https://ntrs.nasa.gov/search.jsp?R=19780019186 2020-03-22T03:03:31+00:00Z

NASA CR 135427
PWA-5544-13

(NASA-CR-135427) FABRICATION AND TEST OF DIGITAL OUTPUT INTERFACE DEVICES FOR GAS TURBINE ELECTRONIC CONTROLS Final Report (Pratt and Whitney Aircraft Group) 59 p HC A04/MF A01 CSCL 21E G3/07

N78-27129

Unclas 25871

NASA

FABRICATION AND TEST OF DIGITAL OUTPUT INTERFACE DEVICES FOR GAS TURBINE ELECTRONIC CONTROLS FINAL REPORT

by
D. M. Newirth
E. W. Koenig

PRATT & WHITNEY AIRCRAFT GROUP
COMMERCIAL PRODUCTS DIVISION
UNITED TECHNOLOGIES CORPORATION

May 1978

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER
CONTRACT NAS3-19898

REPRODUCED BY
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

NOTICE

THIS DOCUMENT HAS BEEN REPRODUCED FROM THE BEST COPY FURNISHED US BY THE SPONSORING AGENCY. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE.

1. Report No CR 135427	2 Government Accession No	3 Recipient's Catalog No.
4. Title and Subtitle Fabrication and Test of Digital Output Interface Devices for Gas Turbine Electronic Controls – Final Report		5 Report Date May 1978 6. Performing Organization Code
7. Author(s) D. M. Newirth E. W. Koenig		8. Performing Organization Report No PWA-5544-13 10. Work Unit No
9. Performing Organization Name and Address Pratt & Whitney Aircraft Group Commercial Products Division United Technologies Corporation East Hartford, CT 06108		11. Contract or Grant No. NAS3-19898 13. Type of Report and Period Covered Contractor Report
12 Sponsoring Agency Name and Address NASA-Lewis Research Center Cleveland, OH 44135		14. Sponsoring Agency Code
15. Supplementary Notes Project Monitor, Leon M. Wenzel Wind Tunnel and Flight Division, NASA-Lewis Research Center, Cleveland, OH		Final Report

16. Abstract

A program was conducted to develop an innovative digital output interface device, a digital effector with optical feedback of the fuel metering valve position, for future electronic controls for gas turbine engines. A digital effector (on-off solenoids driven directly by on-off signals from a digital electronic controller) with optical position feedback was fabricated, coupled with the fuel metering valve, and tested under simulated engine operating conditions. The testing indicated that a digital effector with optical position feedback is a suitable candidate, with proper development for future digital electronic gas turbine controls. The testing also identified several problem areas which would have to be overcome in a final production configuration.

17. Key Words (Suggested by Author(s)) Digital Output Interface Digital Effector Optical Position Feedback		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20 Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev 10-75)

NASA CR 135427
PWA-5544-13

FABRICATION AND TEST OF DIGITAL OUTPUT INTERFACE DEVICES FOR GAS TURBINE ELECTRONIC CONTROLS
FINAL REPORT

by
D. M. Newirth
E. W. Koenig

PRATT & WHITNEY AIRCRAFT GROUP
COMMERCIAL PRODUCTS DIVISION
UNITED TECHNOLOGIES CORPORATION

May 1978

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER
CONTRACT NAS3-19898

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	3
DIGITAL OUTPUT INTERFACE FABRICATION	4
DOI FLOW PACKAGE	4
Hydromechanical Hardware	4
Optical Encoder Head Construction	6
Optic Encoder Installation	6
ELECTRONIC INTERFACE SUITCASE	6
MINICOMPUTER INTERFACE BOX	7
OPTIC CABLE	8
ELECTRICAL CABLES	9
SOFTWARE	9
DOI FLOW BENCH TESTING	10
SUBSYSTEM COMPONENT TESTS	11
Optical Position Sensor and Interface Unit Tests	11
DOI Flow Package Subsystem Tests	11
Flow Package and Optical Position Sensor Assembly Tests	11
On-Off Switches and On-Off Indicator Tests	12
CLOSED LOOP FLOW BENCH PERFORMANCE TEST	12
Test Configuration	13
Test Sequence	15
TEST RESULTS	16
System Operational Verification	16
Steady State Performance Test	16
Transient Performance Test	22
Failsafe Demonstration Tests	31
ENDURANCE TEST	41
POST-TEST INSPECTION AND CALIBRATION	41
RELIABILITY EVALUATION	46
RELIABILITY PREDICTIONS	46
Electrical/Optical Section	46
DOI Flow Package	46
FAILURE MODE AND EFFECTS ANALYSIS	46

TABLE OF CONTENTS (Cont'd)

	Page
CONCLUSIONS	48
APPENDIX A – FAILURE MODE AND EFFECTS ANALYSIS OPTICAL/ ELECTRICAL SECTION	49

SUMMARY

The objective of this program was to pursue the development of an innovative digital output interface (DOI) which shows promise of improving the reliability and maintainability required of future digital electronic controls for aircraft propulsion systems. A DOI is defined as that portion of a digital electronic control which directly converts a digital signal into a mechanical position and consists of a combination of electronic, electro-mechanical and mechanical components.

The program objective has been met by fabricating a digital output interface (DOI), testing and demonstrating its operation and performance under simulated engine operating conditions on a fuel flow bench, and by evaluating its reliability.

The DOI system selected for development uses a digital output effector with on-off solenoids driven directly by discrete signals from a digital electronic controller. The DOI was designed to interface a digital electronic controller with a gas turbine fuel flow metering valve. The DOI also includes an optical feedback of the fuel metering valve position to the electronic controller. (The digital effector is the subject of a U. S. patent application, Adaptive Control System Using Position Feedback, filed on June 11, 1975, U. S. Serial Number 586010, by Anthony N. Martin, and assigned to United Technologies Corporation.)

The DOI was fabricated by Hamilton Standard under subcontract, in a brassboard configuration. The brassboard DOI includes a fuel flow metering valve, solenoid valves, an optical position sensor, fiber optic cable, and optical/electrical interface. The DOI is capable of controlling fuel flow between limits of 204 and 6802 kilograms per hour (450 and 15000 pounds per hour).

DOI testing consisted of subsystem component tests at the subcontractor's facility, closed loop flow bench performance tests, and system endurance tests at Pratt & Whitney's facility. The subsystem component tests were performed on the optical position sensor and its electronic interface, the fuel flow metering system, and the entire DOI assembly to calibrate and verify proper operation of the DOI components.

After the component testing was completed, the DOI was installed on a closed loop flow bench for performance testing at Pratt & Whitney Aircraft. The performance testing successfully demonstrated steady-state stability, transient response for small and large power lever changes, and the capability to tolerate a failure of any one of the DOI solenoids.

An endurance test was run on the same closed loop flow bench. The endurance test consisted of a simulated flight cycle: five minutes at take-off, 55 minutes at climb power, 60 minutes at cruise power, and 60 minutes at idle. The cycle was repeated continuously to operate the DOI 16 hours per day. The DOI operated correctly with no failures during the 342 hours of endurance testing. A total of 461.75 test hours have been accumulated on the hardware with no failures.

The results of the testing indicate that the digital effector with optical fuel metering valve position feedback is a viable candidate, with additional development, for future digital electronic gas turbine controls. The testing successfully demonstrated the digital effector and optical feedback concepts, but also showed several unresolved problem areas which would have to be overcome in a final production configuration. Steady-state performance testing with a simulated turbofan engine showed a low rotor speed limit cycle of ±15 rpm due to the resolution of the optical position feedback. An optical position sensor with more than 8 bits resolution on the fuel metering valve travel would improve steady-state performance. Failures of the optical feedback channels (bits) would make the feedback incapable of controlling. For the brassboard DOI configuration tested, the resolver can be used if the optical feedback fails, but a production configuration would require some redundant measurement of the fuel metering valve position. An interesting feature of the DOI is that fuel valve position becomes fixed if the solenoid interfacing electronics or the power to the electronics fails. Since fuel flow cannot be changed, it would be necessary to shut down an engine through the shut-off solenoid. Failed fixed may be an attractive feature in other servo system applications.

A reliability evaluation of the DOI was conducted. The predicted reliability of the electrical/optical section, which includes all optical position feedback elements and the solenoid drivers, is 15.946 failures per million hours. The predicted failure rate of the flow box is 21.452 failures per million hours. The entire DOI system would have a failure rate of 37.398 per million hours or a mean time between failures of 26,739 hours.

INTRODUCTION

A program to improve the reliability of a digital output interface (DOI) subsystem in digital electronic controls was conducted under NASA Contract NAS3-19898. The initial work of the program consisted of analyses of candidate control system components having the potential of ensuring that the reliability and maintainability required of a digital electronic can be achieved. This initial work led to selection and final design of a DOI subsystem which was to be fully tested under simulated real-life conditions. Results of this initial work were reported under NASA Report CR-135135, and are briefly described below.

During Task 1 of this contract, twenty-one digital output interfaces were configured with conventional devices such as torque motors, stepper motors, resolvers, linear variable differential transformers, and unconventional (for this application) devices such as solenoids and optical position sensors. Component cost, weight, accuracy, and reliability data, furnished by control manufacturers Bendix and Hamilton Standard, were used in a detailed trade study, heavily weighted toward reliability. Based on this study, a DOI was designed which employed a digital output effector (solenoids) and optical position measurement, and which was capable of controlling a gas turbine fuel metering valve (Tasks 2 and 3).

The selected DOI was designed to interface with an existing hydromechanical fuel flow metering system. The design included all details necessary to proceed with the fabrication and test of the digital effector concept. Several optical position sensor designs were considered, the final selection being a design which provided 0.051 mm (0.002 inch) of fuel valve travel resolution. This resolution was achieved using an eight-bit digital, optical encoded word. Solenoids driven by direct digital command were designed to drive the fuel valve. Solenoid pairs were provided for both increase and decrease fuel commands to enhance the failsafe operational characteristics of the system. A resolver was also incorporated in the feedback for instrumentation and redundancy purposes.

Under the present work which is reported herein, the selected DOI was fabricated and demonstrated under simulated operating conditions on a flow bench. Development of the selected DOI was conducted in three tasks:

- Fabrication of a brassboard prototype digital effector with optical fuel metering valve position feedback by the control manufacturer, Hamilton Standard (Task 5)
- Flow bench testing of the DOI (Task 6)
- Reliability evaluation (Task 7)

This report contains a discussion of the fabrication of the DOI, the flow bench testing which consisted of subsystem component calibration testing, closed loop performance testing, endurance testing of the DOI system, and a description of the reliability assessment of the final DOI configuration.

DIGITAL OUTPUT INTERFACE FABRICATION

The DOI system was fabricated by Hamilton Standard under subcontract to Pratt & Whitney Aircraft. A block diagram of the DOI hardware is shown on Figure 1. A hydromechanical fuel flow metering system from an existing fuel control was used as the basis for the flow package. Digital output effectors and solenoid valves were added to the flow package to position the metering valve. The metering valve position was sensed using an optical position sensor; a resolver was also mounted on the flow package to provide a redundant measurement. An electronic interface suitcase was constructed to contain the optic transmitters and receivers, power supplies, resolver converter, solenoid driver electronics, and parallel to serial converter. The suitcase was provided with an air purging inlet and a relief valve to allow operation of the electronics in a fuel lab or engine test cell environment. A computer interface box was fabricated to provide parallel optical feedback and resolver feedback data to the minicomputer and to provide visual indication of the feedback signals by means of data lights on the face of the box. Software was fabricated by Pratt & Whitney Aircraft for the DOI closed loop flow bench testing and included a real-time (transfer function) simulation of a turbofan engine and an electronic controller.

