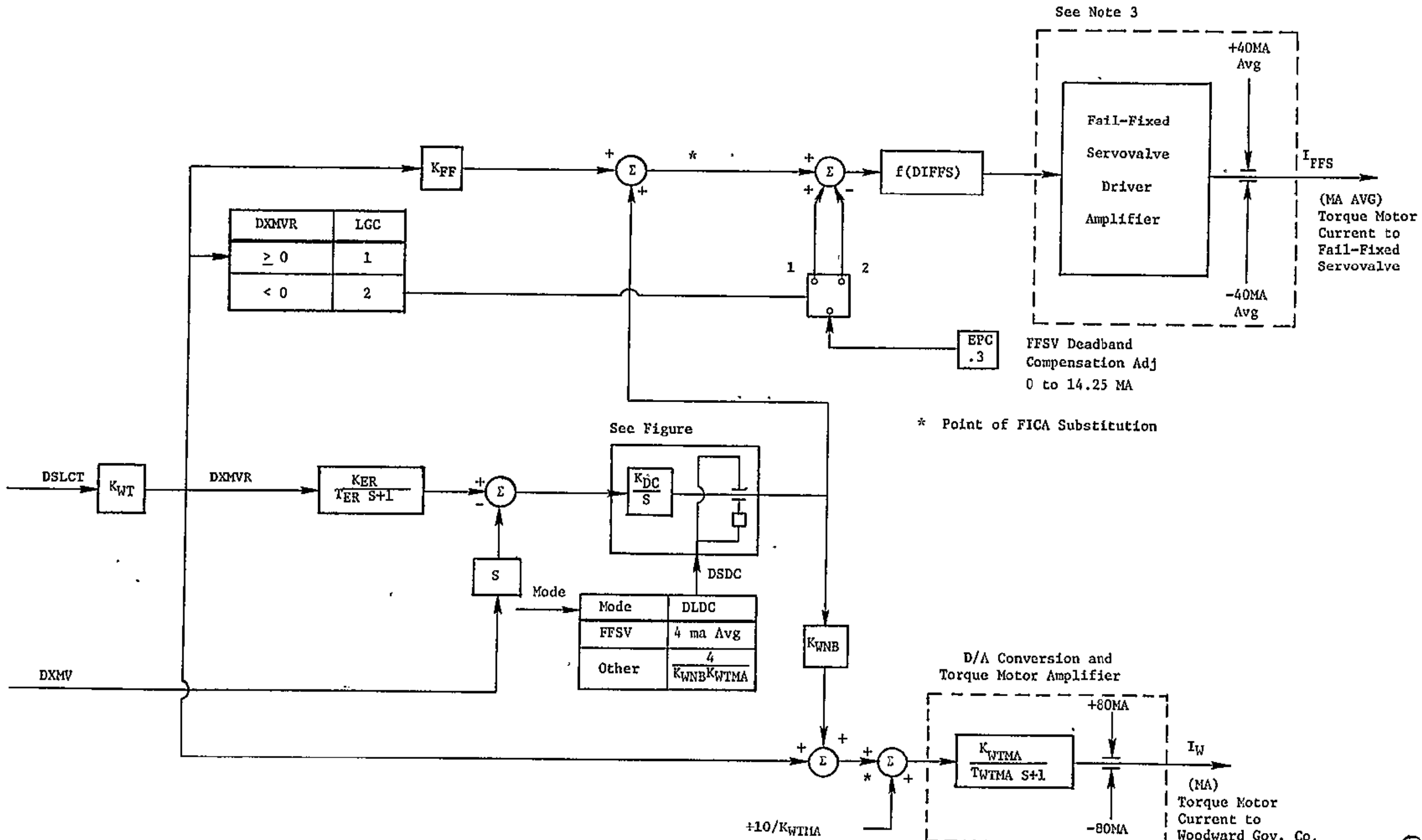


Figure 81. QCSEE OTW Fuel Flow Control Block Diagram.

ORIGINAL PAGE IS OF POOR QUALITY



Notes

EPC XX — Denotes Potentionmeters on Engineering Panel, Figure 65.

Integrating Circuit Mechanized as Shown in Figure 85.

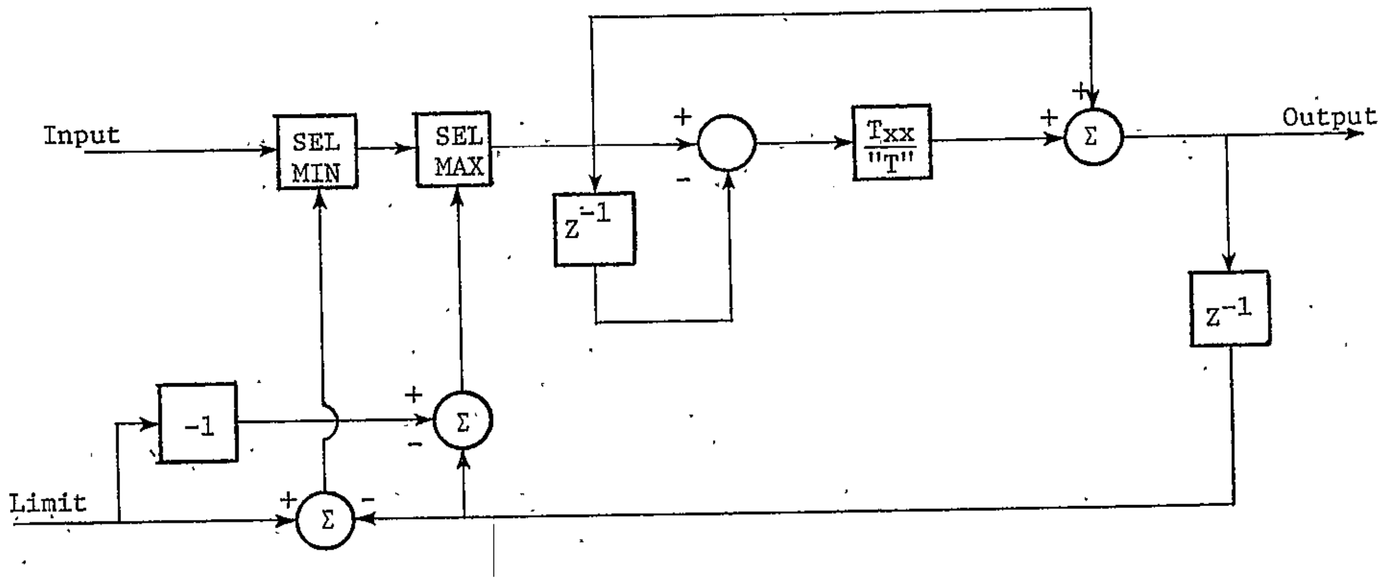
f(DIFF) to be Sized by Digital Design to Provide Linear Gain thru Output (I_{FFS}) Current with Servovalve Operating. Lag Time Constant ≤ 0.01 Second.

Digital Gains	
$K_{WT}\ K_{WTMA}$	See Figure
K_{ER}/K_{WTMA}	4.326E-2
K_{FF}/K_{WTMA}	0.2703
K_{DC}	1.049 MA (AVG)/in.sec
$K_{DC}\ K_{WNB}\ K_{WTMA}$	0.603 MA/in./sec

Time Constants Frequency Range 0.01 to 10 Hz	
Symbol	Value, sec
T_{CR}	0.075
T_{WTMA}	≤ 0.01

ORIGINAL PAGE IS OF POOR QUALITY

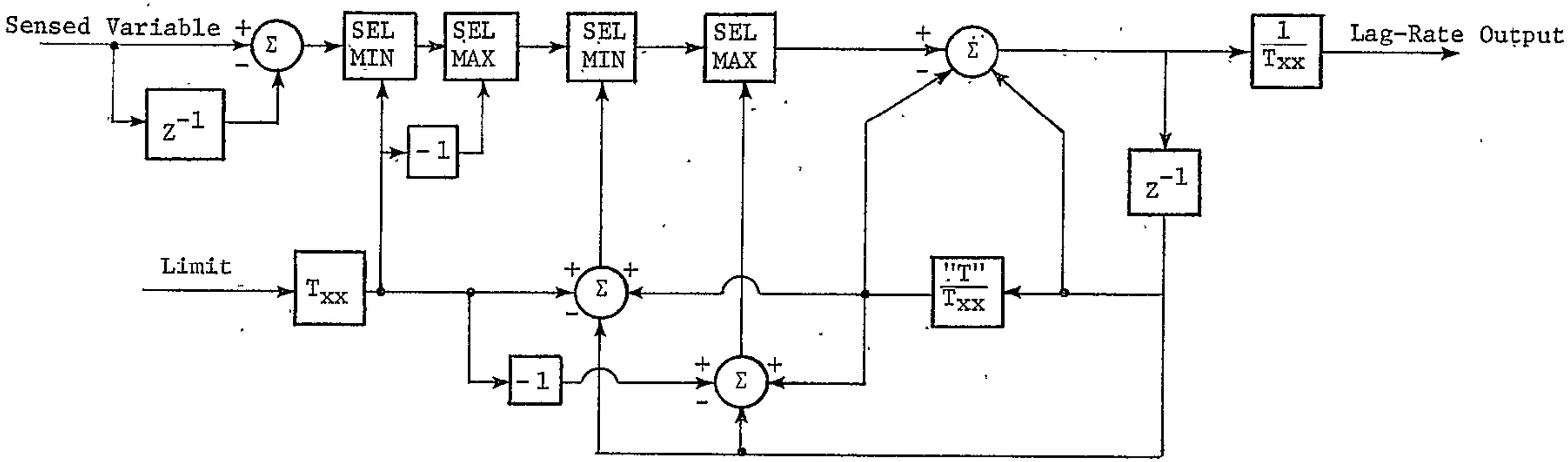
Figure 82. Logic and Dynamics to Control Output Current.



Notes

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

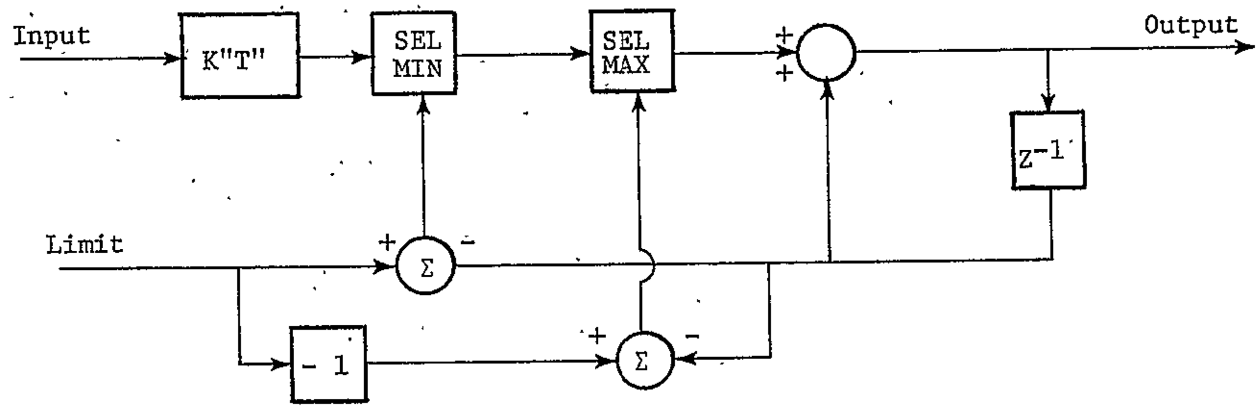
Figure 83. Lead Circuit Mechanization.



Notes

1. T_{xx} Required Time-Lag
2. Z^{-1} Value at Last Iteration
3. "T" Digital Control Sampling Rate
4. Limit Required Limit on Lag-Rate Output

Figure 84. Lag Rate Feedback Circuit Mechanization.



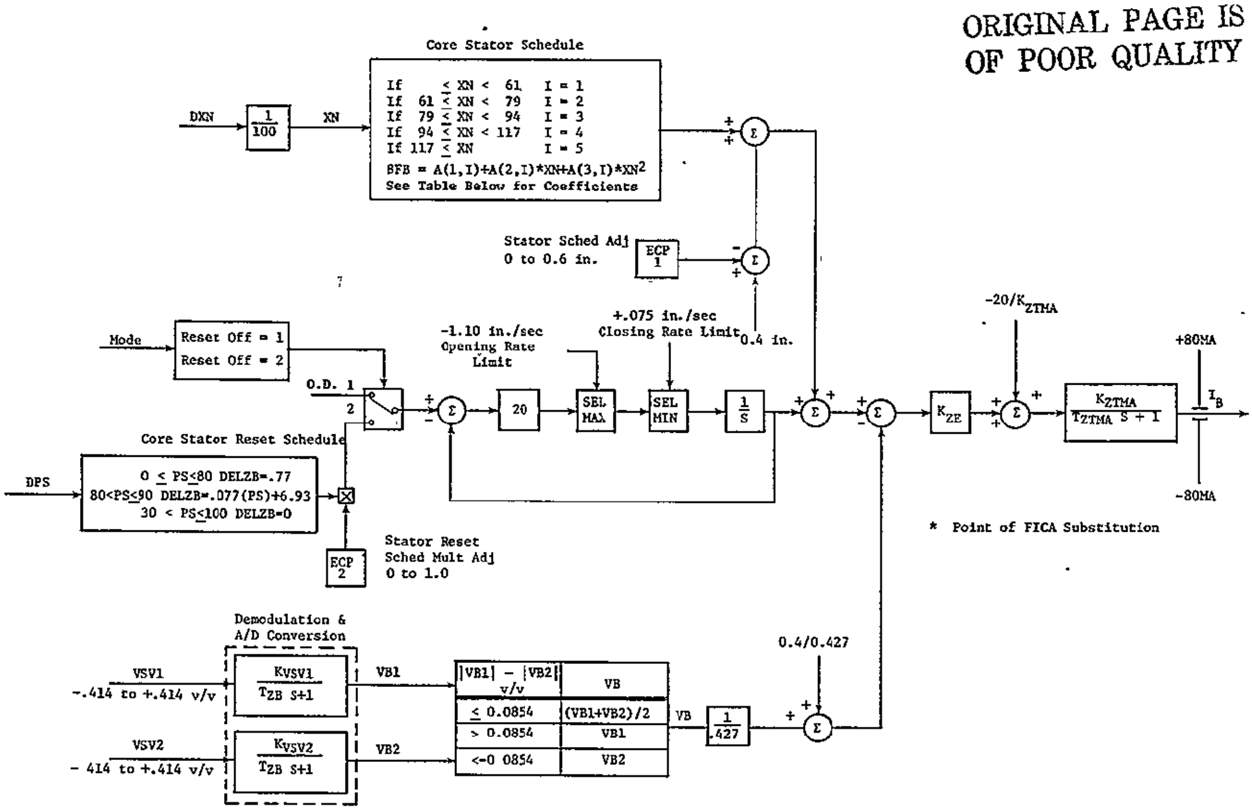
<u>Notes</u>

1. Z^{-1} Value at Last Iteration

2. "T" Digital Control Sampling Rate

Figure 85. Integrating Circuit Mechanization.

ORIGINAL PAGE IS
OF POOR QUALITY



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

Analog

Input Number	Input Name	Ram Storage Address	Scaling
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

Input Number	Input Name	Ram Storage Address	Scaling
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. <u>INPUT ORDER LIST</u> (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
1	One
2	2048
3	Temporary Storage
4	Temporary Storage
5	Temporary Storage
6	Temporary Storage
7	Temporary Storage
8	Temporary Storage
9	Temporary Storage
10	Temporary Storage
11	Temporary Storage
12	Temporary Storage
13	Temporary Storage
14	Temporary Storage
15	Temporary Storage
16	Temporary Storage
17	Temporary Storage
18	Temporary Storage
19	Temporary Storage
20	Remote Mode = 1
21	VSV Reset ON = 1
22	FICA 1 ON = 1
23	FICA 2 ON = 1 Karman
24	EFSV - ϕ, Other = 1
25	βC
26	TER E_{OUT} Z^{-1} MSB
27	TER E_{OUT} Z^{-1} LSB
28	DWF 0-4095, 0-13910
29	T_{TWR} EoZ^{-1} MSB
30	T_{TWR} EoZ^{-1} LSB
31	T41C
32	EoZ^{-1} T_{TW} MSB
33	EoZ^{-1} T_{TW} LSB
34	ΔPS11/PTO 0-2047=0-4.0 PRU
35	1023
36	DT25
37	$\sqrt{\theta 25}$
38	P14-PTO
39	$\sqrt{\theta 12}$
40	VRVDT (MVP F8 Raw)
41	T3
42	N2
43	DXMV
44	PS3
45	N1T
46	T_{12}
47	PTO-PS11
48	PTO
49	DT25
50	DRTH25
51	Remote Direct Velocity Demand
52	DXMV-DXMV Z^{-1}
53	T_{N1WR} EoZ^{-1} MSB
54	T_{N1WR} EoZ^{-1} LSB
55	T_{N1WR} EiZ^{-1}
56	Subroutine Return CTR No. 1
57	Subroutine Return CTR No. 2
58	Subroutine Return CTR No. 3
59	T_{N2WR} EoZ^{-1} MSB
60	T_{N2WR} EoZ^{-1} LSB
61	Test Word Result 1 = OK, ϕ = $\overline{OK}$
62	Decel EiZ^{-1}
63	Accel EiZ^{-1}
64	"Eng. Panel Readout"
65	K_{DC} EoZ^{-1} MSB
66	K_{DC} EoZ^{-1} LSB
67	Fault Word

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

68 A/D-D/A Fault Counter
69 A/D-D/A Test Results 1=OK
70 Vertical Vib.
71 Horizontal Vib.
72 Vib. Counter
73 WF MCI Word
74 PLA
75 βC1 Feedback
76 βC2 Feedback
77 O/S TM Signal
78 Hyd. Pump Outlet Pressure
79 WF Temperature
80 WF Manifold Pressure
81 EGT - T56
82 Wf
83 Oil Inlet Pressure
84 Scavenge Oil Pressure
85 Lub. Inlet Temperature
86 Oil Discharge Temperature
87 T25
88 P5
89 G/B Temperature
90 VSV Position
91 Clock Fail
92 DXN $N2/\sqrt{\theta 25}$ 0 - 2047
93 DZBRST MSB Z^{-1}
94 DZBRST LSB Z^{-1}
95 4095
96 WFTMC
97 VSV TMC
98 FICA WF in PPH
99 FICA T1
100 FICA ZWF in Inches
101 FICA P1
102 FICA PS3
103 FICA SPS3
104 FICA T56
105 FICA VT56
106 FICA P15
107 FICA SP15
108 FICA VPS3
109 FICA ST56
110 FICA VP15
111 FICA SQRT Subroutine CTR
112 FICA Temporary
113 FICA P42
114 FICA XNL
115 FICA T56X
116 FICA Temporary
117 FICA XNH
118 FICA DZWf = X1W
119 FICA DZBETA = X1B
120 FICA T3S
121 FICA DT3S
122 FICA T56S
123 FICA DT56S
124 FICA EIPS3
125 FICA EIT56
126 FICA EIPS56
127 FICA SPS3 (LSB)
128 FICA ST546 (LSB)
129 FICA SP15 (LSB)
130 FICA LSYNC
131 FICA NSYNC
132 FICA XNHC
133 FICA EXNL
134 FICA EPS3
135 FICA EXNH
136 FICA ET56
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
209 FICA 2
210
211
212
213
214
215
216
217 Z^{-1}
218
219
220
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}
243 Decel Schedule Z^{-2}
244 FICA 1 Z^{-2}
245 N1K Schedule Z^{-2}
246 N1K Gain Z^{-2}
247 N1K Max Z^{-2}
248 MVP Feedback Rate Z^{-2}
249 MVP Bias Z^{-2}
250 MVP Gain Z^{-2}
251 T41C Ref. Z^{-2}
252 DPS Power Demand Z^{-2}
253 FICA 3 Z^{-2}
254 FICA 4 Z^{-2}
255 FICA 2 Z^{-2}

5.0 PROGRAM MEMORY LISTING

```
0 LAI 1
1 STO 1
2 INP 1
3 LAI 2048
4 STO 2
5 SUB 1
6 OUT 1
7 RSH 2
8 STO 53
9 LAI 0
10 OUT 0
11 STO 0
12 LAI 4095
13 STO 57
14 STO 95
15 STO 56
16 STO 140
17 STO 55
18 STO 111
19 STO 160
20 INP 1
21 STO 3
22 OUT 14
```

```
23 LAI 683
24 ADD 3
25 SUB 0
26 BRMR 4
27 ROT 0
28 OUT 0
29 JMPR 5
30 LAI 2730
31 ADD 3
32 SUB 0
33 BRMR 3
34 LDA 0
35 JMPR 2
36 LDA 1
37 STO 61
38 INP 0
39 RSHM 2
40 OUT 14
41 STO 0
42 INP 1
43 STO 157
```

Check Command Test Word

```
44 BRMR 5
45 LDA 2
46 RSHM 2
47 ROT 2
48 JMPR 5
49 OUT 0
50 OUT 0
51 OUT 0
52 LDA 0
53 ADD 67
54 STO 67
55 LAI 972
56 STO 4
57 INP 0
58 STO 74
59 INP 1
60 STO 188
61 OUT 14
```

```
62 LDA 6
63 SUB 4
64 BRMR 7
65 LAI 3021
66 ADD 6
67 SUB 0
68 LDA 0
69 BRMR 0
70 JMPR 0
71 ROT 0
72 OUT 0
73 OUT 0
74 JMPR -5
75 LDA 1
76 STO 5
77 ADD 68
78 RSHM 2
79 STO 69
80 LDA 5
81 STO 68
82 LDA 0
83 SUB 69
84 LDA 0
85 BRMR 2
86 LAI 256
87 ADD 67
88 STO 67
```

Check A/D & D/A Test Word

```
89 INP 0
90 OUT 14
91 STO 42
92 INP 1
```

```
93 LDA 235
94 SUB 0
95 BRMR 2
96 JMPR 2
97 LDA 233
98 STO 235
99 LAI 0
100 LSH 2
101 STO 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
```

Decode Mode Word

(cont. to 119)

```
110 STO 21
111 LDA 0
112 LSH 2
113 STO 157
114 LDA 0
115 LSH 2
116 STO 23
117 LDA 0
118 LSH 2
119 STO 22
```

```
120 LDA 0
121 LSH 2
122 STO 24
123 INP 0
124 OUT 14
125 STO 45
126 INP 1
```

```
127 LDA 48
128 RSHM 2
129 STO 7
130 LAI 647
131 MPYM 47
132 STO 8
133 ADD 8
134 ADD 1
135 STO 10
136 SUB 7
137 LDA 10
138 ADD 1
139 BRMR 2
140 JMPR 2
141 LDA 7
142 STO 7
143 LDA 8
144 DIV 7
145 ROT 0
146 STO 34
```

Compute PSTI/PTO

```
147 INP 0
148 OUT 14
149 STO 46
150 INP 1
151 STO 189
152 ROT 0
153 ROT 0
154 INP 0
155 OUT 14
156 STO 41
157 INP 1
158 STO 190
159 ROT 0
160 ROT 0
161 INP 0
162 OUT 14
163 STO 40
164 INP 1
165 STO 191
```

```
166 LAI 126
167 STO 3
168 LDA 40
169 SUB 0
170 BRMR 5
171 SUB 3
172 LDA 40
173 BRMR 6
174 JMPR 6
175 OUT 0
176 OUT 0
177 OUT 0
178 JMPR -4
179 LDA 3
180 STO 3
181 LMI 2212
182 MPYM 3
183 STO 3
184 LAI 3488
185 STO 4
186 LMI 608
187 MPYM 250
188 ADD 4
189 LAI 0
190 MPYM 3
191 STO 3
192 INP 0
193 OUT 14
194 STO 48
195 INP 1
196 STO 192
197 LMI 114
198 MPYM 249
199 STO 4
200 LAI 57
201 SUB 4
202 ADD 3
203 STO 3
204 LDA 2
205 SUB 1
206 STO 4
207 SUB 3
208 LDA 3
209 BRMR 2
210 JMPR 2
211 LDA 4
212 STO 185
213 STO 43
```

HF Feedback Gain & Bias Adjustment

```
214 INP 0
215 OUT 14
216 STO 44
217 INP 1
218 STO 193
```

(Cont'd. on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
219 LAI   2772
220 STO      4
221 LMI   1323
222 MPYM    46
223 ADD      4
224 STO    132
225 INP      0
226 OUT     14
227 STO     47
228 INP      1
229 STO    194
230 LAI   1355
231 STO      5
232 LMI   1232
233 MPYM   132
234 STO      0
235 INP      0
236 OUT     14
237 STO     38
238 INP      1
239 STO    195
240 LAI   1233
241 SUB      0
242 ADD      5
243 STO      5
244 LMI    215
245 MPYM   245
246 ADD      5
247 STO      5
248 INP      0
249 OUT     14
250 INP      1
251 STO    196
252 LAI   1600
253 STO      5
254 LMI    215
255 MPYM   247
256 ADD      5
257 STO      0
258 SUB      5
259 LDA      5
260 BRMR     2
261 JMPR     2
262 LDA      0
263 STO      5
```

Generate Max. N1K Schedule

```
264 INP      0
265 OUT     14
266 STO     75
267 INP      1
268 STO    197
```

```
269 LMI    745
270 MPYM   252
271 STO      6
272 INP      0
273 OUT     14
274 STO     76
275 INP      1
276 STO    198
277 LAI   3418
278 SUB      6
279 LAI      0
280 MPYM   252
281 STO      6
282 INP      0
283 OUT     14
284 STO     77
285 INP      1
286 STO    199
287 LAI   1422
288 ADD      6
289 LAI      0
290 MPY      5
291 STO      5
```

Compute N1K Demand.

```
292 INP      0
293 OUT     14
294 STO     78
295 INP      1
296 STO    200
```

```
297 LAI   1842
298 STO      7
299 LMI   2454
300 MPYM    46
301 RSHM     2
302 RSHM     2
303 RSHM     2
304 STO      6
305 INP      0
306 OUT     14
307 STO     79
308 INP      1
309 STO    201
310 LAI   3471
311 SUB      6
312 LAI      0
313 MPYM    46
314 RSHM     2
315 RSHM     2
316 RSHM     2
317 ADD      7
318 STO     39
```

Compute DRTH12

```
319 LAI      0
320 MPYM     5
321 LSH      2
322 STO    184
323 INP      0
324 OUT     14
325 STO     80
326 INP      1
327 STO    202
```

```
328 LMI    779
329 MPYM    48
```

(Cont'd. to 1854)

```
330 STO    101
331 INP      0
332 OUT     14
333 STO     81
334 LAI    268
335 STO      4
336 LMI    129
337 MPYM    46
338 ADD      4
339 STO     99
340 LAI   1322
341 SUB    132
342 LDA      0
343 BRMR     5
344 OUT      0
345 JMPR     5
346 OUT      0
347 JMPR     5
348 SUB     22
349 BRMR    -3
350 STO    130
351 STO    131
352 LMI   1906
353 MPYM    45
354 STO    150
355 LMI   1586
356 MPYM    42
357 STO    151
358 LMI   1536
359 MPYM    44
360 STO    154
361 LMI    739
362 MPYM    41
363 STO      3
364 LAI    253
365 ADD      3
366 STO    152
367 LAI   3994
368 ADD     43
369 STO      3
370 LMI   3703
371 MPY      3
372 STO    153
373 LAI   3944
374 ADD     25
375 STO      3
376 LMI   3607
377 MPYM     3
378 STO    155
379 LMI   1280
380 MPYM    81
381 STO      3
382 LAI    294
383 ADD      3
384 STO    156
```

FICA