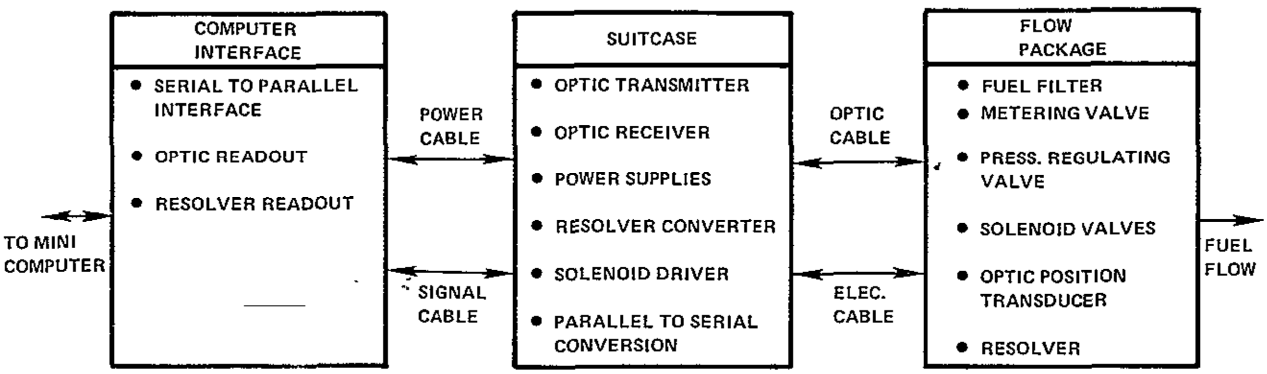


Figure 1 Digital Output Interface Hardware Block Diagram

DOI FLOW PACKAGE

Hydromechanical Hardware

The basic hydromechanical hardware utilized for the flow package was manufactured for development testing from an existing hydromechanical fuel control. The flow package is a cast aluminum block containing all the cored fuel flow passages and machined cavities for the fuel filter and its bypass valve, the fuel metering valve, pressure regulating valve, and minimum pressurizing valve. For the DOI program, the flow package housing was reworked to mount an orifice block and to incorporate the metering valve feedback lever and shaft which were connected to the optical position sensor and the resolver. The orifice block provided mounting and plumbing connections for the shutoff valve solenoid and for the fixed orifices that supply fuel to the digital effector solenoid valves. A schematic of the flow package is shown in Figure 2.

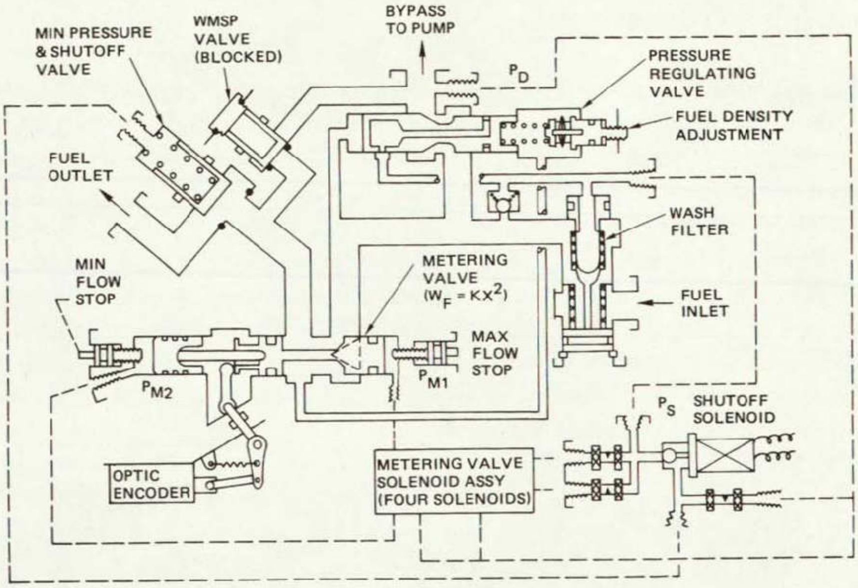


Figure 2 Schematic of Flow Package With Digital Interface

The digital effector valves (solenoids) were purchased "off the shelf" and were selected for their dynamic response and long life characteristics. The solenoid valves were adjusted to allow a fuel flow of 6.55 cm^3/second (.4 in^3/seconds) for each pair of solenoids at a differential pressure of 68.9 newtons/cm^2 (100 pounds/in^2) when energized. A photograph of the completed flow package is shown in Figure 3.

ORIGINAL PAGE IS
OF POOR QUALITY

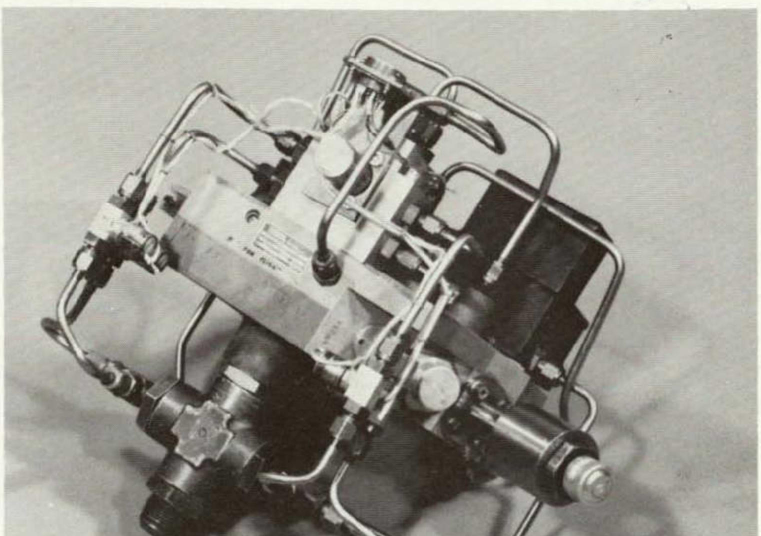


Figure 3 Flow Package Illustrating Solenoid Installation

Optical Encoder Head Construction

The optical encoder head was constructed by placing two aluminum shims between the two halves of the encoder head and bolting them together. Thirty-six 0.056 mm (0.0022 inch) diameter fibers per channel were positioned in the slots of the head. Silicon rubber tubing was placed on each leg of the optic fiber bundles and the bundles were attached to the sensing area with epoxy and to the back of the head (in the exit cavity) with silicon rubber. Slot filler blocks were used to retain the fibers in a rectangular area for exact positioning with relation to the gray code mask slots. The two halves of the optic head were separated with a saw cut. The two surfaces with the exposed fiber ends were ground and polished. The fibers from the optic head were then installed in the connector insert. The ends of the fibers were ground and polished and the connector insert installed in the connector. The assembled optic head with connector is shown in Figure 4.

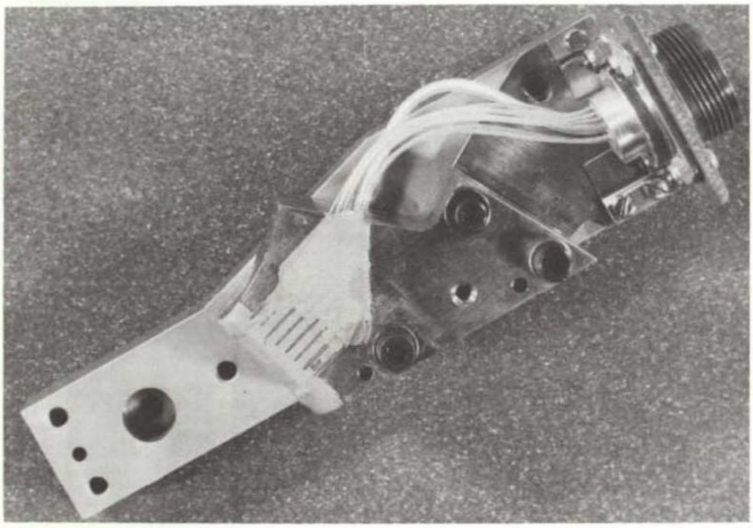


Figure 4 Assembled Optic Head With Connector

Optic Encoder Installation

The optic encoder was installed on the flow package and the gap between the receiver and transmitter halves of the head was set to 0.635 mm (0.025 inches). The feedback lever with the mask attached was to provide a 0.051 mm (0.002 inch) gap between the levers and the housing, and to center the mask within the optic head. The resolver with its flexible coupling and the protective cover was then installed.

ELECTRONIC INTERFACE SUITCASE

The electronic interface suitcase was constructed using a military case with a hinged lid. A base plate mounted with standoffs on the bottom of the case was used to support the following components: power supplies, resolver converter, optic transmitter and receivers, 400 hz. transformer and relay, main electronics card rack and the optic transmitter and receiver card rack.

The ±15 volt, 0.2 ampere power supply and the +5 volt, 1.5 ampere supply were retained to the base plate with metal straps. The +28 volt, 3 ampere supply and the 12 bit resolver-to-digital converter were plugged into an electrical socket in the base plate and mounted on standoffs to the base plate. The optic transmitter light-emitting diode (LED) with its heat sink was mounted on an "L" shaped bracket. The photo diodes were mounted in four blocks, two diodes per each block. The blocks with the photo diodes installed were plugged into sockets in a main wiring housing supported on an "L" shaped bracket. The 400 hz transformer and relay were attached to the main plate to supply power to the resolver. A card rack was fabricated for the solenoid driver card and for the parallel to serial converter card. Another card rack was fabricated for optic transmitter card and optic receiver card.

A film optic pigtail consisting of 100 fibers 0.056 mm (0.0022 inch) diameter in each of the eight receiver bundles and 800 fibers in the transmitter bundle was installed to connect the transmitter LED and receiver pin diodes to the optic connector.

The suitcase with the cover off is shown in Figure 5.

ORIGINAL PAGE IS
OF POOR QUALITY

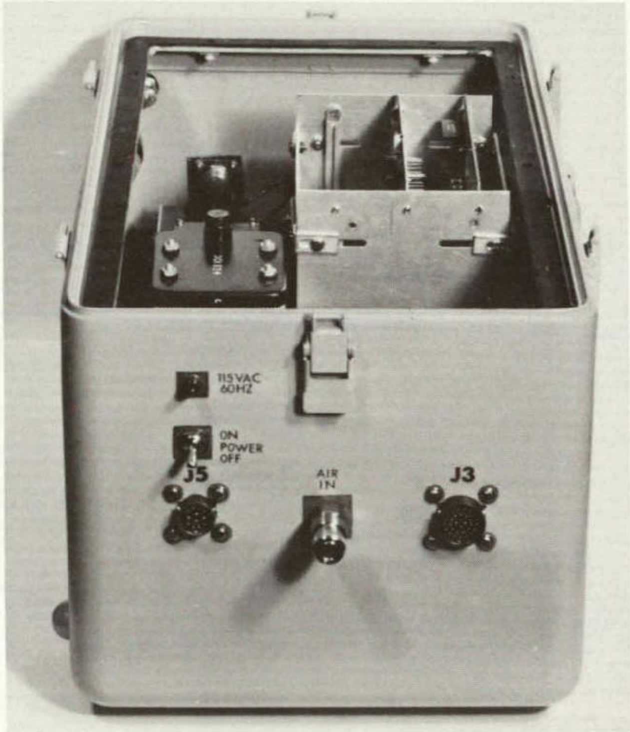


Figure 5 Electronic Suitcase (end view)

MINICOMPUTER INTERFACE BOX

The minicomputer-interface box was constructed with a sloped front cabinet and contained a +5 volt power supply, a serial to parallel data conversion board and two sets of binary output lamps, 12 bits for the resolver output and 8 bits for the optical position sensor output. Two terminal strips were provided on the back of the minicomputer interface box for connections to the minicomputer. The interface box is shown in Figure 6.

Figure 6 Minicomputer Interface Console

OPTIC CABLE

A 1.8 meter (6 foot) long optic cable of nine channels was constructed by United Technologies Research Center. The cable has eight receiver bundles, each of 100 fibers 0.056 mm (0.0022 inch) in diameter and one transmitter bundle of 800 fibers. The cable is covered with a metal braid for abrasion resistance and is terminated with connectors designed to mate with the optic pigtails on each end. The optic cable is shown in Figure 7.