```
385 LDA      0
386 SUB    131
387 BRMP   443
388 LDA    150
389 STO    114
390 LDA    151
391 STO    117
392 LDA    154
393 STO    102
394 LDA    152
395 STO    120
396 LDA    153
397 STO    100
398 LDA    155
399 STO    144
400 LDA    156
401 STO    122
402 LDA     99
403 STO      5
404 LAI    149
405 STO      3
406 JMPP  3903
407 LMI    905
408 MPYM   114
409 DIV      5
410 ROI      0
411 STO    149
412 LMI   2233
413 MPY    149
414 SUB      3
415 LAI      0
416 MPY    149
417 LSH      2
418 STO      3
419 LAI     24
420 ADD      3
421 LAI      0
422 MPY    101
423 LSH      2
424 ADD    101
425 STO    106
426 LDA    150
427 STO    104
428 LDA      0
429 STO    103
430 STO    109
431 STO    107
432 STO    103
433 STO    105
434 STO    110
435 LAI      1
436 OUT      0
437 OUT      0
438 STO      1
439 LAI    304
```

FICA

(Cont'd. on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
440 SUB      1
441 BRMP   662
442 JMPR    -2
443 LDA      1
444 ADD    111
445 STO    111
446 LMI   1132
447 MPY    137
448 ADD    136
449 STO      3
450 LMI   1371
451 MPY      3
452 ADD    134
453 STO      3
454 LMI   3470
455 MPY      3
456 ADD    135
457 STO      3
458 LMI    145
459 MPY      3
460 ADD    133
461 STO      3
462 LMI   3590
463 MPY      3
464 ADD    114
465 STO    114
466 LMI     50
467 MPY    158
468 STO      5
469 ROT      0
470 STO      6
471 LDA    114
472 STO      7
473 LDA    136
474 STO      8
475 JMPP  4019
476 LDA      7
477 STO    114
478 LDA      8
479 STO    136
480 LMI    563
481 MPY    137
482 ADD    139
483 STO      3
484 LMI   3125
485 MPY      3
486 STO      3
487 LDA    133
488 SUB      3
489 STO      3
490 LMI    659
491 MPY      3
492 STO      3
493 LDA    134
494 SUB      3
```

FICA

```
495 STO      3
496 LMI    502
497 MPY      3
498 ADD    135
499 STO      3
500 LMI   3358
501 MPY      3
502 ADD    117
503 STO    117
504 LMI     53
505 MPY    159
506 STO      5
507 ROT      0
508 STO      6
509 LDA    117
510 STO      7
511 LDA    141
512 STO      8
513 JMPP  4019
514 LDA      7
515 STO    117
516 LDA      8
517 STO    141
518 LMI   2732
519 MPY    136
520 ADD    139
521 STO      3
522 LMI   2365
523 MPY      3
524 STO      3
525 LDA    133
526 SUB      3
527 STO      3
528 LMI   3294
529 MPY      3
530 ADD    137
531 STO      3
532 LMI   1076
533 MPY      3
534 ADD    135
535 STO      3
536 LMI   3084
537 MPY      3
538 ADD    134
539 ADD    134
540 STO      3
541 LMI   3231
542 MPY      3
543 ADD    100
544 STO    100
545 LMI   9750
```

FICA

```
546 MPY    118
547 STO      5
548 ROT      0
549 STO      6
550 LDA    100
551 STO      7
552 LDA    142
553 STO      8
554 JMPP  4019
555 LDA      7
556 STO    100
557 LDA      8
558 STO    142
559 LMI    528
560 MPY    135
561 STO      3
562 LDA    134
563 SUB      3
564 STO      3
565 LMI    310
566 MPY      3
567 STO      3
568 LDA    143
569 SUB      3
570 STO      3
571 LMI    570
572 MPY      3
573 ADD    144
574 STO    144
575 LMI    128
576 MPY    119
577 STO      5
578 ROT      0
579 STO      6
580 LDA    144
581 STO      7
582 LDA    145
583 STO      8
584 JMPP  4019
585 LDA      7
586 STO    144
587 LDA      8
588 STO    145
589 LDA    146
590 LAI      0
591 LSH     -2
592 LSH      2
593 LSH      2
594 LDA      0
595 LSH      2
596 STO     10
597 LDA      0
598 LSH      2
599 STO    163
600 LMI   1241
```

FICA

```
601 MPY    134
602 ADD    136
603 STO      3
604 LMI   2066
605 MPY      3
606 ADD    135
607 STO      3
608 LMI   2626
609 MPY      3
610 ADD    133
611 STO      3
612 LMI    816
613 MPY      3
614 ADD    139
615 STO      3
616 LMI   3452
617 MPY      3
618 ADD    120
619 STO      3
620 LDA      0
621 SUB     10
622 LDA      3
623 BRAR     2
624 JMPR     2
625 LDA    120
626 STO    120
627 LMI    147
628 MPY    121
629 STO      5
630 ROT      0
631 STO      6
632 LDA    120
633 STO      7
634 LDA    147
635 STO      8
636 JMPP  4019
637 LDA      7
638 STO    120
639 LDA      8
640 STO    147
641 LMI   1040
642 MPY    134
643 ADD    135
644 STO      3
645 LMI   1369
646 MPY      3
647 ADD    139
648 STO      3
649 LMI   2932
650 MPY      3
651 ADD    133
652 STO      3
653 LMI    948
654 MPY      3
655 ADD    136
```

FICA

(Cont'd. on next page)

```
656 SIO    3
657 LAI -2048
658 MPY    3
659 ADD  122
660 SIO    3
661 LDA    0
662 SUB  183
663 LDA    3
664 BRMR   2
665 JMPR   2
666 LDA  122
667 SIO  122
668 LAI  229
669 MPY  123
670 SIO    5
671 ROT    0
672 SIO    6
673 LDA  122
674 SIO    7
675 LDA  146
676 SIO    8
677 JMPP 4019
678 LDA    7
679 SIO  122
680 LDA    8
681 SIO  148
682 LAI  132
683 ADD  100
684 SIO    7
685 LAI 3048
686 MPYM   7
687 LAI    0
688 MPYM   7
689 LSH    2
690 LSH    2
691 SIO   98
692 LDA   99
693 SIO    5
694 JMPP 3983
695 LDA  102
696 ADD  103
697 ADD  108
698 SIO  102
699 LDA  104
700 ADD  105
701 ADD  109
702 SIO  104
703 LDA  106
704 ADD  107
705 ADD  110
706 SIO  106
707 LAI 2163
708 MPYM 102
709 LSH    2
710 SIO    3
```

FICA

```
711 LMI  1024
712 MPY   106
713 DIV   101
714 ROT     0
715 SIO     6
716 LMI   905
717 MPY   114
718 DIV     5
719 ROT     0
720 SIO     4
721 LMI  3628
722 MPYM    6
723 SIO     7
724 LMI  2152
725 MPYM    4
726 LSH     2
727 SUB     7
728 SIO     7
729 LAI   820
730 ADD     7
731 SIO    12
732 LAI     0
733 MPYM  101
734 RSHM    2
735 RSHM    2
736 DIV     5
737 ROT     0
738 SIO     7
739 LMI  3620
740 MPY     7
741 LSH     2
742 LSH     2
743 LSH     2
744 SIO     9
745 LMI   272
746 MPY     4
747 SIO     7
748 LMI  1776
749 MPYM    6
750 LSH     2
751 SUB     7
752 SIO     7
753 LAI  1195
754 ADD     7
755 LAI     0
756 MPYM   99
757 LSH     2
758 SIO     8
759 LMI  1311
760 MPYM   99
761 SIO     7
762 LMI  2704
763 MPYM    8
764 LSH     2
765 SUB     7
```

FICA

```
766 SIO     5
767 SIO   183
768 JMPP 3983
769 LMI  1034
770 MPYM  117
771 DIV     5
772 ROT     0
773 SIO   132
774 LAI   187
775 SUB   132
776 BRMR    9
777 LAI     1
778 SIO     1
779 LAI    24
780 SUB     1
781 BRMR    2
782 JMPR   -2
783 LDA   106
784 JMPR   16
785 LMI   833
786 MPYM    4
787 SIO     7
788 LAI   588
789 SUB     7
790 LAI     0
791 MPYM    4
792 LSH     2
793 SIO     7
794 LAI   865
795 ADD     7
796 LAI     0
797 MPYM  106
798 LSH     2
799 LSH     2
800 SIO     4
801 LAI  1669
802 SIO     7
803 LAI   540
804 SIO    10
805 SUB   132
806 LDA    10
807 BRMR    4
808 OUT     0
809 OUT     0
810 JMPR    4
811 LDA     7
812 SUB   132
813 LDA   132
814 BRMR    2
815 JMPR    2
816 LDA     7
817 SIO    14
818 LAI  1014
819 SIO    17
820 LAI   295
```

FICA

```
821 SIO    10
822 LAI   764
823 SIO    15
824 LAI  1207
825 SIO     7
826 LDA    14
827 SUB     7
828 SIO     7
829 BRMP  864
830 SUB    10
831 SIO    10
832 BRMP  848
833 LMI  3991
834 MPYM   10
835 LSH     2
836 LSH     2
837 SIO     7
838 LAI  3064
839 SUB     7
840 LAI     0
841 MPYM   10
842 LSH     2
843 LSH     2
844 SIO     7
845 LAI   394
846 SUB     7
847 JMPP  362
848 LMI  2478
849 MPYM    7
850 LSH     2
851 LSH     2
852 LSH     2
853 SIO    10
854 LAI   940
855 ADD    10
856 LAI     0
857 MPYM    7
858 LSH     2
859 LSH     2
860 SIO    10
861 LAI  1078
862 SUB    10
863 JMPP  913
864 LDA    14
865 SUB    17
866 SIO    10
867 BRMP  883
868 LMI  3677
869 MPYM   10
870 LSH     2
871 LSH     2
872 LSH     2
873 SIO     7
874 LAI  3534
875 SUB     7
```

FICA

(Cont'd. on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
876 LAI     0
877 MPYM   10
878 LSH     2
879 STO     7
880 LAI  1284
881 SUB     7
882 JMPP  913
883 LDA    14
884 SUB    15
885 STO     7
886 JMPP  902
887 LAI  3157
888 MPYM    7
889 LSH     2
890 LSH     2
891 LSH     2
892 STO    10
893 LAI  1143
894 ADD    10
895 LAI     0
896 MPYM    7
897 STO    10
898 LAI  1429
899 SUB    10
900 STO     7
901 JMPP  915
902 LAI  2984
903 MPYM   14
904 LSH     2
905 STO     7
906 LAI  3435
907 SUB     7
908 LAI     0
909 MPYM   14
910 STO     7
911 LAI  1879
912 SUB     7
913 OUT     0
914 JMPP  900
915 LAI  2144
916 MPYM    7
917 STO    14
918 LAI   127
919 STO    15
920 LAI  3002
921 SUB    14
922 LAI     0
923 MPYM    7
924 LSH     2
925 SUB    15
926 STO    16
927 LAI  2144
928 MPYM  144
929 STO     7
930 LAI  3002
```

FICA

```
931 SUB     7
932 LAI     0
933 MPY   144
934 LSH     2
935 STO     7
936 LAI  3969
937 ADD     7
938 SUB    16
939 STO    16
940 LMI   819
941 MPYM    3
942 STO    10
943 ADD    10
944 ADD     1
945 STO    14
946 SUB     4
947 LDA    14
948 BRMR    2
949 JMPR    2
950 LDA     4
951 STO    14
952 LDA    10
953 DIV    14
954 ROT     0
955 STO     3
956 LAI  1009
957 STO    14
958 LAI   516
959 STO    17
960 LMI   467
961 MPYM    3
962 STO    10
963 LDA   132
964 SUB    10
965 SUB    14
966 LAI     0
967 MPYM    4
968 DIV     5
969 LDA     0
970 ROT     0
971 RSHM    2
972 DIV    17
973 ROT     0
974 STO     4
975 LMI  1866
976 MPYM  132
977 LAI     0
978 MPYM  132
979 LSH     2
980 SUB   132
981 STO    17
982 LAI  4017
983 SUB    16
984 STO    10
985 LDA     0
```

FICA

```
986 SUB    10
987 BRMR    4
988 JMPR    4
989 OUT     0
990 JMPR   34
991 LDA    10
992 LAI     0
993 MPY    16
994 LSH     2
995 STO    10
996 LAI   863
997 BRMR    3
998 SUB    10
999 JMPR    3
1000 ADD   10
1001 OUT    0
1002 STO   10
1003 LMI 3579
1004 MPYM 132
1005 STO    7
1006 LAI  280
1007 ADD    7
1008 LAI    0
1009 MPY   10
1010 LSH    2
1011 STO   10
1012 LDA    0
1013 SUB   10
1014 BRMR   2
1015 JMPR   2
1016 LDA   10
1017 LAI    0
1018 MPY   16
1019 LSH    2
1020 STO   18
1021 BRMR -32
1022 LDA    0
1023 SUB   18
1024 STO   18
1025 LAI 1016
1026 STO    7
1027 LAI 2187
1028 MPY   18
1029 STO   10
1030 LAI 3801
1031 MPY   17
1032 ADD   10
1033 ADD    7
1034 STO   10
1035 LDA    0
1036 SUB   10
1037 BRMR   4
1038 JMPR   4
1039 OUT    0
1040 JMPR  16
```

FICA

```
1041 LDA   10
1042 LAI    0
1043 MPY   16
1044 LSH    2
1045 LSH    2
1046 LSH    2
1047 STO    7
1048 LSH    2
1049 LSH    2
1050 ADD    7
1051 STO    7
1052 LDA    0
1053 BRMR -14
1054 SUB    7
1055 STO    7
1056 LDA    4
1057 LAI    0
1058 MPY    7
1059 LSH    2
1060 STO    7
1061 LDA    4
1062 SUB    7
1063 STO    4
1064 LMI 3929
1065 MPY    4
1066 STO   16
1067 LMI  223
1068 MPY  132
1069 STO   17
1070 LAI 1160
1071 SUB   17
1072 STO   17
1073 LMI 2462
1074 MPY    3
1075 ADD   17
1076 LAI    0
1077 MPYM 163
1078 STO   17
1079 LSH    2
1080 LSH    2
1081 ADD   17
1082 STO   17
1083 LMI  569
1084 MPY   98
1085 DIV   16
1086 ROT    0
1087 STO    3
1088 LMI 2587
1089 MPY    3
1090 STO    7
1091 LDA    2
1092 SUB    7
1093 LAI    0
1094 MPY    3
1095 LSH    2
```

FICA

(Cont'd. on next page)

```
1096 LSH     2
1097 STO     7
1098 LAI    53
1099 MPY     7
1100 ADD     7
1101 STO     7
1102 LAI    26
1103 ADD     7
1104 STO     7
1105 LAI  3277
1106 MPY    17
1107 ADD     7
1108 STO    13
1109 STO     5
1110 LAI   819
1111 MPY     3
1112 LAI     0
1113 MPY    16
1114 ADD    16
1115 STO    18
1116 JMPP 3983
1117 LAI  3554
1118 MPY     5
1119 LAI     0
1120 MPY    16
1121 LSH     2
1122 STO    19
1123 LAI   405
1124 STO    14
1125 LAI   410
1126 MPY     4
1127 STO     7
1128 LDA     9
1129 SUB     7
1130 STO    10
1131 LAI     0
1132 MPY    10
1133 ROT     2
1134 STO   106
1135 LDA     0
1136 MPYM    8
1137 DIV    14
1138 ROT     0
1139 STO     5
1140 LAI    67
1141 MPY     5
1142 STO    14
1143 LAI   134
1144 ADD    14
1145 LAI     0
1146 MPY     5
1147 LSH     2
1148 STO    14
1149 LDA   106
1150 SUB    14
```

FICA

```
1151 STO     5
1152 LAI   243
1153 STO    14
1154 LMI   114
1155 MPY    98
1156 ADD     4
1157 STO    15
1158 LAI     0
1159 MPYM   14
1160 DIV     5
1161 LDA     0
1162 MPYM   15
1163 LAI     0
1164 MPY   104
1165 ADD     5
1166 STO    14
1167 LMI   819
1168 MPY    19
1169 DIV    14
1170 ROT     0
1171 STO   112
1172 LAI   895
1173 SUB   112
1174 BRMR   17
1175 LAI   737
1176 STO   181
1177 LAI   297
1178 ADD   112
1179 LAI     0
1180 MPY   112
1181 LSH     2
1182 STO     7
1183 LAI   350
1184 ADD     7
1185 LAI     0
1186 MPY    14
1187 DIV   181
1188 ROT     0
1189 OUT     0
1190 JMPR   17
1191 LAI   100
1192 MPY   112
1193 STO     7
1194 LAI  1340
1195 ADD     7
1196 LAI     0
1197 MPY   112
1198 LSH     2
1199 STO     7
1200 LAI     9
1201 ADD     7
1202 LAI     0
1203 MPY    14
1204 LSH     2
1205 LSH     2
```

FICA

```
1206 LSH     2
1207 STO   113
1208 LMI   163
1209 MPY   113
1210 DIV    19
1211 ROT     0
1212 STO     7
1213 LAI  1674
1214 ADD     7
1215 LAI     0
1216 MPY    13
1217 LSH     2
1218 STO   112
1219 LMI   141
1220 MPY    14
1221 DIV   113
1222 ROT     0
1223 RSH     2
1224 STO     7
1225 LAI   509
1226 SUB     7
1227 LAI     0
1228 MPY    14
1229 DIV   113
1230 ROT     0
1231 STO     7
1232 LAI  1287
1233 ADD     7
1234 LAI     0
1235 MPY   112
1236 LSH     2
1237 STO   115
1238 LMI    11
1239 MPY    98
1240 ADD     9
1241 STO   116
1242 LAI   404
1243 MPY   104
1244 STO     7
1245 LAI     9
1246 ADD     7
1247 LAI     0
1248 MPYM   15
1249 STO     7
1250 LMI  3906
1251 MPY     8
1252 LAI     0
1253 MPY    10
1254 ADD     7
1255 DIV   116
1256 ROT     0
1257 STO     8
1258 LDA   244
1259 RSHM    2
1260 STO     7
```

FICA

```
1261 LMI    94
1262 MPY   116
1263 DIV   101
1264 LDA     0
1265 MPY   116
1266 DIV     7
1267 LDA     0
1268 MPY     8
1269 DIV     7
1270 ROT     0
1271 STO     7
1272 LDA   101
1273 ADD     7
1274 STO    10
1275 LMI   868
1276 MPY   116
1277 LAI     0
1278 MPY     8
1279 DIV    10
1280 LDA     0
1281 MPY   116
1282 STO     7
1283 LDA    10
1284 SUB     7
1285 STO     8
1286 LSH    12
1287 LAI     0
1288 MPY    12
1289 LSH     2
1290 STO    12
1291 LAI    61
1292 STO     7
1293 LMI  2840
1294 MPY    12
1295 LSH     2
1296 SUB     7
1297 LAI     0
1298 MPY    12
1299 LSH     2
1300 STO     7
1301 LAI   102
1302 ADD     7
1303 STO   116
1304 LAI  1021
1305 STO     7
1306 LAI   252
1307 STO   180
1308 LAI   614
1309 STO   181
1310 LDA     6
1311 SUB     7
1312 LAI     0
1313 MPY     9
1314 DIV   181
1315 LDA     0
```

FICA

(Cont'd. on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
1316 MPY    99
1317 DIV   100
1318 ROT     0
1319 STO     6
1320 LDA    17
1321 SUB   183
1322 LAI     0
1323 MPY     4
1324 LSH     2
1325 LSH     2
1326 STO     7
1327 LMI  2263
1328 MPY     7
1329 LSH     2
1330 LSH     2
1331 STO     9
1332 LMI   925
1333 MPY    19
1334 DIV   113
1335 ROT     0
1336 STO     7
1337 LMI   602
1338 ADD     7
1339 STO     7
1340 LMI   556
1341 MPY    13
1342 ADD     7
1343 STO     4
1344 LMI   369
1345 MPY     3
1346 STO     7
1347 LMI  1843
1348 ADD     7
1349 LAI     0
1350 MPY     4
1351 LSH     2
1352 LAI     0
1353 MPY    13
1354 LSH     2
1355 LAI     0
1356 MPY    16
1357 LSH     2
1358 STO     4
1359 LAI  3641
1360 MPY     4
1361 LSH     2
1362 STO     4
1363 LMI   268
1364 MPY   113
1365 DIV    14
1366 ROT     0
1367 STO     7
1368 LMI  1309
1369 SUB     7
1370 LAI     0
```

FICA

```
1371 MPY   113
1372 DIV    14
1373 ROT     0
1374 STO     7
1375 LAI  3586
1376 ADD     7
1377 STO   183
1378 LMI   369
1379 MPY     3
1380 STO     7
1381 LAI  1843
1382 ADD     7
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 STO   183
1394 LMI  2913
1395 MPY   183
1396 LSH     2
1397 STO   183
1398 LMI  4055
1399 MPY   183
1400 SUB     6
1401 STO     7
1402 LDA     0
1403 SUB     7
1404 BRMR    2
1405 JMPR    2
1406 LDA     7
1407 STO     7
1408 LMI  2047
1409 MPY     7
1410 DIV   114
1411 ROT     0
1412 STO     7
1413 LDA     0
1414 BRMR    3
1415 SUB     7
1416 JMPR    3
1417 LDA     7
1418 OUT     0
1419 STO   183
1420 LMI   207
1421 MPY   183
1422 ADD   183
1423 STO   158
1424 LDA     4
1425 SUB     9
```

FICA

```
1426 STO     7
1427 LDA     0
1428 SUB     7
1429 BRMR    2
1430 JMPR    2
1431 LDA     7
1432 STO     7
1433 LMI  1345
1434 MPY     7
1435 DIV   117
1436 ROT     0
1437 STO     7
1438 LDA     0
1439 BRMR    3
1440 SUB     7
1441 JMPR    3
1442 LDA     7
1443 OUT     0
1444 STO     4
1445 LMI  1262
1446 MPY     4
1447 ADD     4
1448 STO   159
1449 LDA    17
1450 SUB   120
1451 STO     7
1452 LDA    16
1453 LAI     0
1454 MPY     7
1455 LSH     2
1456 STO   121
1457 LDA   104
1458 SUB   122
1459 STO     7
1460 LDA    15
1461 LAI     0
1462 MPY     7
1463 LSH     2
1464 STO   123
1465 LDA   102
1466 SUB    19
1467 STO   124
1468 LDA   104
1469 SUB   115
1470 STO   125
1471 LDA     5
1472 SUB     8
1473 STO   126
1474 LMI  2416
1475 MPY   124
1476 STO   108
1477 ROT     0
1478 STO     7
1479 LMI     5
1480 MPY   125
```

FICA

```
1481 ROT     0
1482 SUB     7
1483 STO     7
1484 ROT     0
1485 SUBC  106
1486 STO   108
1487 LMI   204
1488 MPY   126
1489 ROT     0
1490 ADD     7
1491 STO     7
1492 ROT     0
1493 ADDC  108
1494 STO   108
1495 LDA   127
1496 ADD     7
1497 STO   127
1498 LDA   108
1499 ADDC  103
1500 STO   103
1501 LMI   610
1502 MPY   124
1503 STO   105
1504 ROT     0
1505 STO     7
1506 LMI  2956
1507 MPY   125
1508 ROT     0
1509 ADD     7
1510 STO     7
1511 ROT     0
1512 ADDC  105
1513 STO   105
1514 LMI   927
1515 MPY   126
1516 ROT     0
1517 SUB     7
1518 STO     7
1519 ROT     0
1520 SUBC  105
1521 STO   105
1522 LDA   128
1523 ADD     7
1524 STO   128
1525 LDA   105
1526 ADDC  109
1527 STO   109
1528 LMI    13
1529 MPY   124
1530 STO   110
1531 ROT     0
1532 STO     7
1533 LMI  1860
1534 MPY   126
1535 ROT     0
```

FICA

(Cont'd. on next page)

```
1536 ADD    7
1537 STO    7
1538 RSH    0
1539 ADDC 110
1540 STO  110
1541 LAI   44
1542 MPY  125
1543 RSH    0
1544 SUB    7
1545 STO    7
1546 RSH    0
1547 SUBC 110
1548 STO  110
1549 LDA  129
1550 ADD    7
1551 STO  129
1552 LDA  110
1553 ADDC 107
1554 STO  107
1555 LDA  130
1556 SUB  114
1557 STO  133
1558 LDA  151
1559 SUB  117
1560 STO  135
1561 LDA  152
1562 SUB  120
1563 STO  139
1564 LDA  153
1565 SUB  100
1566 STO  137
1567 LDA  155
1568 SUB  144
1569 STO  143
1570 LDA  154
1571 SUB   19
1572 STO  134
1573 LDA  155
1574 SUB  122
1575 STO  135
1576 LDA  133
1577 STO    3
1578 JMPP 4048
1579 LDA    3
1580 STO  161
1581 LDA  133
1582 STO    3
1583 JMPP 4048
1584 LDA    3
1585 STO  162
1586 LDA  139
1587 STO    3
1588 JMPP 4048
1589 LDA    3
1590 STO  155
```

FICA

```
1591 LDA  136
1592 STO    3
1593 JMPP 4048
1594 LDA    3
1595 STO  164
1596 LDA  137
1597 STO    3
1598 JMPP 4048
1599 LDA    3
1600 STO  165
1601 LDA  143
1602 STO    3
1603 JMPP 4048
1604 LDA    3
1605 STO  166
1606 LDA  134
1607 STO    3
1608 JMPP 4048
1609 LDA    3
1610 STO  167
1611 LDA    0
1612 STO  146
1613 SUB  130
1614 BRMR   7
1615 SUB    1
1616 BRMR   7
1617 LDA    0
1618 SUB   23
1619 BRMR   7
1620 JMPR   7
1621 OUT    0
1622 JMPR  -5
1623 OUT    0
1624 OUT    0
1625 JMPR  -5
1626 JMPP 1725
1627 LAI   77
1628 SUB  161
1629 LDA    2
1630 BRMR   3
1631 OUT    0
1632 JMPR   3
1633 ADD  146
1634 STO  146
1635 LAI   70
1636 SUB  162
1637 LDA    2
1638 RSHM   2
1639 STO  174
1640 BRMR   3
1641 OUT    0
1642 JMPR   3
1643 ADD  146
1644 STO  146
1645 LAI   42
```

FICA

```
1646 SUB  163
1647 LDA  174
1648 RSH    2
1649 RSH    2
1650 STO  175
1651 BRMR   3
1652 OUT    0
1653 JMPR   3
1654 ADD  146
1655 STO  146
1656 LAI   54
1657 SUB  164
1658 LDA  175
1659 RSH    2
1660 STO  176
1661 BRMR   3
1662 OUT    0
1663 JMPR   3
1664 ADD  146
1665 STO  146
1666 LAI  466
1667 SUB  165
1668 LDA  176
1669 RSH    2
1670 RSH    2
1671 STO  177
1672 BRMR   3
1673 OUT    0
1674 JMPR   3
1675 ADD  146
1676 STO  146
1677 LAI   77
1678 SUB  166
1679 LDA  177
1680 RSH    2
1681 STO  178
1682 BRMR   3
1683 OUT    0
1684 JMPR   3
1685 ADD  146
1686 STO  146
1687 LAI   69
1688 SUB  167
1689 LDA  178
1690 RSH    2
1691 RSH    2
1692 STO  179
1693 BRMR   3
1694 OUT    0
1695 JMPR   3
1696 ADD  146
1697 STO  146
1698 LDA  131
1699 ADD    1
1700 STO  131
```

FICA

```
1701 LDA    0
1702 SUB  146
1703 BRMR   7
1704 SUB    1
1705 BRMR   7
1706 LAI   10
1707 SUB  131
1708 BRMR   9
1709 JMPR   7
1710 OUT    0
1711 JMPR  -5
1712 OUT    0
1713 LAI    1
1714 STO  130
1715 OUT    0
1716 JMPR   3
1717 LDA    0
1718 STO  131
1719 LAI    1
1720 STO    1
1721 LAI   43
1722 SUB    1
1723 BRMP 1655
1724 JMPR  -2
1725 LAI   77
1726 SUB  161
1727 LAI 2201
1728 MPY  114
1729 LSH    2
1730 LSH    2
1731 STO    4
1732 LDA    0
1733 BRMR   7
1734 OUT    0
1735 OUT    0
1736 OUT    0
1737 OUT    0
1738 OUT    0
1739 JMPR   7
1740 STO  133
1741 LDA    4
1742 STO   45
1743 LDA    2
1744 ADD  146
1745 STO  146
1746 LAI   70
1747 SUB  162
1748 LAI 2545
1749 MPY  117
1750 BRMR   3
1751 LAI    0
1752 JMPR  14
1753 LSH    2
1754 LSH    2
1755 STO   42
```

FICA

ORIGINAL PAGE IS
OF POOR QUALITY

(Cont'd. on next page)