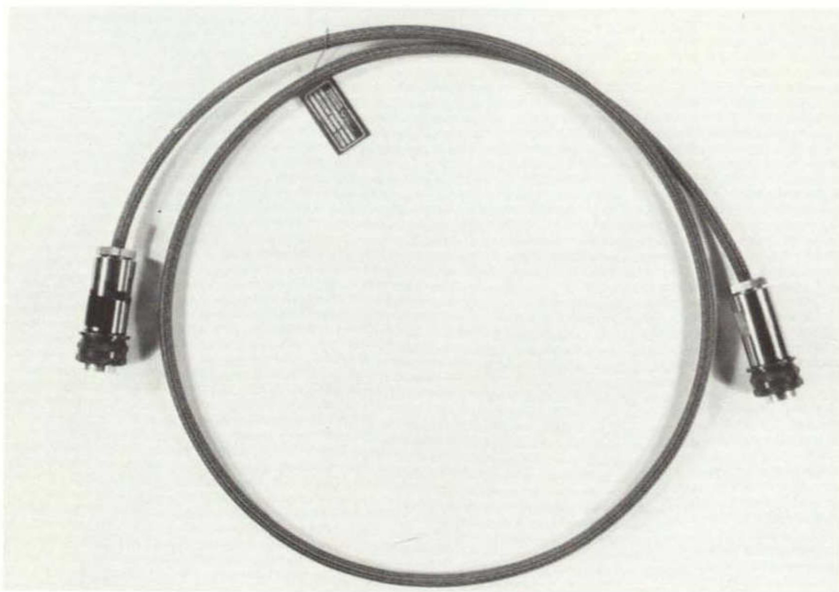


Figure 7 Optic Cable

ORIGINAL PAGE IS
OF POOR QUALITY

ELECTRICAL CABLES

Two electrical cables were made for the DOI system: a 1.8 meter (6 foot) cable to connect from the flow box to the electronic interface suitcase and consisted of eight shielded twisted pairs, and a 22.9 meter (75 foot) cable to connect the suitcase to the minicomputer interface box and consisted of nine twisted shielded pairs and eleven individual leads.

SOFTWARE

The software for the DOI testing was programmed in a minicomputer and consisted of a real-time transfer function simulation of a turbofan engine, an electronic controller, and adaptive logic to compensate the dynamics of the digital effectors. The turbofan simulation calculated rotor speeds, burner inlet pressure, and compressor inlet temperature at three flight conditions: sea level static; 4572 meters (15,000 feet), 0.6 Mach number; and 10668 meters (35,000 feet) 0.8 Mach numbers. The simulation was verified by inputting a transient schedule of fuel flow versus time and comparing the results to a simulation of the turbofan engine on a large time-sharing computer.

The electronic controller schedules fuel flow to the simulated turbofan engine as a function of the rotor speeds, burner pressure and compressor inlet temperature of the engine, power lever angle, flight condition, and the fuel metering valve position feedback from the DOI flow package. The electronic controller uses adaptive logic, which adjusts a gain in the software to control the open loop gain of the metering valve position control loop. The electronic controller was checked out by operating the controller and the engine simulation with a simulation of the DOI hardware and verifying steady-state stability and transient response.

DOI FLOW BENCH TESTING

The DOI was tested on a fuel flow bench for performance evaluation and endurance testing. Subsystem tests were conducted at Hamilton Standard to adjust and calibrate the components of the DOI system and to test the system open loop to verify satisfactory operation with correct component gains. The DOI was delivered to Pratt & Whitney Aircraft after the subsystem tests were completed and installed in a closed loop flow bench. A closed loop flow bench test was then conducted to evaluate steady-state and transient performance, and response to simulated failures. An endurance test was performed to establish a basic level of system durability. After testing, the DOI flow box was disassembled and inspected for wear. After reassembly, the DOI was installed on the closed loop fuel flow bench at Pratt & Whitney Aircraft for a calibration check.

The DOI testing successfully demonstrated steady-state stability, transient response for small and large power lever excursions, and the capability to tolerate a failure of any one of the DOI solenoids. The results of the testing indicate that the digital effector with optical fuel metering valve position feedback is a suitable candidate, with proper development, for future digital electronic gas turbine controls.

The testing successfully demonstrated the digital effector and optical feedback concepts, but uncovered several unresolved problem areas which would have to be overcome in a final production configuration of a digital effector with optical feedback. Performance testing showed that the simulated turbofan engine would limit cycle ±15 rpm low rotor speed due to the resolution of the optical position feedback. The feedback is an 8-bit signal with a resolution of 0.051 mm (0.002 inch). This is equivalent to 47.2 kilograms per hour (104 pounds per hour) at takeoff power and 15.4 kilograms per hour (34 pounds per hour) at idle. An optical position sensor with a better resolution would be required to improve steady-state stability.

Failsafe testing showed that the digital effector can continue to control with any single solenoid failure, but that failures of the optical feedback channels (bits) would make the feedback incapable of providing control. For the brassboard DOI configuration tested, the resolver can be used if the optical feedback fails; but, in a production configuration, a failure of the optical feedback would require some redundant measurement of the fuel metering valve position.

Testing also showed that a failure of the solenoid interfacing electronics or a loss of power to the electronics would keep the digital effector solenoids closed, which holds the fuel valve position fixed. Since fuel flow cannot be changed, it would be necessary to shut down an engine with the shut-off solenoid. Failed fixed may be an attractive feature in other servo system applications.

The DOI completed 461.75 hours of testing and 6.95 million cycles of the digital effector solenoids with no performance degradation or failures. Total hours and solenoid cycles are tabulated for each of the portions of the test in Table I.

TABLE I

SUBSYSTEM TESTS OF DOI

Test	Hours	Number of Solenoid Cycles			
		I_1 Solenoid	I_2 Solenoid	D_1 Solenoid	D_2 Solenoid
Subsystem Component Tests	25.0	115,850	114,466	214,387	204,388
Performance Test	83.75	313,548	303,744	721,937	756,813
Endurance Test	342.0	628,387	628,387	1,296,252	1,296,252
Post-inspection Recalibration Test	11.0	122,185	80,070	86,686	69,966
Total	461.75	1,179,970	1,126,667	2,319,262	2,327,419

SUBSYSTEM COMPONENT TESTS

Subsystem tests were performed to adjust the components and to test the system open loop. These tests are described below.

Optical Position Sensor and Interface Unit Tests

The optical position sensor and interfacing electronics were tested to measure the optic receivers with and without the gray code mask in the position encoder and to align the encoder with the mask. The levels at which the comparators of the optic receivers switched were also set in relation to the optic output of each channel to ensure reliable and positive "on" and "off" indications. Calibrations of the encoder outputs to the fuel metering valve position were made over the full range of valve travel at temperatures from 283°K (50°F) to 322°K (120°F).

DOI Flow Package Subsystem Tests

The following tests were performed to adjust and check the flow package operation: set pressure regulating valve and maximum and minimum flow stops, check the functions of the fuel shutoff solenoid, check fuel flow versus valve position, and set the solenoid flow rates to achieve the correct fuel valve velocity versus solenoid on-time.

Flow Package and Optical Position Sensor Assembly Test

A calibration of fuel flow, optic encoder and resolver outputs versus valve position was run to verify operation of the whole system after adjusting and testing the individual components. This test also verified the integrity of the interconnecting cabling.

On-Off Switches and On-Off Indicator Tests

This test verified that the system could be shut off from either the electronic interface or the minicomputer interface box and hold a constant fuel flow rate when shut off.

CLOSED LOOP FLOW BENCH PERFORMANCE TEST

A closed loop flow bench test was performed on the DOI which interfaced a digital electronic control with a fuel flow metering unit to evaluate the performance of the DOI as a subsystem of a closed loop digital electronic control system. The electronic control sets steady state power with an isochronous low rotor speed governor and provides acceleration/deceleration fuel flow limiting. Rotor speeds, pressure, and temperature measurements from a real-time computer simulation of a turbofan engine are inputs to the electronic control. A fuel flow measurement from the metering unit was input to the engine simulation to calculate speeds, pressure, and temperature. A block diagram of the DOI control loop is shown in Figure 8.

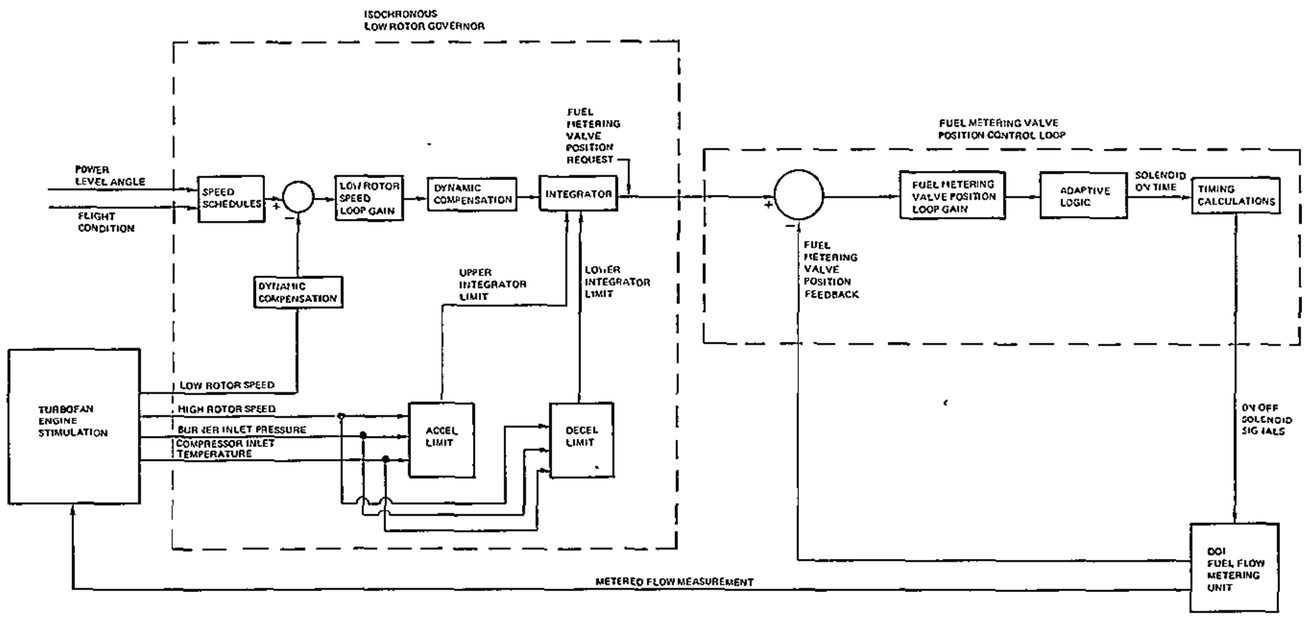


Figure 8 Digital Output Interface Control Loop

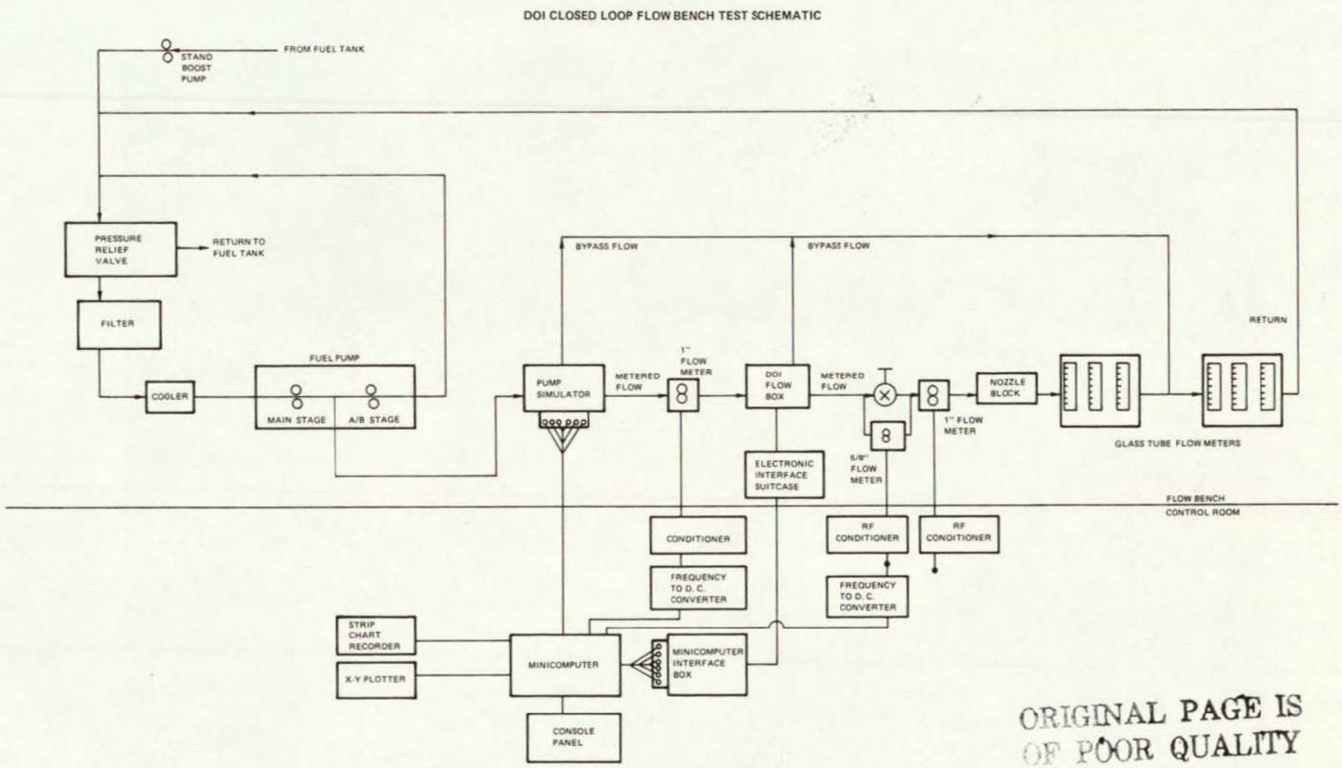
The operation and the performance of the DOI was demonstrated over a range of flight conditions typical for a modern commercial air transport: sea level static; climb at 4572 meters (15,000 feet), 0.6 Mach number; and cruise at 10,668 meters (35,000 feet), 0.8 Mach number.

The test hardware of the system included the following:

- DOI flow box
- Electronic interface suitcase
- 1.8 meter (6 foot) optical cable
- 22.9 meter (75 foot) data cable
- Minicomputer Interface Box
- Minicomputer

Test Configuration

The DOI was tested on a fuel flow bench with a constant-speed motor driving the fuel pump. Since only a constant fuel supply was available at the flow bench, an electrically modulated bypass valve was used to simulate a variable-speed positive-displacement pump running at the high rotor speed of the simulated turbofan engine (this valve is part of the P&WA FT4C engine control system, and is referred to as a pump simulator in the following text). A schematic of the DOI closed loop flow bench test configuration is shown in Figure 9. The salient features of the DOI system, as mounted on the closed loop bench, are highlighted in Figures 10, 11, and 12.



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 9 Schematic of Digital Output Interface Closed Loop Flow Bench Test

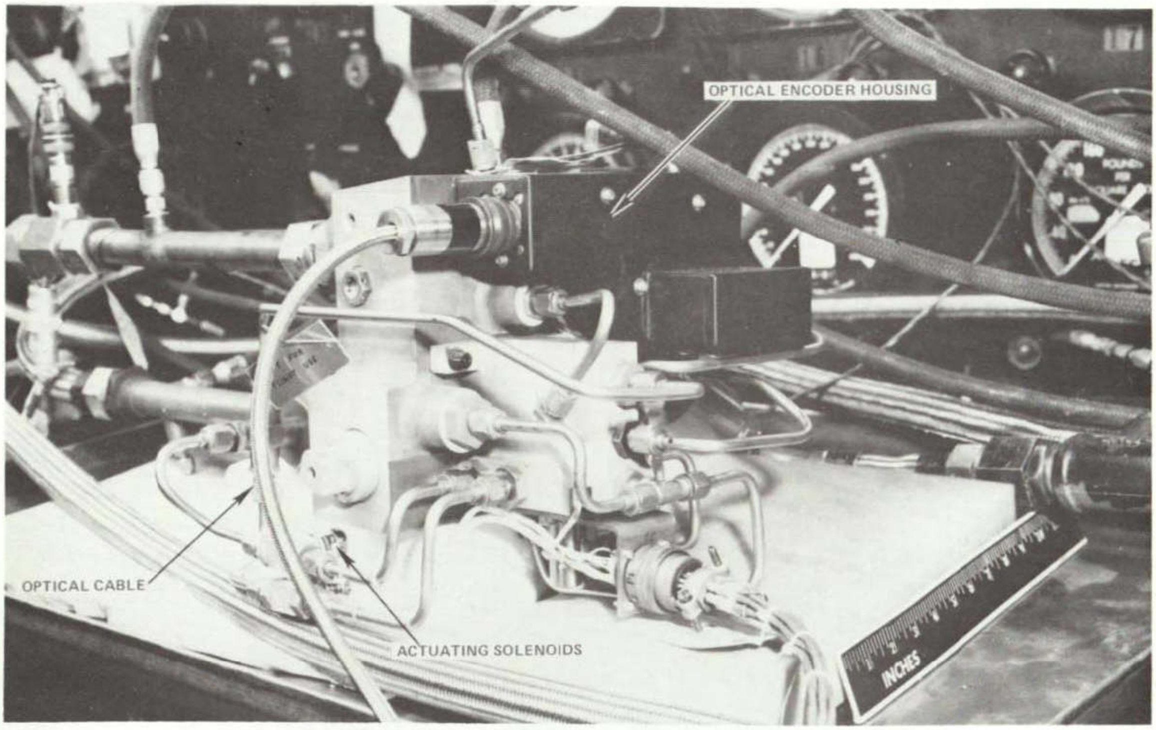


Figure 10 *Digital Output Interface Flow Package With View of Optical Encoder Housing*

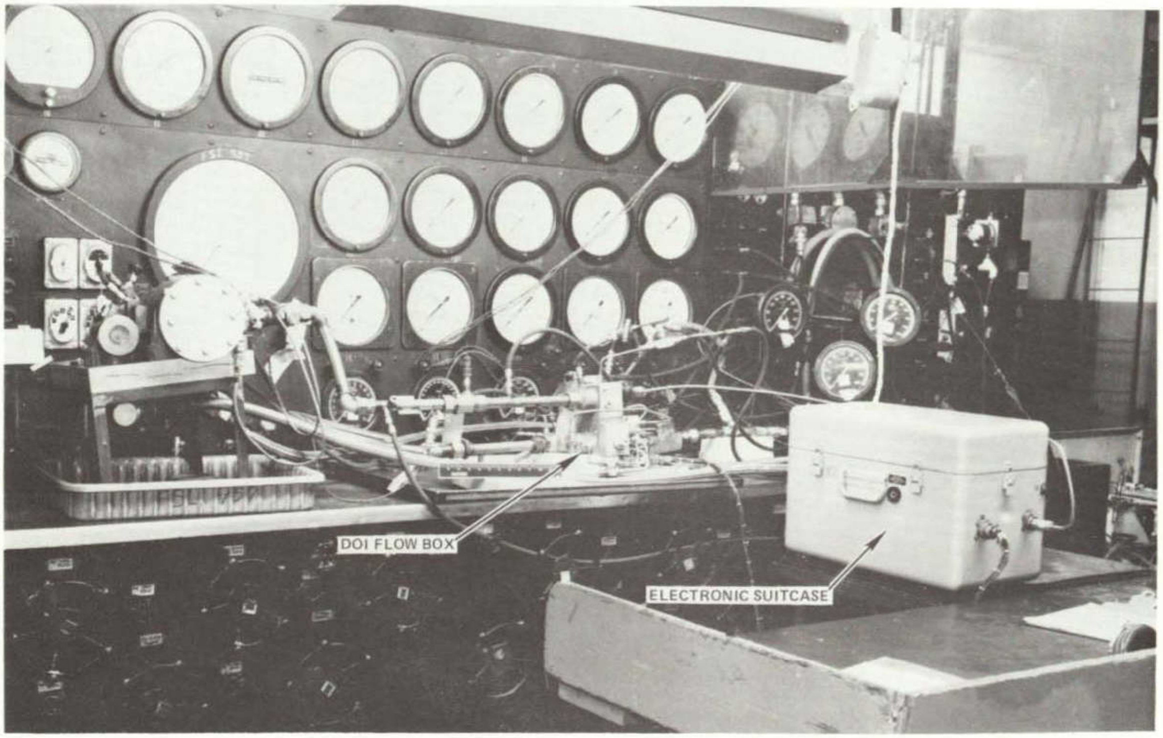
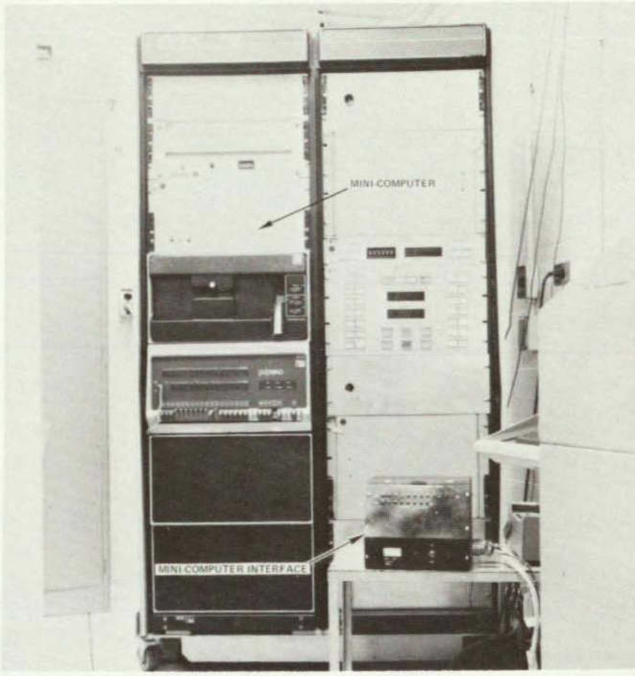


Figure 11 *Digital Output Interface Installed in Closed Loop Flow Bench (DOI flow box and electronic interface suitcase)*



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 12 Closed Loop Flow Bench (mini-computer, console panel, and mini-computer interface)

The simulated turbofan engine and the electronic controller were programmed on a minicomputer. The input to the simulated engine was the fuel flow measurement downstream of the DOI. A 2.54 cm (1.0 inch) flowmeter was used above 2267 kilograms per hour (5000 pounds per hour) fuel flow, and a 1.58 cm (5/8 inch) flowmeter was used to provide improved measurement accuracy at low fuel flow. An electrical power lever angle signal was input to the controller from the console panel located next to the minicomputer.

Test stand instrumentation included pressure gauges and glass tube fuel flow meters for steady state measurements. An 8-channel strip chart recorder and an X-Y plotter connected to the minicomputer provided transient recordings. Metered flow from the pump simulator and the DOI were digitally displayed on the console panel.

Test Sequence

The test was conducted in four parts:

- System Operational Verification to check out the engine simulation, and to calibrate the pump simulator, the DOI, and the fuel flow inputs to the minicomputer.
- Steady State Performance Test to verify steady state stability and determine solenoid actuation frequency.
- Transient Performance Test of small and large power lever transients to determine response time, overshoot, and acceleration/deceleration schedule tracking.
- Failsafe Demonstrate Test to determine the effects of solenoid, optical feedback, and electronic interface failures on steady state and transient performance.

Steady-state and transient performance were compared to analytical predictions of the system's performance. The analytical predictions were obtained from a simulation of the DOI hardware's software run on a large-timing sharing computer.