FICA

```
1756 LDA    0
1757 STO  135
1758 LDA  174
1759 OUT    0
1760 OUT    0
1761 ADD  146
1762 STO  146
1763 OUT    0
1764 OUT    0
1765 OUT    0
1766 LAI   42
1767 SUB  163
1768 LAI 3840
1769 ADD  125
1770 STO    4
1771 LMI 2085
1772 MPY    4
1773 BRMR   6
1774 LDA   95
1775 ADD   95
1776 SUB   95
1777 BRMR  -1
1778 JMPR   8
1779 LSH    2
1780 LSH    2
1781 LSH    2
1782 STO   41
1783 LDA    0
1784 STO  137
1785 LDA  175
1786 ADD  146
1787 STO  146
1788 LAI   54
1789 SUB  164
1790 LDA    0
1791 BRMR   5
1792 OUT    0
1793 OUT    0
1794 OUT    0
1795 JMPR   5
1796 STO  136
1797 LDA  176
1798 ADD  146
1799 STO  146
1800 LAI  102
1801 STO    8
1802 LAI  467
1803 SUB  165
1804 LMI 2267
1805 MPY  100
1806 LSH    2
1807 ADD    5
1808 BRMR   5
1809 LDA    1
1810 SUB    1
```

FICA

```
1811 BRMR   8
1812 JMPR  -2
1813 STO   43
1814 LDA    0
1815 STO  137
1816 LDA  177
1817 ADD  146
1818 STO  146
1819 LAI  152
1820 STO    8
1821 LAI   77
1822 SUB  166
1823 LMI 2326
1824 MPY  144
1825 LSH    2
1826 ADD    5
1827 BRMR   5
1828 LDA    1
1829 SUB    1
1830 BRMR   8
1831 JMPR  -2
1832 STO   25
1833 LDA    0
1834 STO  143
1835 LDA  178
1836 ADD  146
1837 STO  146
1838 LAI   69
1839 SUB  167
1840 LMI 2731
1841 MPY  102
1842 LSH    2
1843 LSH    2
1844 BRMR   5
1845 LDA    1
1846 SUB    1
1847 BRMR   8
1848 JMPR  -2
1849 STO   44
1850 LDA    0
1851 STO  134
1852 LDA  179
1853 ADD  146
1854 STO  146
1855 LDA   45
1856 RSHM   2
1857 STO    7
1858 LAI 1792
1859 STO    6
1860 SUB  184
1861 LDA  184
1862 BRMR   2
1863 JMPR   2
1864 LDA    6
1865 SUB    7
```

(Cont'd. to 1925)

Compute N1 Error Through KN1

```
1866 STO    5
1867 INP    1
1868 STO  203
1869 LAI  662
1870 STO    7
1871 LAI 3414
1872 MPYM 246
1873 ADD    7
1874 STO    6
1875 RSHM   2
1876 STO    7
1877 LAI 1433
1878 LAI  102
1879 DIV    7
1880 ROT    0
1881 STO    7
1882 INP    0
1883 OUT   14
1884 STO   82
1885 INP    1
1886 STO  204
1887 LDA    5
1888 SUB    0
1889 BRMR   5
1890 SUB    7
1891 BRMR   4
1892 LDA    7
1893 JMPR   4
1894 JMPR  -3
1895 LDA    5
1896 OUT    0
1897 STO    5
1898 LDA    0
1899 SUB    7
1900 STO    7
1901 INP    0
1902 OUT   14
1903 STO   83
1904 INP    1
1905 STO  205
1906 LDA    5
1907 SUB    0
1908 BRMR   2
1909 JMPR   2
1910 SUB    7
1911 BRMR   3
1912 LDA    5
1913 JMPR   3
1914 LDA    7
1915 OUT    0
1916 STO    5
1917 LMI 2561
1918 MPYM   6
1919 LAI    0
1920 MPY    5
```

Compute N1 Loop Rate Feedback

```
1921 LSH    2
1922 LSH    2
1923 LSH    2
1924 LSH    2
1925 STO    5
1926 INP    0
1927 OUT   14
1928 STO   84
1929 INP    1
1930 STO  206
1931 LAI  777
1932 STO    7
1933 LMI 3319
1934 MPYM 246
1935 ADD    7
1936 LAI    3
1937 MPYM   6
1938 STO    6
1939 INP    0
1940 OUT   14
1941 STO   85
1942 INP    1
1943 STO  207
1944 LAI 1679
1945 MPYM   6
1946 STO    6
1947 INP    0
1948 OUT   14
1949 STO   86
1950 INP    1
1951 STO  208
1952 LDA  185
1953 SUB   55
1954 STO   52
1955 LDA  185
1956 STO   55
1957 LDA    0
1958 SUB   53
1959 LDA    6
1960 BRMR   2
1961 JMPR   2
1962 SUB   53
1963 STO    8
1964 SUB    0
1965 LDA   52
1966 BRMR   7
1967 SUB    0
1968 BRMR   6
1969 SUB    6
1970 LDA    8
1971 BRMR   7
1972 JMPR   7
1973 SUB    0
1974 BRMR  -5
1975 JMPR  -5
```

(Cont'd. on next page)

```
1976 OUT    0
1977 JMPR  -5
1978 LDA   52
1979 STO    7
1980 LDA    7
1981 SUB    0
1982 LDA    0
1983 BRMR   7
1984 SUB    7
1985 LDA    7
1986 BRMR   2
1987 JMPR   2
1988 LDA    0
1989 JMPR   0
1990 LDA    0
1991 SUB    0
1992 SUB    7
1993 ADD    7
1994 BRMR   2
1995 JMPR   2
1996 LDA    7
1997 STO    7
1998 LDA   53
1999 SUB    0
2000 LDA    0
2001 BRMR   3
2002 SUB    6
2003 JMPR   3
2004 SUB    5
2005 SUB   53
2006 STO    6
2007 SUB    0
2008 LDA    7
2009 BRMR   7
2010 SUB    0
2011 BRMR   8
2012 SUB    6
2013 LDA    7
2014 [illegible] 7
2015 BRMR   7
2016 SUB    0
2017 BRMR  -5
2018 JMPR  -5
2019 OUT    0
2020 JMPR  -6
2021 LDA    3
2022 STO    6
2023 LAI  111
2024 MPY   53
2025 STO    8
2026 INP    0
2027 STO    9
2028 LDA   54
2029 SUB    9
2030 STO   54
```

Compute N1
Loop Rate
Feedback

```
2031 LDA    53
2032 SUBC    8
2033 ADD     6
2034 STO    55
2035 INP     0
2036 OUT    14
2037 STO    87
2038 INP     1
2039 STO   209
2040 LAI  2160
2041 MPY    53
2042 LSH     2
2043 STO    10
2044 JMPP 3799
2045 LDA     5
2046 STO     6
2047 INP     0
2048 OUT    14
2049 STO    88
2050 LAI  1491
2051 MPY   234
2052 STO     5
2053 JMPP 3799
2054 LDA     5
2055 STO    51
2056 INP     0
2057 OUT    14
2058 STO    89
2059 LDA     2
2060 SUB     1
2061 STO     7
2062 LDA     0
2063 SUB    20
2064 LDA     7
2065 BRMR    2
2066 JMPR    2
2067 LDA     5
2068 STO     5
2069 RSH     2
2070 STO     7
2071 LDA     6
2072 RSH     2
2073 SUB     7
2074 LDA     5
2075 BRMR    2
2076 JMPR    2
2077 LDA     6
2078 STO     6
2079 LDA    39
2080 RSHM    2
2081 STO     5
2082 LAI  3584
2083 LAI   255
2084 DIV     5
2085 ROI     0
```

Remote Input
Selection Steps

(Cont'd to 2199)

```
2086 STO     5
2087 ADD     5
2088 LAI     0
2089 MPYM   45
2090 STO     7
2091 INP     0
2092 OUT    14
2093 STO    71
2094 LAI  1048
2095 SUB     7
2096 BRMR   34
2097 LAI   605
2098 SUB     7
2099 BRMR   16
2100 LAI  1350
2101 MPYM    7
2102 STO     4
2103 OUT     0
2104 LAI   197
2105 ADD     4
2106 LAI     0
2107 MPYM    7
2108 STO     4
2109 OUT     0
2110 OUT     0
2111 LAI    18
2112 ADD     4
2113 OUT     0
2114 JMPR   49
2115 LAI   521
2116 STO     8
2117 LAI  2468
2118 MPYM    7
2119 LSH     2
2120 SUB     8
2121 LAI     0
2122 MPYM    7
2123 STO     4
2124 OUT     0
2125 OUT     0
2126 LAI    40
2127 ADD     4
2128 OUT     0
2129 JMPR   34
2130 LAI  1570
2131 SUB     7
2132 BRMR   16
2133 LAI  3395
2134 MPYM    7
2135 STO     4
2136 OUT     0
2137 LAI    56
2138 ADD     4
2139 LAI     0
2140 MPYM    7
```

Compute T25

```
2141 STO     4
2142 LAI     7
2143 STO     6
2144 LDA     4
2145 SUB     6
2146 OUT     0
2147 JMPR   16
2148 LAI  2373
2149 MPYM    7
2150 LSH     2
2151 STO     4
2152 LAI  3436
2153 SUB     4
2154 LAI     0
2155 MPYM    7
2156 LSH     2
2157 LSH     2
2158 STO     4
2159 LAI  2736
2160 SUB     4
2161 STO     4
2162 ADD     4
2163 STO     4
2164 INP     0
2165 OUT    14
2166 STO    70
2167 LDA   255
2168 SUB     2
2169 STO     8
2170 LAI  1639
2171 MPY     8
2172 STO     8
2173 INP     0
2174 OUT    14
2175 STO    90
2176 LDA     4
2177 LAI     0
2178 MPY     6
2179 ADD     4
2180 STO     4
2181 LAI  3367
2182 MPYM  162
2183 STO     9
2184 SUB     2
2185 STO    49
2186 INP     0
2187 OUT    14
2188 STO    91
2189 LDA     9
2190 LAI     0
2191 MPYM    4
2192 ADD    49
2193 SUB     0
2194 BRMR    5
2195 ADD     2
```

(Compute T25)

(Cont'd on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
2196 JMPR    3
2197 LDA    95
2198 OUT     0
2199 STO    49
2200 LMI   493
2201 MPYM   49
2202 STO     4
2203 LAI  2167
2204 SUB     4
2205 LAI     0
2206 MPYM   49
2207 STO     4
2208 LAI   785
2209 ADD     4
2210 STO    50
2211 LAI  1907
2212 STO     4
2213 LDA   252
2214 SUB     0
2215 BRMR    7
2216 SUB     4
2217 LDA     4
2218 BRMR    2
2219 JMPR    2
2220 LDA   252
2221 JMPR    6
2222 LDA     4
2223 OUT     0
2224 OUT     0
2225 OUT     0
2226 OUT     0
2227 STO     4
2228 LAI  1903
2229 STO     8
2230 LAI  4060
2231 MPYM    4
2232 ADD     8
2233 LAI     0
2234 MPYM   50
2235 STO     4
2236 LAI  1745
2237 STO     6
2238 LAI   160
2239 MPYM  240
2240 ADD     8
2241 STO     8
2242 SUB     4
2243 LDA     4
2244 BRMR    2
2245 JMPR    2
2246 LDA     8
2247 STO     4
2248 LDA    42
2249 RSH     2
2250 STO    11
```

Compute N2 Error

```
2251 LDA     4
2252 SUB    11
2253 STO     7
2254 LDA     4
2255 ADD     4
2256 LAI     0
2257 MPY     7
2258 STO     4
2259 LAI  1008
2260 STO    12
2261 LDA     4
2262 SUB     0
2263 BRMR    5
2264 SUB    12
2265 BRMR    4
2266 LDA    12
2267 JMPR    4
2268 JMPR   -3
2269 LDA     4
2270 OUT     0
2271 STO     4
2272 LDA     0
2273 SUB    12
2274 STO    13
2275 LDA     4
2276 SUB     0
2277 BRMR    2
2278 JMPR    2
2279 SUB    13
2280 BRMR    3
2281 LDA     4
2282 JMPR    3
2283 LDA    13
2284 OUT     0
2285 STO     4
2286 LDA    97
2287 SUB     2
2288 OUT    13
2289 LMI  3924
2290 MPY     4
2291 LSH     2
2292 STO     5
2293 LMI   148
2294 MPYM  239
2295 STO     9
2296 LDA   114
2297 OUT    13
2298 LAI   181
2299 SUB     9
2300 STO     9
2301 SUB    59
2302 STO     6
2303 LAI  3954
2304 STO    10
2305 LDA    52
```

Compute N2 Error

```
2306 SUB     0
2307 LDA     9
2308 BRMR    7
2309 SUB    52
2310 LDA    52
2311 BRMR    2
2312 JMPR    2
2313 LDA     7
2314 JMPR    0
2315 OUT     0
2316 LDA    10
2317 SUB    52
2318 ADD    52
2319 BRMR    2
2320 JMPR    2
2321 LDA    52
2322 STO     7
2323 SUB     8
2324 LDA     8
2325 BRMR    2
2326 JMPR    2
2327 LDA     7
2328 STO     7
2329 LDA    10
2330 SUB    59
2331 STO     9
2332 SUB     7
2333 LDA     9
2334 BRMR    2
2335 JMPR    2
2336 LDA     7
2337 STO     9
2338 LDA    96
2339 SUB     2
2340 OUT    13
2341 LMI   111
2342 MPY    59
2343 STO     8
2344 ROT     0
2345 STO    10
2346 LDA    62
2347 OUT    13
2348 LDA    60
2349 SUB    10
2350 STO    60
2351 LDA    59
2352 SUBC    8
2353 ADD     9
2354 STO    59
2355 LMI  2160
2356 MPY    59
2357 LSH     2
2358 STO    10
2359 LDA   140
2360 OUT    13
```

Compute N2 Error

```
2361 JMPP 3799
2362 LDA     5
2363 RSH     2
2364 STO     7
2365 LDA     6
2366 RSH     2
2367 SUB     7
2368 LDA     5
2369 BRMR    2
2370 JMPR    2
2371 LDA     6
2372 STO     6
2373 LAI   512
2374 BRMR    2
2375 JMPR    2
2376 LDA     0
2377 STO    73
2378 LDA    25
2379 ADD    25
2380 OUT    13
2381 LAI   951
2382 STO     7
2383 LMI   794
2384 MPYM  241
2385 ADD     7
2386 STO     7
2387 SUB    11
2388 STO    11
2389 LDA    60
2390 OUT    13
2391 LDA     7
2392 ADD     7
2393 LAI     0
2394 MPY    11
2395 STO    11
2396 SUB     0
2397 BRMR    5
2398 SUB    12
2399 BRMR    4
2400 LDA    12
2401 JMPR    4
2402 JMPR   -3
2403 LDA    11
2404 OUT     0
2405 STO    11
2406 LMI  3924
2407 MPY    11
2408 LSH     2
2409 STO     5
2410 LDA    31
2411 OUT    13
2412 JMPP 3199
2413 LDA     5
2414 STO     7
2415 LAI  1944
```

Compute N2 Idle Error