TEST RESULTS

System Operational Verification

Correct operation of all subsystems was verified. The engine simulation, the pump simulator and the DOI were successfully calibrated.

The minicomputer engine simulation was checked out by inputting a fuel flow versus time transient and comparing rotor speeds, burner pressure, and compressor inlet temperature to the simulation of the turbofan engine on a large time-sharing computer. The data shows excellent agreement at sea level static (Figure 13). Similar agreement was also achieved at 4572 meters (15,000 feet), 0.6 Mach number and at 10668 meters (45,000 feet), 0.8 Mach number.

The FT4C liquid valve was installed in the flow bench before the DOI was received. The FT4C valve and one fuel flow input to the minicomputer were calibrated. After calibration, the FT4C valve was controlled closed loop with the fuel flow as a function of the high rotor speed of the simulated engine to act as a positive displacement fuel pump.

The DOI was installed in the flow bench and calibrated. The calibration of fuel flow, resolver feedback, and optical feedback to fuel valve position closely matched the results of the open loop test performed by Hamilton Standard (Figure 14). The 1.58 cm (5/8 inch) flow meter input and the other 2.54 cm (1.0 inch) flow meter input to the mini-computer were then calibrated.

Steady State Performance Test

Steady state performance was investigated at several power settings for three flight conditions. Typical steady state data from the strip chart recorder is shown in Figure 15 for sea level static. The data shows periods of good steady state stability with intermittent limit cycling. The magnitude of the limit cycling and the solenoid cycling frequency were both greater than analytical predictions. Table II shows a comparison of steady state stability and solenoid cycling frequency to the analytical predictions for all three of the flight conditions examined. Several changes were attempted in the electronic controller to lower the magnitude of the limit cycling. The low rotor speed loop gain and the fuel metering valve loop gain were lowered; adjustments were made to the compensation, but the limit cycling was unchanged.

The steady state limit cycling is due to the resolution of the fuel metering valve position feedback. Substituting resolver feedback for optical position feedback improved the limit cycling (Table III) because of the finer resolution of the resolver feedback. (The resolver feedback resolution is .031 mm [.0012 inch] as compared to the .051 mm [.002 inch] resolution of the optical feedback.) Typical steady state data at sea level static with the resolver feedback is shown in Figure 16. For the test points (steady state at high, mid and idle power at three flight conditions) tabulated in Table III, the average speed limit cycle is ± 14.8 rpm with optical feedback, and ± 11.2 rpm with the resolver feedback. It is expected that further improvement in the feedback resolution would continue to decrease steady state limit cycling and improve steady state stability.

In summary, the DOI testing showed good steady state performance with intermittent limit cycling larger than predicted. The steady state performance of the DOI would be improved by the development of an optical position sensor with better resolution.