```
2416 STO     4
2417 SUB   155
2418 LDA   155
2419 BRMR    2
2420 JMPR    2
2421 LDA     4
2422 STO     5
2423 LDA    54
2424 OUT    13
2425 LAI   130
2426 SUB     3
2427 [illegible]  15
2428 LAI    31
2429 STO     5
2430 LAI  2257
2431 [illegible]   3
2432 LAI     0
2433 [illegible]   3
2434 LDA     2
2435 LSH     2
2436 LSR     2
2437 ADD     5
2438 STO     4
2439 ROT     0
2440 ROT     0
2441 JMPR   15
2442 LAI   152
2443 STO     5
2444 LAI  3919
2445 MPYM    3
2446 LAI     0
2447 MPY     3
2448 LSH     2
2449 LSH     2
2450 SUB     5
2451 STO     5
2452 LAI  1488
2453 [illegible]   5
2454 [illegible]   5
2455 OUT     0
2456 STO    26
2457 SUB    52
2458 STO     5
2459 LDA    59
2460 OUT    13
2461 LAI   554
2462 MPY     5
2463 STO     5
2464 ROT     0
2465 ADD    33
2466 STO    33
2467 LDA     5
2468 ADDC   52
2469 STO    52
2470 LDA    44
```

Compute WF

(Cont'd to 2559)

```
2471 RSHM    2
2472 STO     8
2473 LDA   252
2474 OUT    13
2475 LMI   943
2476 MPYM   52
2477 STO     9
2478 ADD     9
2479 ADD     1
2480 ADD     1
2481 STO     5
2482 SUB     8
2483 LDA     5
2484 BRMR    2
2485 JMPR    2
2486 LDA     8
2487 STO     5
2488 LDA     9
2489 DIV     5
2490 ROT     0
2491 STO     5
2492 LAI    75
2493 STO    10
2494 SUB     5
2495 LDA    10
2496 BRMR    2
2497 JMPR    2
2498 LDA     5
2499 STO     5
2500 LDA    74
2501 OUT    13
2502 LAI    59
2503 STO    10
2504 LMI  2426
2505 MPYM    5
2506 STO     9
2507 LDA    45
2508 OUT    13
2509 LAI  3900
2510 SUB     9
2511 LAI     0
2512 MPYM    5
2513 STO     9
2514 LDA    42
2515 OUT    13
2516 LAI  2296
2517 ADD     9
2518 LAI     0
2519 MPYM    5
2520 LSH     2
2521 SUB    10
2522 STO     5
2523 LAI   498
2524 STO     9
2525 LDA   111
```

Compute T41C Error

```
2526 OUT    13
2527 LMI  1455
2528 MPYM  -41
2529 ADD     9
2530 STO     9
2531 LDA     5
2532 SUB     0
2533 LDA    95
2534 BRMR    5
2535 OUT     0
2536 OUT     0
2537 OUT     0
2538 JMPR    5
2539 SUB     5
2540 STO    10
2541 SUB     9
2542 BRMR    3
2543 LDA     9
2544 JMPR    3
2545 LDA    10
2546 OUT     0
2547 ADD     5
2548 STO    31
2549 RSHM    2
2550 STO     9
2551 LDA   166
2552 OUT    13
2553 LAI  1301
2554 STO     5
2555 LMI   593
2556 MPYM  251
2557 ADD     5
2558 SUB     9
2559 STO     5
2560 LDA     0
2561 OUT    13
2562 LMI  2645
2563 MPY     5
2564 STO     5
2565 LAI    33
2566 STO     9
2567 SUB    29
2568 STO     4
2569 LDA    52
2570 SUB     0
2571 LDA     9
2572 BRMR    7
2573 SUB    52
2574 LDA    52
2575 BRMR    2
2576 JMPR    2
2577 LDA     9
2578 JMPR    6
2579 LDA     0
2580 SUB     9
```

Compute T41C Error

Compute T41C Rate Feedback

```
2581 SUB    52
2582 ADD    52
2583 BRMR    2
2584 JMPR    2
2585 LDA    52
2586 STO    12
2587 SUB     4
2588 LDA     4
2589 BRMR    2
2590 JMPR    2
2591 LDA    12
2592 STO    12
2593 LDA     9
2594 SUB     9
2595 STO     9
2596 SUB    29
2597 STO     4
2598 SUB    12
2599 LDA     4
2600 BRMR    2
2601 JMPR    2
2602 LDA    12
2603 STO     9
2604 LDA     6
2605 OUT    13
2606 LMI   554
2607 MPY    29
2608 STO     4
2609 ROT     0
2610 STO    12
2611 LDA    30
2612 SUB    12
2613 STO    30
2614 LDA    29
2615 SUBC    4
2616 ADD     9
2617 STO    29
2618 LDA    67
2619 OUT    13
2620 LDA     0
2621 STO    67
2622 LMI   221
2623 MPY    29
2624 ADD    29
2625 STO    10
2626 LDA     5
2627 SUB    10
2628 STO     5
2629 RSH     2
2630 STO     4
2631 LDA     6
2632 RSH     2
2633 SUB     4
2634 LDA     5
2635 BRMR    2
```

Compute T41C Rate Feedback

Select max. WF Channel Error

(Cont'd on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
2636 JMPR    2
2637 LDA     6
2638 STO     6
2639 LAI  1024
2640 BRMR    2
2641 JMPR    2
2642 LDA    73
2643 STO    73
2644 LDA    46
2645 OUT    13
2646 LAI  1638
2647 STO    12
2648 LDA    71
2649 BRMR    2
2650 SUB    12
2651 BRMR   16
2652 LDA    70
2653 RSHM    2
2654 SUB    12
2655 BRMR   16
2656 LDA    72
2657 SUB     1
2658 STO    72
2659 BRMR   15
2660 LDA     0
2661 OUT     0
2662 OUT     0
2663 OUT     0
2664 OUT     0
2665 OUT     0
2666 JMPR   16
2667 OUT     0
2668 OUT     0
2669 OUT     0
2670 OUT     0
2671 LAI     9
2672 STO    72
2673 JMPR   12
2674 LDA    95
2675 STO    72
2676 LDA     0
2677 SUB   157
2678 LDA     2
2679 BRMR    2
2680 JMPR    2
2681 STO     6
2682 RSHM    2
2683 ADD    67
2684 STO    67
2685 LDA     6
2686 RSH     2
2687 STO     4
2688 LDA    48
2689 OUT    13
2690 LDA     7
```

Select Max. WF Channel Error

Check for Excess Vibration

```
2691 RSH     2
2692 SUB     4
2693 LDA     7
2694 BRMR    2
2695 JMPR    2
2696 LDA     6
2697 STO     6
2698 LAI  1536
2699 BRMR    2
2700 JMPR    2
2701 LDA    73
2702 STO    73
2703 LDA    67
2704 LSH     2
2705 SUB     0
2706 LDA    73
2707 BRMR    2
2708 JMPR    2
2709 LDA    95
2710 STO    73
2711 LDA    38
2712 OUT    13
2713 LAI   433
2714 STO     4
2715 LMI   427
2716 MPYM   49
2717 STO     5
2718 LDA    47
2719 OUT    13
2720 LAI  2632
2721 SUB     5
2722 LAI     0
2723 MPYM   49
2724 ADD     4
2725 STO     4
2726 LDA    44
2727 OUT    13
2728 LAI  3406
2729 MPYM   50
2730 STO     5
2731 LDA     2
2732 RSHM    2
2733 RSHM    2
2734 ADD     1
2735 LAI   767
2736 DIV     5
2737 ROI     0
2738 STO     5
2739 LMI  2273
2740 MPYM    5
2741 LSH     2
2742 LAI     0
2743 MPYM   42
2744 STO    92
2745 LAI   344
```

Check for Excess Vibration

Compute Accel WF

```
2746 STO     7
2747 LAI   555
2748 STO     9
2749 LAI   450
2750 STO    10
2751 LDA    43
2752 ADD    43
2753 OUT    13
2754 LDA    92
2755 SUB     7
2756 BRMR   91
2757 STO     7
2758 SUB     9
2759 BRMR   58
2760 STO     7
2761 SUB    10
2762 BRMR   28
2763 STO     7
2764 LAI  1108
2765 STO     9
2766 LMI  2799
2767 MPY     7
2768 LSH     2
2769 STO    10
2770 LAI  2528
2771 SUB    10
2772 LAI     0
2773 MPY     7
2774 LSH     2
2775 LSH     2
2776 LSH     2
2777 STO    10
2778 LAI  3727
2779 ADD    10
2780 STO    10
2781 LDA     7
2782 LAI     0
2783 MPY    10
2784 LSH     2
2785 LSH     2
2786 ADD     9
2787 OUT     0
2788 OUT     0
2789 JMPR   69
2790 LMI  2092
2791 MPY     7
2792 LSH     2
2793 LSH     2
2794 LSH     2
2795 STO    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 STO    10
2804 LAI  4044
2805 ADD    10
2806 STO    10
2807 LDA     7
2808 LAI     0
2809 MPY    10
2810 LSH     2
2811 LSH     2
2812 STO    10
2813 LAI  1570
2814 SUB    10
2815 OUT     0
2816 JMPR   42
2817 LMI  2994
2818 MPY    92
2819 LSH     2
2820 STO    10
2821 LAI  2546
2822 SUB    10
2823 LAI     0
2824 MPY    92
2825 LSH     2
2826 LSH     2
2827 LSH     2
2828 STO    10
2829 LAI  2296
2830 SUB    10
2831 LAI     0
2832 MPY    92
2833 LSH     2
2834 LSH     2
2835 LSH     2
2836 LSH     2
2837 STO    10
2838 LAI  1909
2839 SUB    10
2840 OUT     0
2841 OUT     0
2842 OUT     0
2843 OUT     0
2844 OUT     0
2845 OUT     0
2846 JMPR   12
2847 ROI     0
2848 ROI     0
2849 ROI     0
2850 ROI     0
2851 ROI     0
2852 ROI     0
2853 ROI     0
2854 ROI     0
2855 ROI     0
```

Compute Accel WF

(Cont'd on next page)

```
2856 ROT     5
2857 LAI   724
2858 STO     7
2859 L I  2333
2860 [illegible] 72
2861 STO     9
2862 LDA    15
2863 OUT    13
2864 L I  2211
2865 [illegible] 49
2866 STO    10
2867 LAI    12
2868 SUB    10
2869 SUB     9
2870 STO     9
2871 LAI  2590
2872 STO    10
2873 ADD     7
2874 STO    11
2875 LDA    16
2876 OUT    13
2877 LDA     9
2878 [illegible] 10
2879 SUB    11
2880 LDA     1
2881 BRMR    2
2882 JMPR    2
2883 LDA     9
2884 LAI     0
2885 MPYM    4
2886 LSH     2
2887 LAI     0
2888 MPYM   44
2889 STO     4
2890 LMI  1640
2891 MPYM  242
2892 STO     5
2893 LAI   120
2894 OUT    13
2895 LMI  1228
2896 ADD     5
2897 LAI     0
2898 MPYM    4
2899 SUB     0
2900 BRMR    3
2901 OUT     0
2902 JMPR    3
2903 LDA     2
2904 SUB     1
2905 LSH     2
2906 SUB     0
2907 BRMR    3
2908 OUT     0
2909 JMPR    3
2910 LDA     2
```

Compute Accel WF

```
2911 SUB     1
2912 LSH     2
2913 STO     4
2914 LDA   100
2915 OUT    13
2916 LMI   637
2917 MPYM   44
2918 STO     5
2919 LMI  1640
2920 MPYM  243
2921 STO     7
2922 LDA    41
2923 OUT    13
2924 LAI  2876
2925 SUB     7
2926 LAI     0
2927 MPY     5
2928 LSH     2
2929 LSH     2
2930 STO     5
2931 LDA    28
2932 STO     8
2933 OUT    13
2934 JMPP 3840
2935 LDA     6
2936 STO    10
2937 LDA     4
2938 STO     6
2939 LDA   235
2940 OUT    13
2941 JMPP 3840
2942 LDA     8
2943 SUB    10
2944 STO     4
2945 LDA     5
2946 STO     8
2947 LDA   144
2948 OUT    13
2949 JMPP 3840
2950 LDA     8
2951 SUB    10
2952 STO     8
2953 STO     5
2954 LDA    62
2955 STO    10
2956 LDA    79
2957 OUT    13
2958 JMPP 3900
2959 LDA     8
2960 STO    62
2961 LDA     5
2962 STO    11
2963 LDA     4
2964 STO     5
2965 LDA    63
```

Compute Decel WF

Compare WF to Accel/Decel Schedules

Accel/Decel Lead Compensation

(cont'd to 2974)

```
2966 STO    10
2967 LDA    90
2968 OUT    13
2969 JMPP 3906
2970 LDA     4
2971 STO    63
2972 LDA     5
2973 RSH     2
2974 STO     9
2975 LDA    81
2976 OUT    13
2977 LDA     6
2978 RSH     2
2979 SUB     9
2980 LDA     5
2981 BRMR    2
2982 JMPR    2
2983 LDA     6
2984 STO     6
2985 LDA     2
2986 BRMR    2
2987 JMPR    2
2988 LDA    15
2989 STO    13
2990 LDA     6
2991 RSH     2
2992 STO     9
2993 LDA    11
2994 RSH     2
2995 SUB     9
2996 LDA    11
2997 BRMR    2
2998 JMPR    2
2999 LDA     6
3000 STO     6
3001 LAI  2560
3002 BRMR    2
3003 JMPR    2
3004 LDA    13
3005 STO    13
3006 LAI   726
3007 STO     9
3008 LDA     6
3009 SUB     0
3010 BRMR    5
3011 SUB     9
3012 BRMR    4
3013 LDA     9
3014 JMPR    4
3015 JMPR   -3
3016 LDA     6
3017 OUT     0
3018 STO     5
3019 LDA     0
3020 SUB     9
```