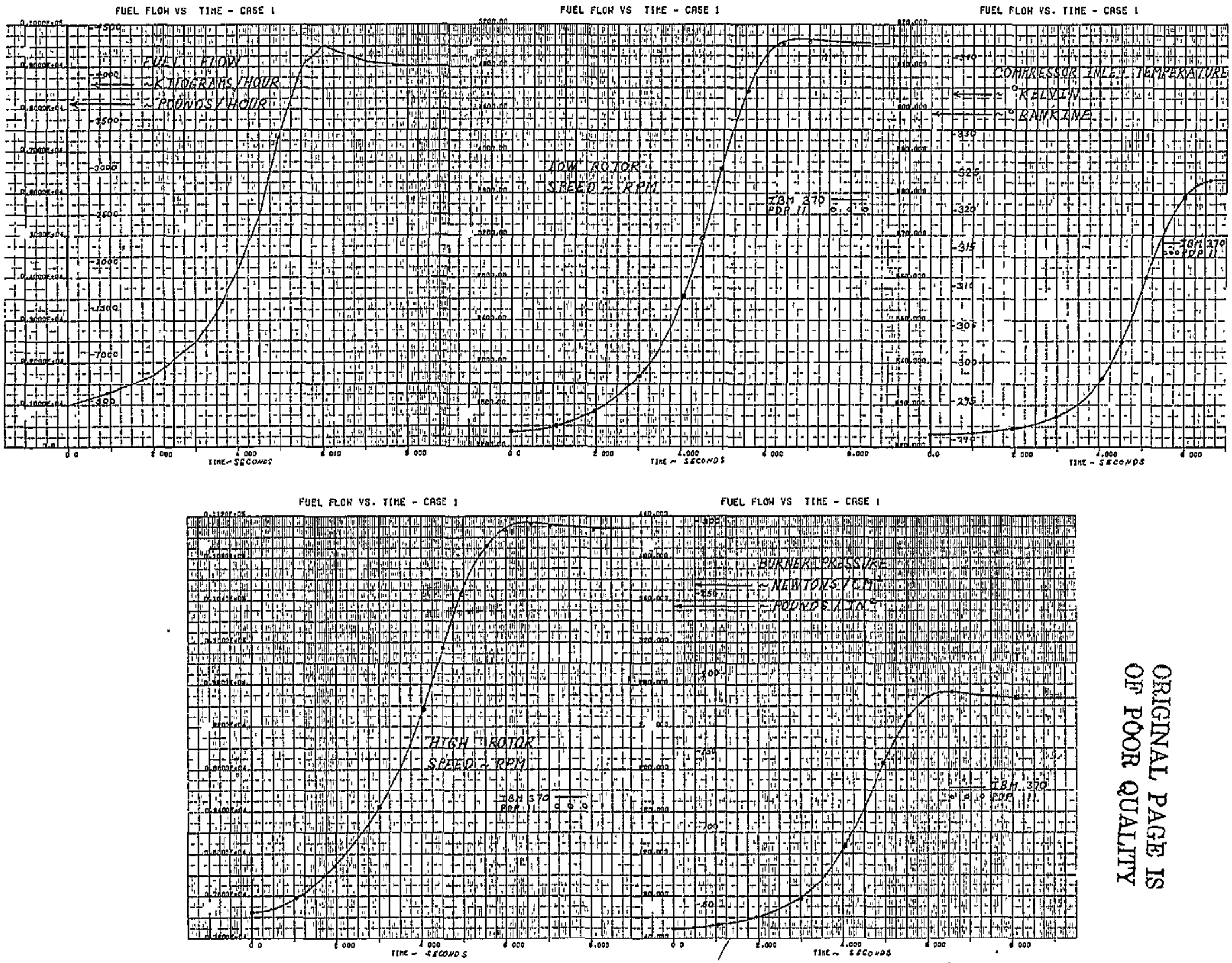


Figure 13 Engine Simulation Verification at Sea Level Static

ORIGINAL PAGE IS
OF POOR QUALITY

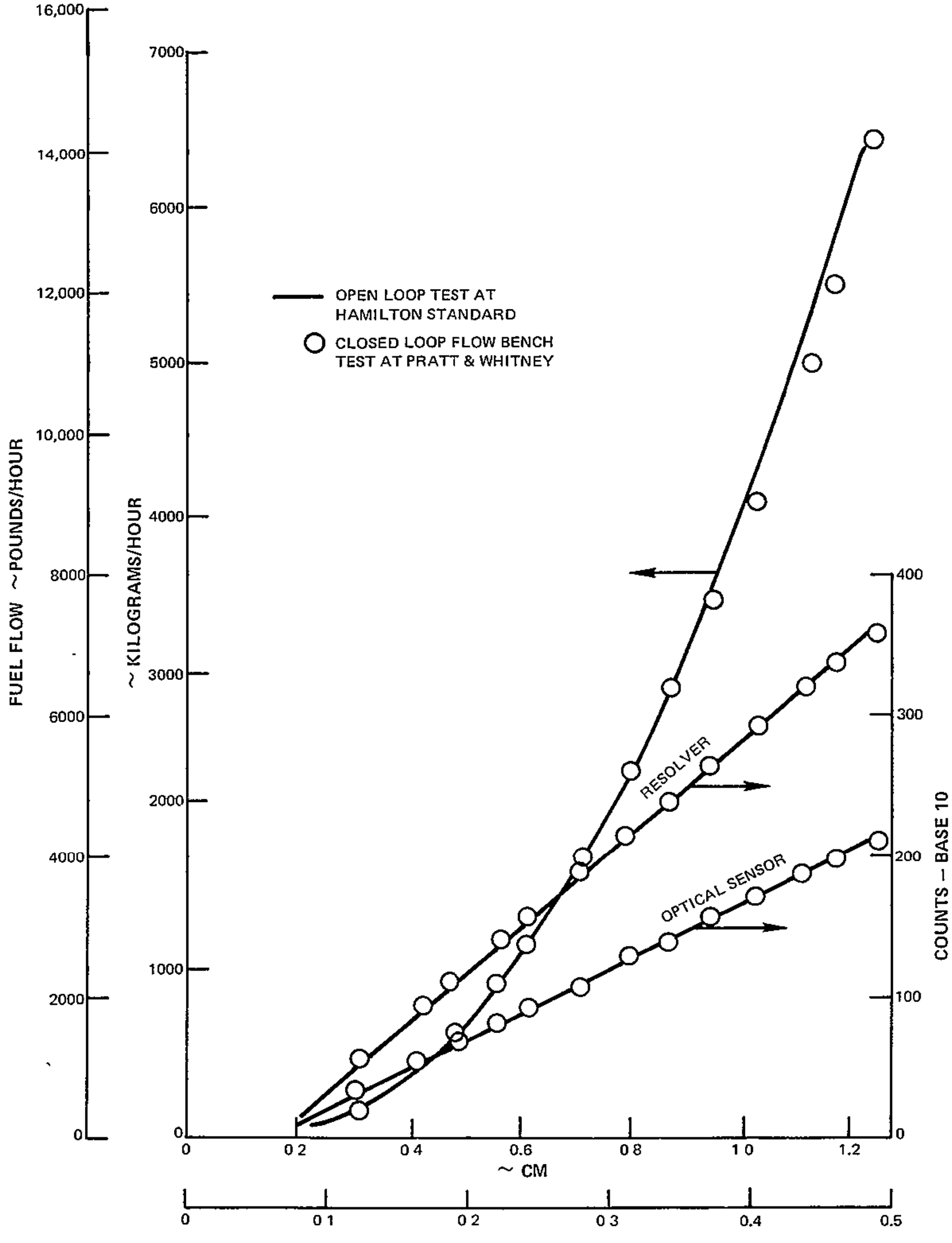


Figure 14 Digital Output Interface Metering Valve Calibration

ORIGINAL PAGE IS
OF POOR QUALITY

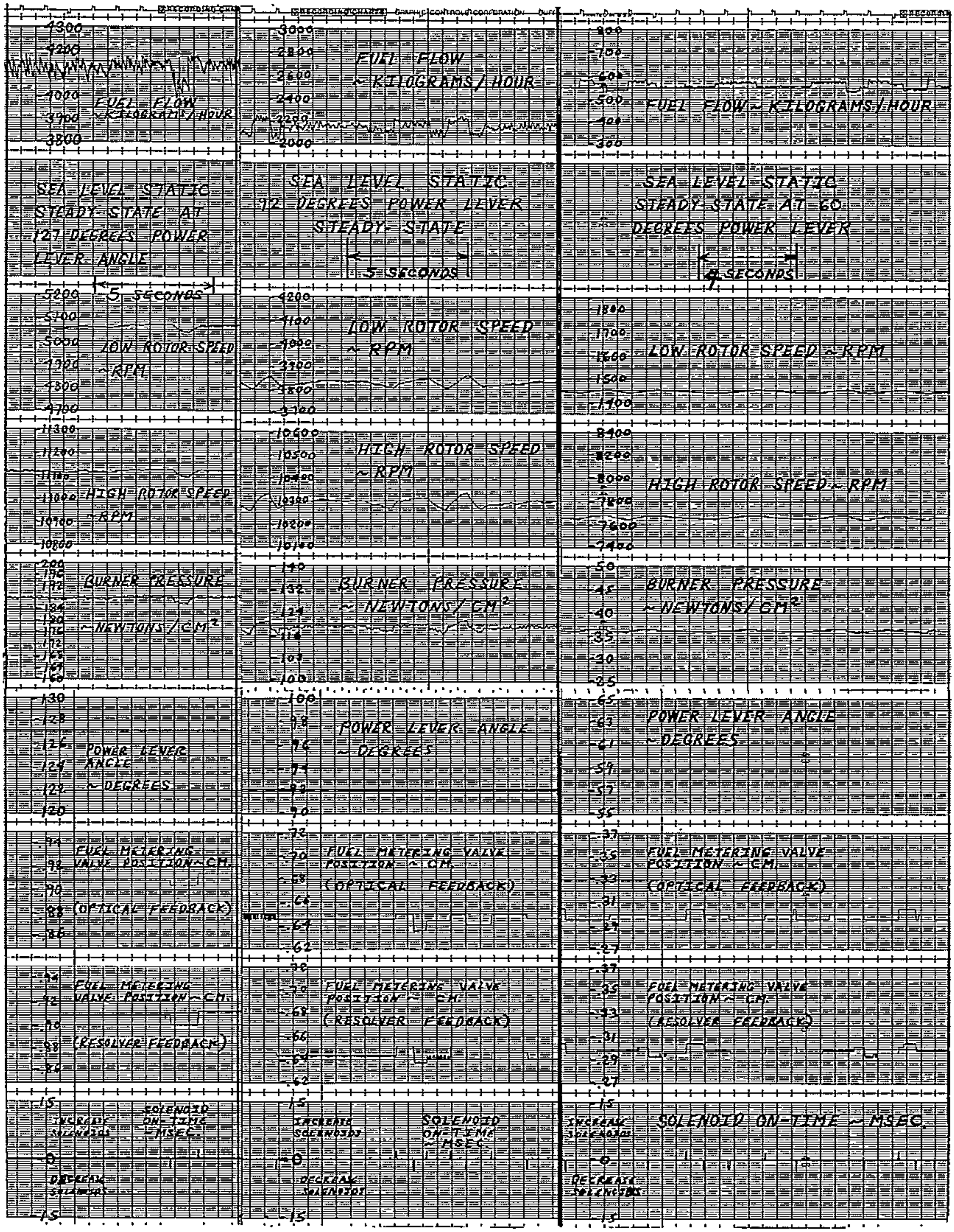


Figure 15 Steady State Performance at Sea Level Static With Optical Feedback

TABLE II

COMPARISON OF DOI STEADY STATE STABILITY AND SOLENOID CYCLING FRFQUENCY TO ANALYTICAL PREDICTIONS - OPTICAL POSITION FEEDBACK

Flight Condition	Power Lever Angle ~ Degrees	Steady State Low Rotor Speed Limit Cycle (± rpm)		Solenoid Cycling Frequency ~ Cycles/Second			
				Increase Solenoids		Decrease Solenoids	
		Predicted	Test Data	Predicted	Test Data	Predicted	Test Data
Sea Level Static	127	9	15	0.85	0.54	0.37	0.38
Sea Level Static	92	10	25	0.85	1.12	0.53	1.10
Sea Level Static	60	4	8	0.73	0.70	0.46	0.76
4572 Meters (15,000 feet), 0.6 Mach number	127	8	15	1.04	1.12	0.69	0.97
4572 Meters (15,000 feet), 0.6 Mach number	92	9	17	0.98	0.81	0.65	0.86
4572 Meters (15,000 feet), 0.6 Mach number	60	5	10	0.76	0.86	0.49	0.92
10668 Meters (35,000 feet), 0.8 Mach number	127	10	15	0.80	0.30	0.52	0.31
10668 Meters (35,000 feet), 0.8 Mach number	92	10	15	0.78	0.69	0.46	0.73
10668 Meters (35,000 feet), 0.8 Mach number	60	9	10	0.72	1.22	0.46	1.49

TABLE III

EFFECT OF FUEL METERING VALVE POSITION FEEDBACK RESOLUTION ON DOI STEADY STATE STABILITY

Flight Condition	Power Lever Angle	Steady State Low Rotor Speed Limit Cycle (± rpm) Fuel Valve Position Feedback Resolution	
		0.051 mm[1] (0.002 inch)	0.031 mm[2] (0.0012 inch)
Sea Level Static	127	15	12
Sea Level Static	92	25	20
Sea Level Static	60	8	7
4572 Meters (15,000 feet), 0.6 Mach number	127	18	12
4572 Meters (15,000 feet), 0.6 Mach number	92	17	10
4572 Meters (15,000 feet), 0.6 Mach number	60	10	10
10668 Meters (35,000 feet), 0.8 Mach number	127	15	10
10668 Meters (35,000 feet), 0.8 Mach number	92	15	10
10668 Meters (35,000 feet), 0.8 Mach number	60	10	10

1) Optical Fuel Metering Valve Position Feedback
2) Resolver Fuel Metering Valve Position Feedback

ORIGINAL PAGE IS
OF POOR QUALITY

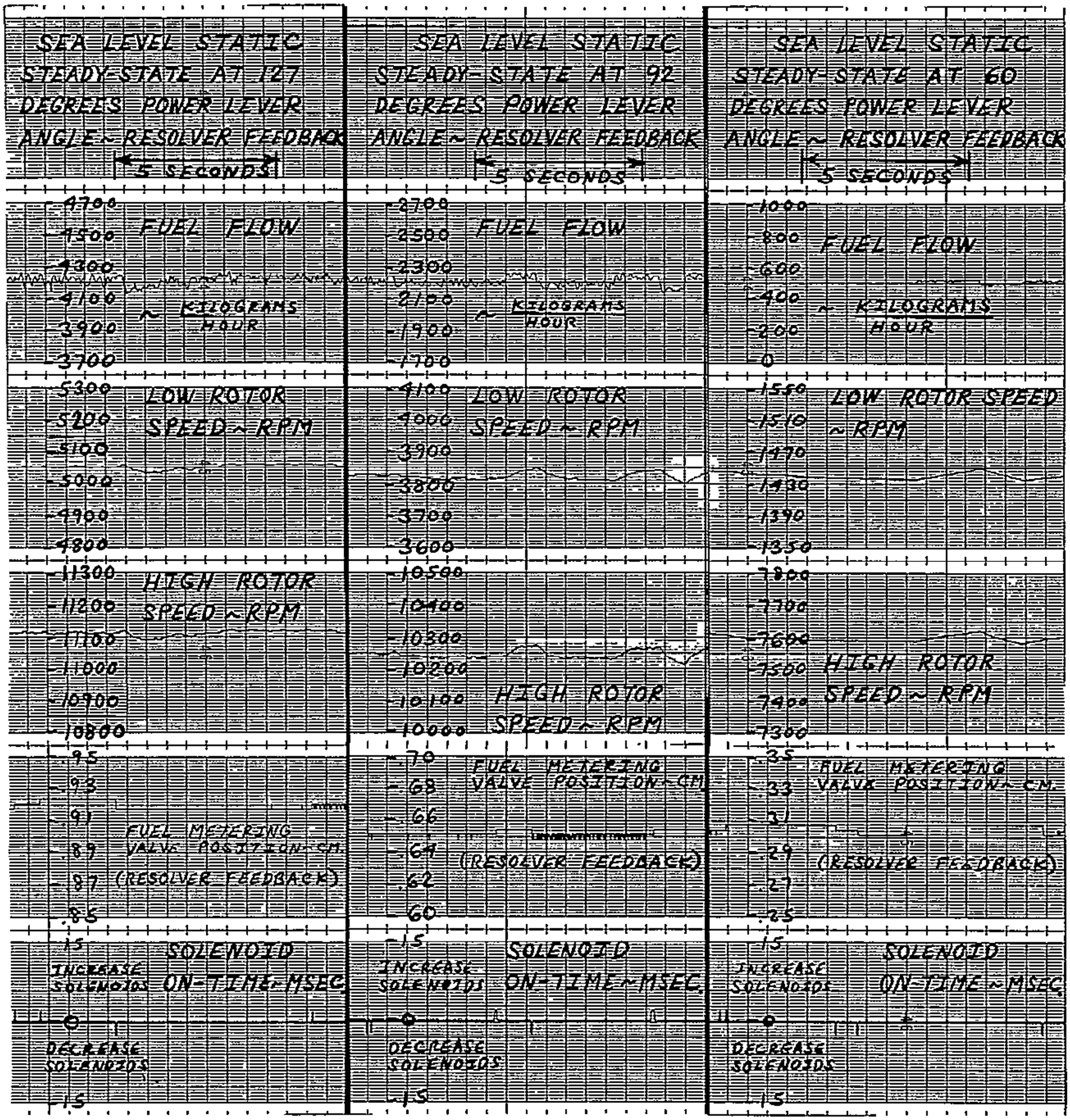


Figure 16 Steady State Performance at Sea Level Static ~ Resolver Feedback

Transient Performance Test

Small Power Lever Transients - This portion of the transient performance test showed that the DOI is capable fo providing good engine response with little or no overshoot for small power changes. Transient response and overshoot for small power lever changes at the three flight conditions examined are tabulated in Table IV.

TABLE IV

COMPARISON OF DOI RESPONSE AND OVERSHOOT TO ANALYTICAL PREDICTIONS – SMALL POWER LEVER TRANSIENTS

Flight Condition	Power Lever Angle Transient Degrees	Transient Response Time(1) ~ Seconds		Percent Overshoot(2)	
		Predicted	Test Data	Predicted	Test Data
Sea Level Static	60 - 63	2 30	2.65	0	0
Sea Level Static	92 - 97	90	74	0	0
Sea Level Static	122 - 127	96	99	0	0
4572 Meters (15,000 feet), 6 Mach number	60 - 63	1 65	1 80	7	0
4572 Meters (15,000 feet), 6 Mach number	62 - 97	.89	.84	10	0
4572 Meters (15,000 feet), .6 Mach number	122 - 127	85	1.15(3)	8	4
10668 Meters (35,000 feet), 8 Mach number	60 - 63	1.42	1 80(4)	30	5
10668 Meters (35,000 feet), .8 Mach number	87 - 92	1 15	1.13	33	0
10668 Meters (35,000 feet), 8 Mach number	123 - 127	1 05	.95	33	0

Notes (1) Transient response time is the time for 90% of the requested speed change

(2) $\text{Percent Overshoot} = \frac{\text{Max Speed - Final Speed}}{\text{Final Speed - Initial Speed}} \times 100$

(3) Predicted response shows more initial overshoot, response of test data slows down as steady-state is approached

(4) Faster response of predicted data due to large overshoot

Test results of the response of the governing parameter, low rotor speed, for small power lever changes, are compared to analytical predictions at high, mid, and idle power at sea level static in Figure 17. The DOI response is slower than predicted at idle, but faster at mid and high power. Similar agreement was achieved at the other two test flight conditions. Transient overshoot was equal to or less than predicted at all test points. Typical DOI test data for small power lever transients is shown in Figure 18.

Large Power Lever Transients - This test showed that the DOI is capable of providing good acceleration and deceleration response. Testing at sea level static showed small, brief acceleration schedule overshoot at the beginning of a transient and no deceleration schedule undershoot (Figure 19). Similar results were obtained at the other flight conditions.