Select Controlling WF Channel Error

Apply WF Channel Overflow Limits

(cont'd to 3032)

```
3021 STO     9
3022 LDA     5
3023 SUB     0
3024 BRMR    2
3025 JMPR    2
3026 SUB     9
3027 BRMR    3
3028 LDA     5
3029 JMPR    3
3030 LDA     9
3031 OUT     0
3032 STO     6
3033 LDA    85
3034 OUT    13
3035 LMI  2885
3036 MPY     6
3037 LSH     2
3038 LSH     2
3039 STO     6
3040 SUB    20
3041 STO     7
3042 LMI   759
3043 MPY     7
3044 STO     7
3045 ROT     0
3046 ADD    27
3047 STO    27
3048 LDA     7
3049 ADDC   20
3050 STO    26
3051 SUB    52
3052 STO     9
3053 LDA    80
3054 OUT    13
3055 LMI    13
3056 MPY     9
3057 RSH     2
3058 RSH     2
3059 STO     8
3060 ROT     0
3061 STO     9
3062 LDA    83
3063 OUT    13
3064 LAI    28
3065 STO     5
3066 LDA     0
3067 SUB    24
3068 LAI   162
3069 BRMR    2
3070 JMPR    2
3071 LDA     5
3072 STO     5
3073 LDA    84
3074 OUT    13
3075 LDA     5
```

Generate WF Torque Motor Signal

(cont'd on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
3076 SUB    65
3077 STO    10
3078 LDA     8
3079 SUB     0
3080 LDA    10
3081 BRMR    7
3082 SUB     0
3083 BRMR    6
3084 SUB     8
3085 LDA     8
3086 BRMR    7
3087 JMPR    7
3088 SUB     0
3089 BRMR   -5
3090 JMPR   -5
3091 OUT     0
3092 JMPR   -6
3093 LDA    10
3094 STO     6
3095 LDA     0
3096 SUB     5
3097 SUB    65
3098 STO     5
3099 LDA     8
3100 SUB     0
3101 LDA     5
3102 JMPR    7
3103 SUB     0
3104 BRMR    8
3105 SUB     6
3106 LDA     5
3107 JMPR    7
3108 JMPR    7
3109 SUB     0
3110 BRMR   -5
3111 JMPR   -5
3112 OUT     0
3113 JMPR   -6
3114 LDA     8
3115 STO     8
3116 LDA    66
3117 ADD     9
3118 STO    66
3119 LDA    65
3120 ADD     8
3121 STO    65
3122 LDA    37
3123 OUT    13
3124 LAI  3032
3125 MPY    65
3126 LSH     2
3127 LSH     2
3128 STO    10
3129 STO   118
3130 LDA     6
```

Generate WF Torque Motor Signal

```
3131 ADD   118
3132 STO   118
3133 LAI   205
3134 ADD    10
3135 STO    10
3136 LDA    88
3137 OUT    13
3138 LDA     6
3139 SUB     0
3140 BRMR    6
3141 ADD    10
3142 SUB     0
3143 BRMR    8
3144 OUT     0
3145 JMPR    8
3146 ADD    10
3147 OUT     0
3148 OUT     0
3149 OUT     0
3150 JMPR    3
3151 LDA     2
3152 SUB     1
3153 STO    10
3154 OUT     1
3155 STO    96
3156 LAI  1099
3157 MPYR  238
3158 STO     9
3159 LDA    89
3160 OUT    13
3161 LAI  1385
3162 MPY     0
3163 STO     6
3164 STO   119
3165 SUB     0
3166 BRMR    3
3167 ADD     9
3168 JMPR    3
3169 SUB     9
3170 OUT     0
3171 ADD    65
3172 STO     6
3173 LDA    65
3174 ADD   119
3175 STO   119
3176 LAI  3275
3177 MPY   119
3178 STO   119
3179 LDA     0
3180 SUB    24
3181 LDA   119
3182 BRMR    2
3183 JMPR    2
3184 LDA   118
3185 STO   118
```

Generate WF Torque Motor Signal

Modify for Fail-Fixed Servovalve

```
3186 LDA    71
3187 OUT    13
3188 LAI  3094
3189 STO     4
3190 LAI  1011
3191 STO     5
3192 LDA     6
3193 SUB     0
3194 BRMR    5
3195 SUB     5
3196 LDA     5
3197 BRMR    8
3198 JMPR    8
3199 SUB     4
3200 LDA     6
3201 BRMR    2
3202 JMPR    4
3203 LDA     4
3204 JMPR    3
3205 LDA     6
3206 OUT     0
3207 ADD     2
3208 STO     6
3209 LAI  1177
3210 STO     5
3211 LAI  3076
3212 MPYR    6
3213 RSHR    2
3214 STO     4
3215 LDA    70
3216 OUT    13
3217 LAI  2298
3218 SUB     4
3219 LAI     0
3220 MPYR    6
3221 LSH     2
3222 STO     4
3223 LDA   122
3224 OUT    13
3225 LAI  2026
3226 SUB     4
3227 LAI     0
3228 MPYR    6
3229 LSH     2
3230 LSH     2
3231 SUB     5
3232 LSH     2
3233 SUB     2
3234 STO     6
3235 LDA   102
3236 OUT    13
3237 LDA    69
3238 SUB   157
3239 LDA     2
3240 BRMR    2
```

Modify for Fail-Fixed Servovalve

(cont'd to 3242)

```
3241 LDA     6
3242 OUT     7
3243 BRMR    2
3244 OUT     2
3245 LDA    95
3246 BRMR    2
3247 LDA    73
3248 STO   186
3249 LAI   732
3250 STO     7
3251 LAI   410
3252 STO     4
3253 LAI  1228
3254 STO     5
3255 LDA   252
3256 SUB     2
3257 STO     6
3258 BRMR   12
3259 SUB     5
3260 STO     6
3261 BRMR   11
3262 SUB     4
3263 BRMR   12
3264 LAI     0
3265 ROT     0
3266 OUT     0
3267 OUT     0
3268 OUT     0
3269 JMPR   12
3270 OUT     0
3271 JMPR  -10
3272 LAI   732
3273 OUT     0
3274 JMPR   -9
3275 LAI  3665
3276 MPY     6
3277 LSH     2
3278 STO     6
3279 LDA     7
3280 SUB     6
3281 STO     4
3282 LDA   237
3283 LAI     0
3284 MPY     4
3285 STO     4
3286 LDA   234
3287 OUT    13
3288 LDA     0
3289 SUB    21
3290 LDA     0
3291 BRMR    2
3292 JMPR    2
3293 LDA     4
3294 STO     4
3295 SUB    93
```

Stator Re-set Generation and Activation

(cont'd on next page)

```
3296 STO     6
3297 LAI     3
3298 STO     5
3299 LDA     6
3300 SUB     0
3301 BRMR    3
3302 SUB     5
3303 BRMR    4
3304 LDA     5
3305 JMPR    4
3306 JMPR   -3
3307 LDA     0
3308 OUT     0
3309 STO     0
3310 LAI  4044
3311 STO     3
3312 LDA     0
3313 SUB     0
3314 BRMR    2
3315 JMPR    2
3316 SUB     5
3317 BRMR    3
3318 LDA     0
3319 JMPR    3
3320 LDA     5
3321 OUT     0
3322 STO     6
3323 LAI  1108
3324 MPY     0
3325 STO     0
3326 OUT     0
3327 MPY    94
3328 STO    94
3329 LDA     6
3330 ADD    93
3331 STO    93
3332 SUB     0
3333 LAI     2
3334 BRMR    3
3335 JMPR    3
3336 SUB     1
3337 STO    93
3338 [illegible] 70
3339 [illegible] 2
3340 [illegible] 3
3341 SUB    30
3342 STO     5
3343 BRMR    3
3344 OUT     0
3345 JMPR    3
3346 LAI     0
3347 SUB     5
3348 STO     5
3349 LDA    75
3350 [illegible] 2
```

Stator Re-set Generation and Activation

```
3351 STO     6
3352 SUB    35
3353 STO     7
3354 BRMR    3
3355 OUT     0
3356 JMPR    3
3357 LDA     0
3358 SUB     7
3359 SUB     5
3360 STO     4
3361 LAI   190
3362 STO     5
3363 SUB     4
3364 BRMR   16
3365 LDA     0
3366 SUB     5
3367 SUB     4
3368 LDA     3
3369 BRMR    2
3370 JMPR   16
3371 RSHM    2
3372 STO     3
3373 LDA     6
3374 RSHM    2
3375 ADD     3
3376 OUT     0
3377 OUT     0
3378 OUT     0
3379 JMPR   15
3380 LDA     6
3381 OUT     0
3382 OUT     0
3383 OUT     0
3384 OUT     0
3385 OUT     0
3386 STO     3
3387 LDA     1
3388 ADD     1
3389 ADD     1
3390 ADD     1
3391 ADD    67
3392 STO    67
3393 LDA     3
3394 STO    25
3395 LAI   530
3396 STO    10
3397 LAI   173
3398 STO     9
3399 LAI   304
3400 STO     4
3401 LAI   195
3402 STO     5
3403 LAI   236
3404 STO     6
3405 LAI   806
```

Average or Select Between Stator Feedbacks

Generate Stator Schedule

```
3406 STO     7
3407 LDA    92
3408 SUB     7
3409 STO     7
3410 BRMR   90
3411 SUB     6
3412 STO     6
3413 BRMR   61
3414 SUB     5
3415 STO     5
3416 BRMR   42
3417 SUB     4
3418 STO     4
3419 BRMR   23
3420 SUB     9
3421 LDA     9
3422 BRMR    3
3423 STO     4
3424 JMPR    2
3425 OUT     0
3426 LAI  2180
3427 MPY     4
3428 LSH     2
3429 LSH     2
3430 LSH     2
3431 STO     8
3432 LAI  3442
3433 SUB     8
3434 LAI     0
3435 MPY     4
3436 LSH     2
3437 LSH     2
3438 STO     8
3439 LAI   488
3440 SUB     8
3441 JMPR   78
3442 LAI  2714
3443 MPY     5
3444 LSH     2
3445 LSH     2
3446 LSH     2
3447 STO     8
3448 LAI  1031
3449 ADD     8
3450 LAI     0
3451 MPY     5
3452 LSH     2
3453 LSH     2
3454 STO     8
3455 LAI  1276
3456 SUB     8
3457 JMPR   37
3458 LAI  2075
3459 MPY     6
3460 LSH     2
```

Generate Stator Schedule

```
3461 LSH     2
3462 LSH     2
3463 LSH     2
3464 STO     8
3465 LAI  4092
3466 SUB     8
3467 LAI     0
3468 MPY     6
3469 LSH     2
3470 STO     8
3471 LAI  1519
3472 SUB     8
3473 JMPR   20
3474 LAI  3268
3475 MPY     7
3476 LSH     2
3477 LSH     2
3478 LSH     2
3479 STO     8
3480 LAI  1264
3481 ADD     8
3482 LAI     0
3483 MPY     7
3484 STO     8
3485 LAI  1692
3486 SUB     8
3487 OUT     0
3488 OUT     0
3489 OUT     0
3490 OUT     0
3491 OUT     0
3492 OUT     0
3493 OUT     0
3494 OUT     0
3495 OUT     0
3496 OUT     0
3497 OUT     0
3498 OUT     0
3499 JMPR   20
3500 LDA    92
3501 SUB    10
3502 LDA    92
3503 BRMR    2
3504 JMPR    2
3505 LDA    10
3506 STO    10
3507 LAI  3268
3508 MPY    10
3509 LSH     2
3510 STO     8
3511 LAI  3870
3512 SUB     8
3513 LAI     0
3514 MPY    10
3515 STO     8
```

Generate Stator Schedule

(cont'd on next page to 3519)

ORIGINAL PAGE IS OF POOR QUALITY

```
3516 LAI  2197
3517 SUB     8
3518 JMPR  -29
3519 STO     4
3520 LAI   139
3521 STO     9
3522 LAI   571
3523 MPY   236
3524 STO     0
3525 LAI   380
3526 SUB     0
3527 STO     0
3528 SUB     0
3529 BRMR   14
3530 LDA     4
3531 SUB     9
3532 ADD     0
3533 STO     7
3534 LAI  1703
3535 STO     8
3536 SUB     7
3537 LDA     7
3538 BRMR    2
3539 JMPR    2
3540 LDA     8
3541 ADD     9
3542 JMPR   14
3543 LAI   190
3544 STO     0
3545 ADD     4
3546 ADD     0
3547 STO     7
3548 SUB     8
3549 LDA     7
3550 OUT     0
3551 BRMR    2
3552 JMPR    2
3553 LDA     8
3554 SUB     8
3555 OUT     0
3556 STO     4
3557 LAI   102
3558 ADD    93
3559 ADD     4
3560 STO     4
3561 SUB     0
3562 LAI  1944
3563 STO     5
3564 BRMR    7
3565 SUB     4
3566 LDA     4
3567 BRMR    2
3568 JMPR    2
3569 LDA     5
3570 JMPR    3
```

Stator Schedule Adjustment

Add Stator Reset and Compute Stator Error

(cont'd to 3574)

```
3571 OUT     0
3572 JMPR   -5
3573 SUB    25
3574 STO     4
3575 LAI   209
3576 STO     5
3577 LDA     4
3578 SUB     0
3579 BRMR    5
3580 SUB     5
3581 BRMR    4
3582 LDA     5
3583 JMPR    4
3584 JMPR   -3
3585 LDA     4
3586 OUT     0
3587 STO     4
3588 LDA     0
3589 SUB     5
3590 STO     5
3591 LDA     4
3592 SUB     0
3593 BRMR    2
3594 JMPR    2
3595 SUB     5
3596 BRMR    3
3597 LDA     4
3598 JMPR    3
3599 LDA     5
3600 OUT     0
3601 STO     4
3602 LAI   410
3603 STO     5
3604 LMI  2500
3605 MPY     4
3606 LSH     2
3607 LSH     2
3608 LSH     2
3609 LSH     2
3610 STO     4
3611 STO   119
3612 SUB     0
3613 BRMR    3
3614 SUB     5
3615 JMPR    6
3616 SUB     5
3617 BRMR    3
3618 LDA     2
3619 JMPR    3
3620 STO     4
3621 OUT     0
3622 STO    97
3623 OUT     1
3624 LDA    69
3625 SUB   157
```

Generate Stator Torque Motor Signal