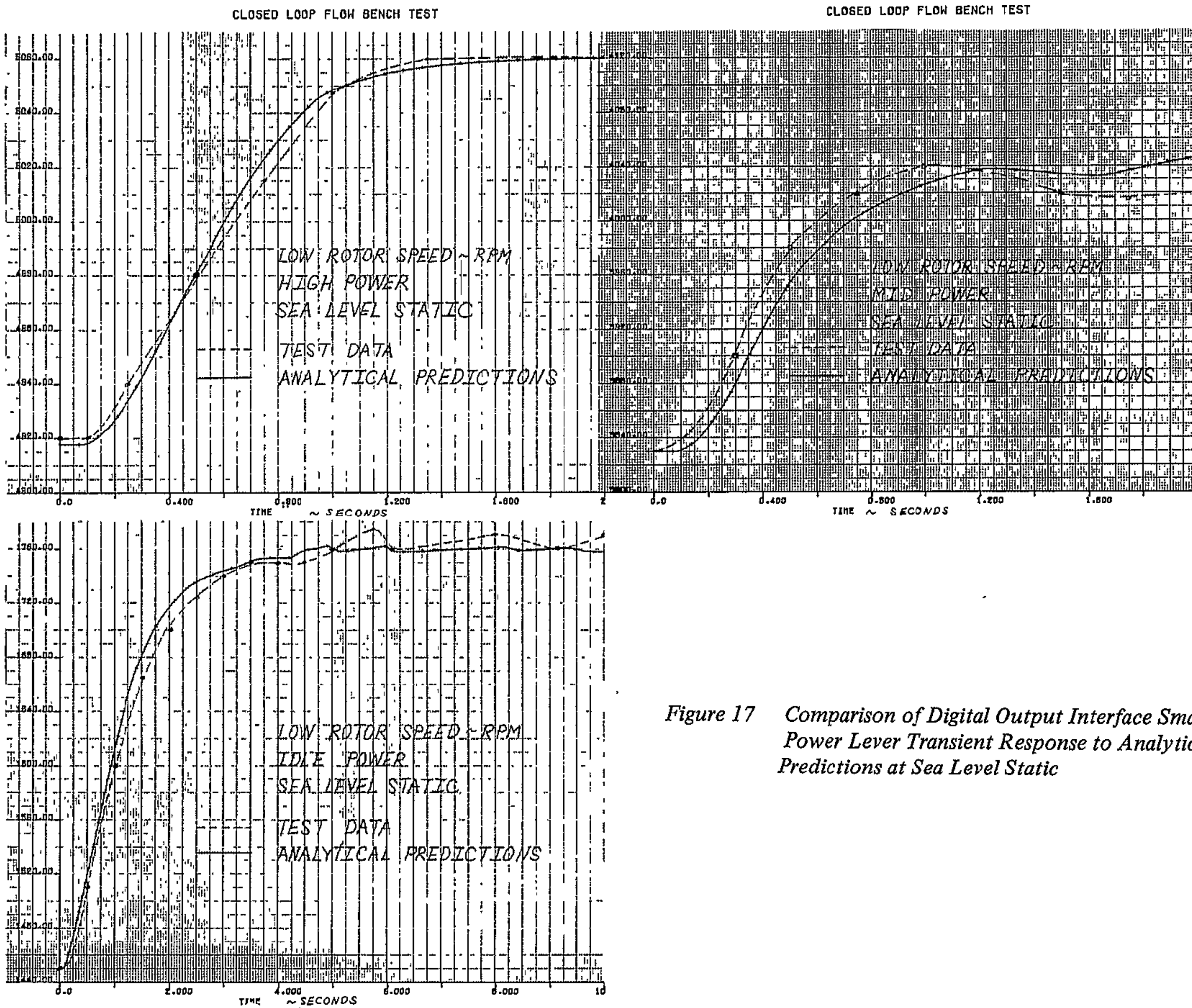


Figure 17 Comparison of Digital Output Interface Small Power Lever Transient Response to Analytical Predictions at Sea Level Static

ORIGINAL PAGE IS OF POOR QUALITY

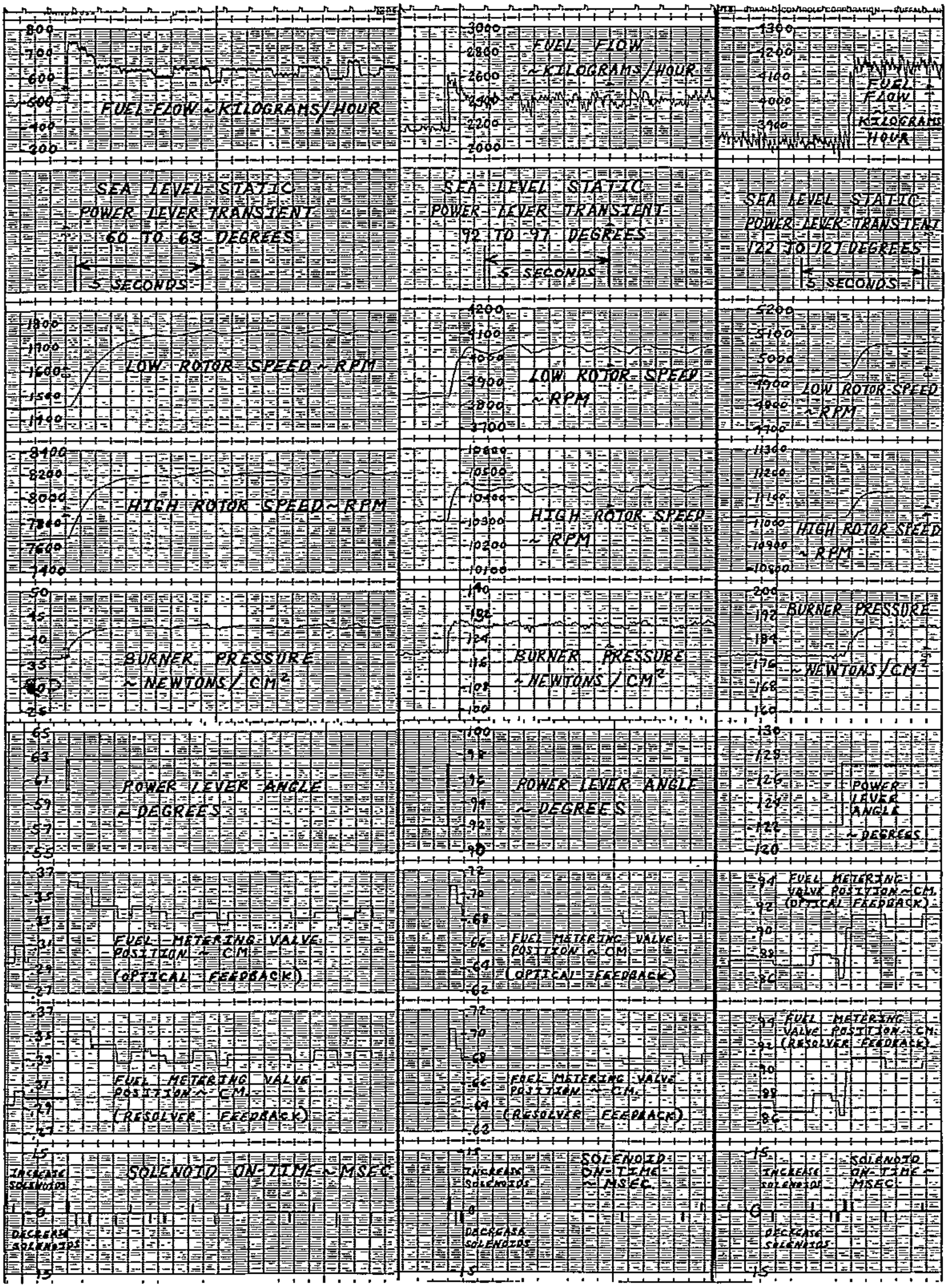


Figure 18 Small Power Lever Transients at Sea Level Static

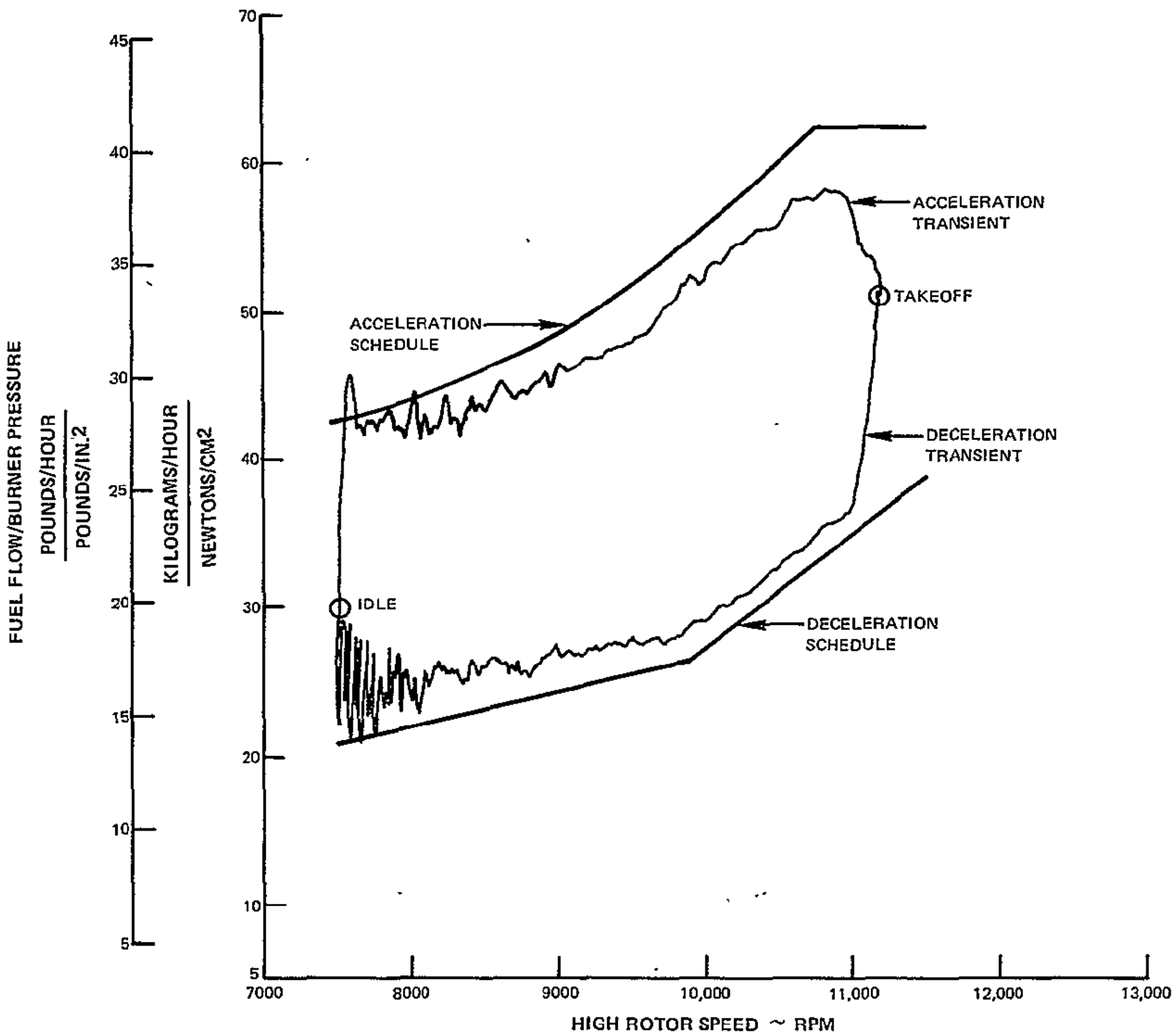


Figure 19 Acceleration and Deceleration Schedule Transients at Sea Level Static

Accelerations from idle to takeoff power and decelerations from takeoff power to idle with the DOI hardware were slightly slower than predicted. The DOI also showed more acceleration schedule overshoot than predicted at the beginning of a transient. DOI transient response time and acceleration schedule overshoot are compared to analytical predictions in Table V. Typical low rotor speed response with the DOI hardware is compared to analytical predictions in Figures 20-22. The typical test data for large power lever transients is shown in Figures 23-25 at all three test flight conditions.