```
3626 BRMR    2
3627 OUT     4
3628 LDA    35
3629 SUB    91
3630 LDA     0
3631 BRMR    2
3632 JMPR    2
3633 LDA     1
3634 ADD    67
3635 STO    67
3636 LAI   409
3637 STO     5
3638 LDA    77
3639 RSHM    2
3640 SUB     5
3641 LAI   128
3642 STO     4
3643 BRMR    2
3644 JMPR    2
3645 LAI     0
3646 ADD    67
3647 STO    67
3648 LAI  1474
3649 STO     3
3650 LDA    85
3651 RSHM    2
3652 SUB     3
3653 LDA     4
3654 RSHM    2
3655 STO     4
3656 BRMR    2
3657 JMPR    2
3658 LDA     0
3659 ADD    67
3660 STO    67
3661 LDA    83
3662 RSHM    2
3663 SUB     5
3664 LDA     4
3665 RSHM    2
3666 STO     4
3667 LAI  1529
3668 STO     6
3669 LDA    42
3670 RSHM    2
3671 BRMR    4
3672 OUT     0
3673 OUT     0
3674 JMPR    5
3675 SUB     6
3676 LDA     4
3677 BRMR    2
3678 JMPR    2
3679 LDA     0
3680 ADD    67
```

Check for Clock Failure

Check For Overspeed Trip

Check For Lube Overtemperature

Check for Low Lube Pressure

(cont'd to 3681)

```
3681 STO    67
3682 LAI  1802
3683 STO     3
3684 LDA    89
3685 RSHM    2
3686 SUB     3
3687 LDA     4
3688 RSHM    2
3689 BRMR    2
3690 JMPR    2
3691 LDA     0
3692 ADD    67
3693 STO    67
3694 OUT     0
3695 LDA     0
3696 SUB    61
3697 BRMR    9
3698 OUT     0
3699 OUT     0
3700 LAI     1
3701 STO     1
3702 LAI    21
3703 SUB     1
3704 BRMR   94
3705 JMPR   -2
3706 LDA   210
3707 STO   233
3708 LDA   211
3709 STO   234
3710 LDA   212
3711 STO   235
3712 LDA   213
3713 STO   236
3714 LDA   214
3715 STO   237
3716 LDA   215
3717 STO   238
3718 LDA   216
3719 STO   239
3720 LDA   217
3721 STO   240
3722 LDA   218
3723 STO   241
3724 LDA   219
3725 STO   242
3726 LDA   220
3727 STO   243
3728 LDA   221
3729 STO   244
3730 LDA   222
3731 STO   245
3732 LDA   223
3733 STO   246
3734 LDA   224
3735 STO   247
```

Check For Gearbox Bearing Temperature

(cont'd on next page)

```
3736 LDA  225
3737 STO  248
3738 LDA  226
3739 STO  249
3740 LDA  227
3741 STO  250
3742 LDA  228
3743 STO  251
3744 LDA  229
3745 STO  252
3746 LDA  230
3747 STO  253
3748 LDA  231
3749 STO  254
3750 LDA  232
3751 STO  255
3752 LDA  187
3753 STO  210
3754 LDA  188
3755 STO  211
3756 LDA  189
3757 STO  212
3758 LDA  190
3759 STO  213
3760 LDA  191
3761 STO  214
3762 LDA  192
3763 STO  215
3764 LDA  193
3765 STO  216
3766 LDA  194
3767 STO  217
3768 LDA  195
3769 STO  218
3770 LDA  196
3771 STO  219
3772 LDA  197
3773 STO  220
3774 LDA  198
3775 STO  221
3776 LDA  199
3777 STO  222
3778 LDA  200
3779 STO  223
3780 LDA  201
3781 STO  224
3782 LDA  202
3783 STO  225
3784 LDA  203
3785 STO  226
3786 LDA  204
3787 STO  227
3788 LDA  205
3789 STO  228
3790 LDA  206
```

Transfer Data To Peripheral Units

```
3791 STO  229
3792 LDA  207
3793 STO  230
3794 LDA  208
3795 STO  231
3796 LDA  209
3797 STO  232
3798 OUT  15
3799 LAI  1
3800 STO  1
3801 ADD  56
3802 STO  56
3803 LDA  5
3804 SUB  0
3805 BRMR 17
3806 LDA  10
3807 SUB  0
3808 BRMR 7
3809 LDA  5
3810 SUB  10
3811 OUT  0
3812 OUT  0
3813 OUT  0
3814 JMPR 17
3815 LDA  5
3816 SUB  10
3817 BRMR 2
3818 JMPR -5
3819 LDA  2
3820 SUB  1
3821 JMPR 10
3822 LDA  10
3823 SUB  0
3824 BRMR -15
3825 LDA  5
3826 SUB  10
3827 BRMR -15
3828 LDA  2
3829 OUT  0
3830 OUT  0
3831 STO  5
3832 LDA  56
3833 SUB  1
3834 BRMP 2045
3835 SUB  1
3836 BRMP 2054
3837 SUB  1
3838 BRMP 2302
3839 JMPP 2413
3840 LAI  1
3841 STO  1
3842 ADD  57
3843 STO  57
3844 LDA  8
3845 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

```
3846 STO  9
3847 LAI  823
3848 SUB  9
3849 BRMR 36
3850 LAI  379
3851 SUB  8
3852 BRMR 22
3853 LAI  2832
3854 MPY  8
3855 LSH  2
3856 LSH  2
3857 STO  9
3858 LAI  2545
3859 SUB  9
3860 LAI  0
3861 MPY  8
3862 LSH  2
3863 LSH  2
3864 ADD  1
3865 ADD  1
3866 ADD  1
3867 OUT  0
3868 OUT  0
3869 OUT  0
3870 OUT  0
3871 OUT  0
3872 OUT  0
3873 JMPR 26
3874 LAI  2310
3875 MPY  8
3876 STO  9
3877 LAI  3178
3878 SUB  9
3879 LAI  0
3880 MPY  8
3881 STO  9
3882 LAI  297
3883 ADD  9
3884 JMPR 15
3885 LAI  430
3886 MPYR 8
3887 STO  9
3888 LAI  1834
3889 SUB  9
3890 LAI  0
3891 MPYR 8
3892 STO  9
3893 LAI  542
3894 ADD  9
3895 STO  9
3896 ROI  0
3897 LDA  9
3898 OUT  0
3899 STO  8
3900 LDA  57
```

Subroutine For Computing Metering Valve Position From WF

(cont'd to 1905)

```
3901 SUB  1
3902 BRMP [illegible]
3903 SUB  1
3904 BRMP 2742
3905 JMPP 2950
3906 LAI  1
3907 STO  1
3908 ADD  58
3909 STO  58
3910 LAD  553
3911 STO  9
3912 LAI  3567
3913 MPY  10
3914 STO  10
3915 LDA  5
3916 SUB  10
3917 STO  5
3918 BRMR 5
3919 SUB  9
3920 BRMR 4
3921 LDA  9
3922 JMPR 4
3923 JMPR -3
3924 LDA  5
3925 OUT  0
3926 STO  5
3927 LDA  0
3928 SUB  9
3929 STO  9
3930 LDA  5
3931 SUB  0
3932 BRMR 2
3933 JMPR 2
3934 SUB  9
3935 BRMR 3
3936 LDA  5
3937 JMPR 3
3938 LDA  9
3939 OUT  0
3940 STO  5
3941 LAI  940
3942 MPY  5
3943 LSH  2
3944 LSH  2
3945 LSH  2
3946 LSH  2
3947 STO  5
3948 LAI  447
3949 STO  9
3950 LDA  5
3951 SUB  0
3952 BRMR 5
3953 SUB  9
3954 BRMR 4
3955 LDA  9
```

Subroutine For Rate Feedback With Lag

(cont'd on next page)

ORIGINAL PAGE IS OF POOR QUALITY

```
3956 JMPR     4
3957 JMPR    -3
3958 LDA      5
3959 SUB      0
3960 STO      5
3961 LDA      0
3962 SUB      9
3963 STO      9
3964 LDA      5
3965 SUB      0
3966 BRMR     2
3967 JMPR     2
3968 [illegible] 9
3969 [illegible] 3
3970 LDA      5
3971 JMPR     3
3972 LDA      9
3973 SUB      0
3974 STO      5
3975 LAI   2060
3976 [illegible] 5
3977 LDA      2
3978 STO      5
3979 LDA     56
3980 SUB      1
3981 JMPP  2959
3982 JMPP  2970
3983 LAI      1
3984 STO      1
3985 ADD    111
3986 STO    111
3987 LAI   2810
3988 [illegible] 5
3989 STO     10
3990 LAI   3958
3991 SUB     10
3992 LAI      0
3993 [illegible] 5
3994 STO     10
3995 LAI   2269
3996 SUB     10
3997 LAI      0
3998 [illegible] 5
3999 LDA      2
4000 LDA      2
4001 STO     10
4002 LAI   3700
4003 SUB     10
4004 LAI      0
4005 [illegible] 5
4006 LDA      2
4007 STO     10
4008 LAI    325
4009 ADD     10
4010 STO      5
```

Subroutine For Rate Feedback With Lag

Square Root Subroutine

(cont'd to 4018)

```
4011 LDA    111
4012 SUB      1
4013 BRMP   407
4014 SUB      1
4015 BRMP   695
4016 SUB      1
4017 BRMP   769
4018 JMPP  1117
4019 LAI      1
4020 STO      1
4021 ADD    140
4022 STO    140
4023 STO     10
4024 LDA      5
4025 SUB      0
4026 BRMR     2
4027 JMPR     2
4028 LDA      9
4029 BRMR     3
4030 LDA      8
4031 ADD      6
4032 STO      8
4033 LDA      7
4034 ADDC     5
4035 STO      7
4036 LDA    140
4037 SUB      1
4038 BRMP   476
4039 SUB      1
4040 BRMP   514
4041 SUB      1
4042 BRMP   555
4043 SUB      1
4044 BRMP   585
4045 SUB      1
4046 BRMP   637
4047 JMPP   678
4048 LAI      1
4049 STO      1
4050 ADD    160
4051 STO    160
4052 LDA      3
4053 SUB      0
4054 BRMR     3
4055 OUT      0
4056 JMPR     3
4057 LDA      0
4058 SUB      3
4059 STO      3
4060 LDA    160
4061 SUB      1
4062 BRMP  1579
4063 SUB      1
4064 BRMP  1584
4065 SUB      1
```

Integrator Subroutine

Absolute Value Subroutine

(cont'd to 4073)

```
4066 BRMP  1589
4067 SUB      1
4068 BRMP  1594
4069 SUB      1
4070 BRMP  1599
4071 SUB      1
4072 BRMP  1604
4073 JMPP  1609
```

APPENDIX D

REFERENCES

1. Astrom, K., Introduction to Stochastic Control Theory, Academic Press, NY, 1970.

2. Anderson, T.W., An Introduction to Multivariate Statistical Analysis, J. Wiley and Sons, Inc., NY.

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).

DISTRIBUTION LIST

AiResearch Division
Garret Corporation
F.B. Wallace
P.O. Box 5217
Phoenix, Arizona 85010

American Airlines
Maintenance and Engineering Center
K. Grayson
Tulsa, Oklahoma 74151

Andrews Air Force Base
Lt. Col. G. Strand
AFSC Headquarters
Washington, D.C. 20334

AVCO/Lycoming
S. Deckert
550 S. Main Street
Stratford, Connecticut 06497

The Boeing Company
H. Higgins
P.O. Box 3999
Seattle, Washington 98124

The Boeing Company
Wichita Division
D. Torkelson
Wichita, Kansas 67210

Bolt, Beranek and Newman, Inc.
R. Hayden
50 Moulton Street
Cambridge, Massachusetts 02138

Curtiss-Wright Corporation
Power Systems Division
W. Johnson
One Passaic Street
Wood Ridge, New Jersey 07075

Department of Transportation
NASA/DOT Joint Office of Noise Abatement
C. Foster
Office of Secretary
Washington, D. C. 20590

Detroit Diesel Allison Division of General Motors
F. Walters
Suite 312
333 West First Street
Dayton, Ohio 45402

Douglas Aircraft Company
L. Malthan
3855 Lakewood Boulevard
Long Beach, California 90801

Environment Protection Agency
J. Schettino
1835 "K" Street, NW
Washington, D.C. 20460

Federal Aviation Administration
Noise Abatement Division
J. Woodall
Washington, D.C. 20590

General Dynamics Convair Division
G. Nicoloff
San Diego, California 92112

Grumman Aerospace Corporation
C. Hoeltzer
South Oyster Bay Road
Bethpage, New York 11714

Hamilton Standard
Division of United Aircraft
A. Jackson
Windsor Locks, Connecticut 06096

Lockheed Aircraft Corporation
T. Higgins
Burbank, California 91503

Lockheed Georgia Company
H.S. Sweet
Marietta, Georgia 30060

NASA Installations

NASA Headquarters
N.F. Rekos
Washington, D.C. 20546

NASA-Ames Research Center
L. Roberts
Moffett Field, California 94035

NASA-Flight Research Center
D.R. Scott
Edwards, California 93523

NASA-Langley Research Center
R. Kuhn
Hampton, Virginia 23665

NASA-Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

M.A. Beheim
D.N. Bowditch
L.J. Chelko
C.C. Ciepluch
E.W. Conrad
A. Ginsburg
M.J. Hartmann
R.H. Kemp
Lewis Library
R.W. Luidens
D.L. Nored
Report Control Office
L.W. Schopen
R.W. Schroeder
M.F. Valerino

NASA/Air Force Liaison
Wright-Patterson Air Force Base
Dayton, Ohio 45433

L. Obery
C. Simpson
Col. C.E. Painter
G.K. Richey
G.P. Peterson

Pratt & Whitney Aircraft
Division of United Aircraft Corp.
J. Chew
20800 Center Ridge Road
Rocky River, Ohio 44116

Rohr Corporation
F. Hom
Box 878
Foot and H Street
Chula Vista, California 92012

Wyle Laboratories
L. Sutherland
128 Maryland Street
El Segundo, California 90245

Rockwell International
Los Angeles Division
Attn: D. Schlundt
International Airport
Los Angeles, California 90009