TABLE V

COMPARISON OF DOI ACCELERATION SCHEDULE OVERSHOOT AND
LARGE POWER LEVER TRANSIENT RESPONSE TIME TO ANALYTICAL PREDICTIONS

		Acceleration Schedule Overshoot - Deceleration Schedule Undershoot Kilograms/Hour / Newtons/Cm² (Pounds/Hour / Pounds/In ²)		Transient Response (1) Time ~ Seconds	
Flight Condition	Transient	Predicted	Test Data	Predicted	Test Data
Sea Level Static	Acceleration from Idle to Max. Power	1.2 (0.8)	2.6 (1 7)	5.0	5 5
Sea Level Static	Deceleration from Max. Power to Idle	0 (0)	0 (0)	5 6	7.5(2)
4572 Meters (15,000 feet), .6 Mach number	Acceleration from Idle to Max. Power	7 (.5)	3 0 (2.0)	4.7	5.0
4572 Meters (15,000 feet), .6 Mach number	Deceleration from Max. Power to Idle	0 (0)	0 (0)	6.8	10.0(2)
10668 Meters (35,000 feet), .8 Mach number	Acceleration from Idle to Max Power	.5 (3)	3.7 (2.5)	7.7	8 0
10668 Meters (35,000 feet), .8 Mach number	Deceleration from Max. Power to Idle	0 (0)	0 (0)	9 2	12 0(2)

Notes: (1) Transient response time is the time to change the low rotor speed to within 100 rpm of the final steady-state value
(2) Deceleration transient "tails in" slowly at the end of the transients, approximately 0.5 seconds slower than predicted during most of the transient

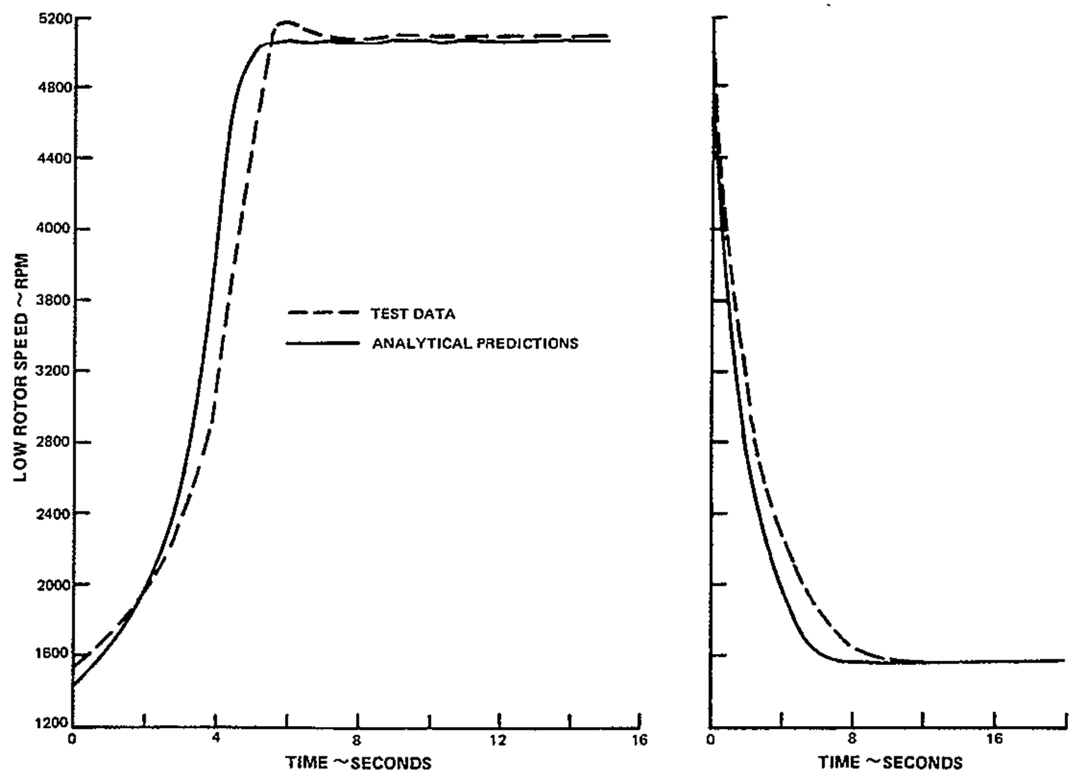


Figure 20 Comparison of Digital Output Interface Large Power Lever Transient Response to Analytical Predictions at Sea Level Static

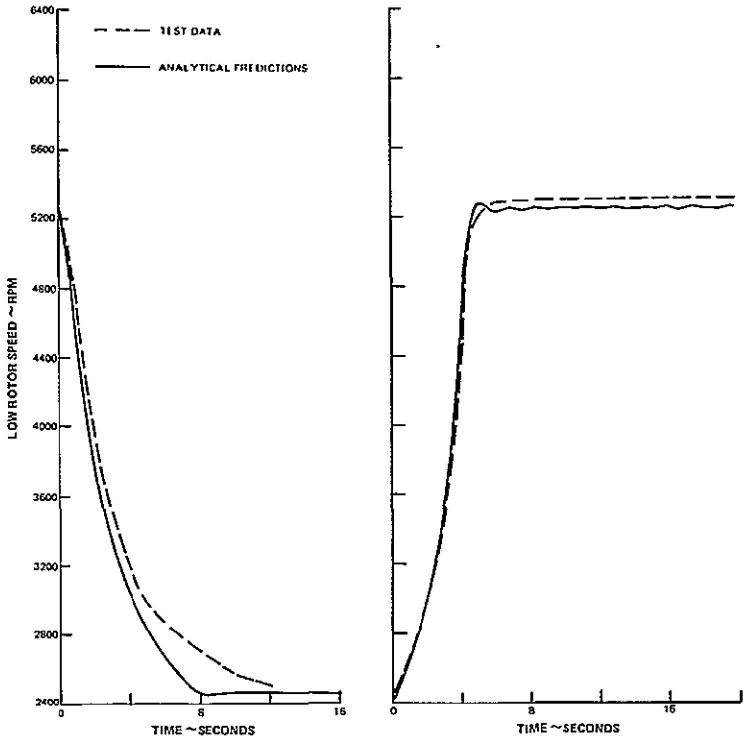


Figure 21 *Comparison of Digital Output Interface Large Power Lever Transient Response to Analytical Predictions at 4572 meters (5,000 feet), 0.6 Mn.*

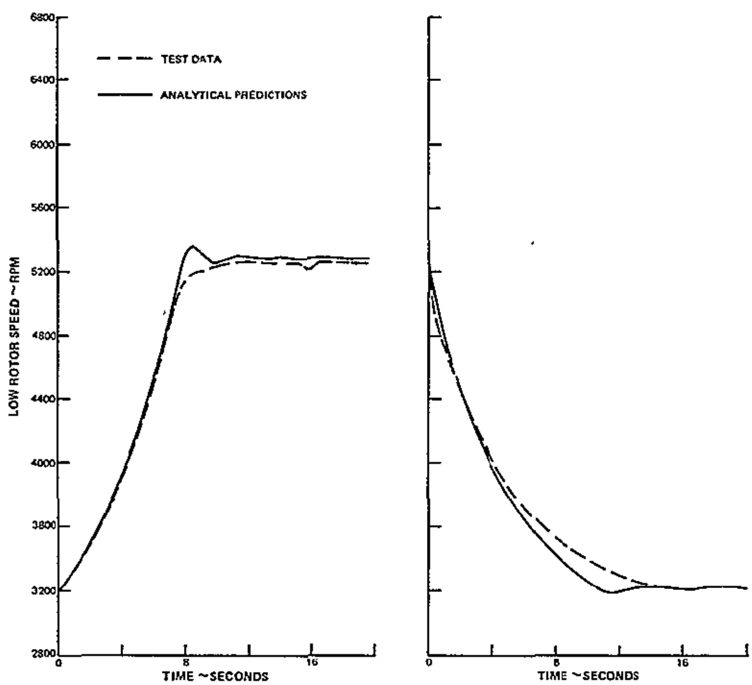


Figure 22 *Comparison of Digital Output Interface Large Power Lever Transient Response to Analytical Predictions at 10668 meters (35,000 ft), 0.8 Mn.*

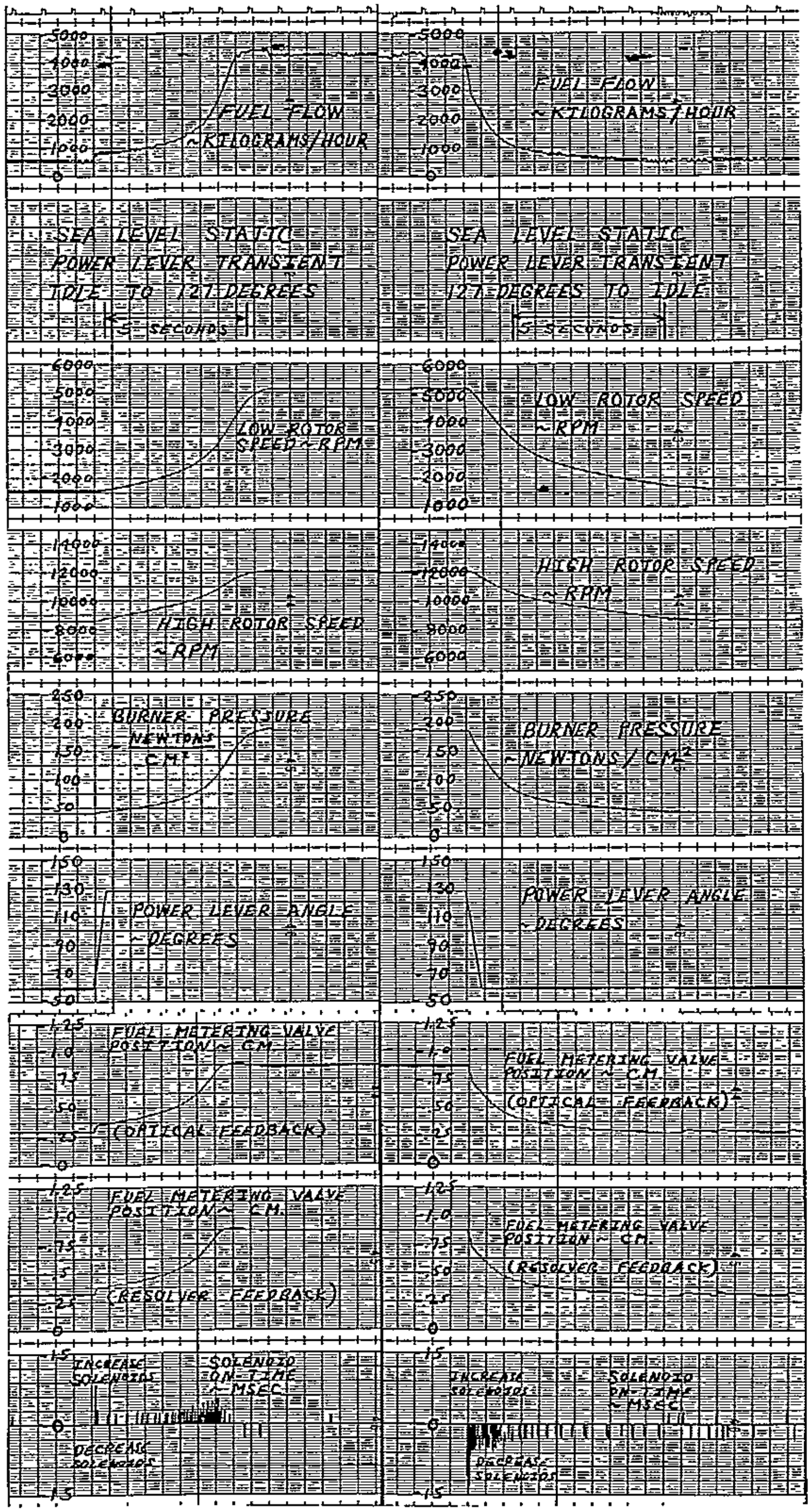


Figure 23 Large Power Lever Transients at Sea Level Static

ORIGINAL PAGE IS
OF POOR QUALITY

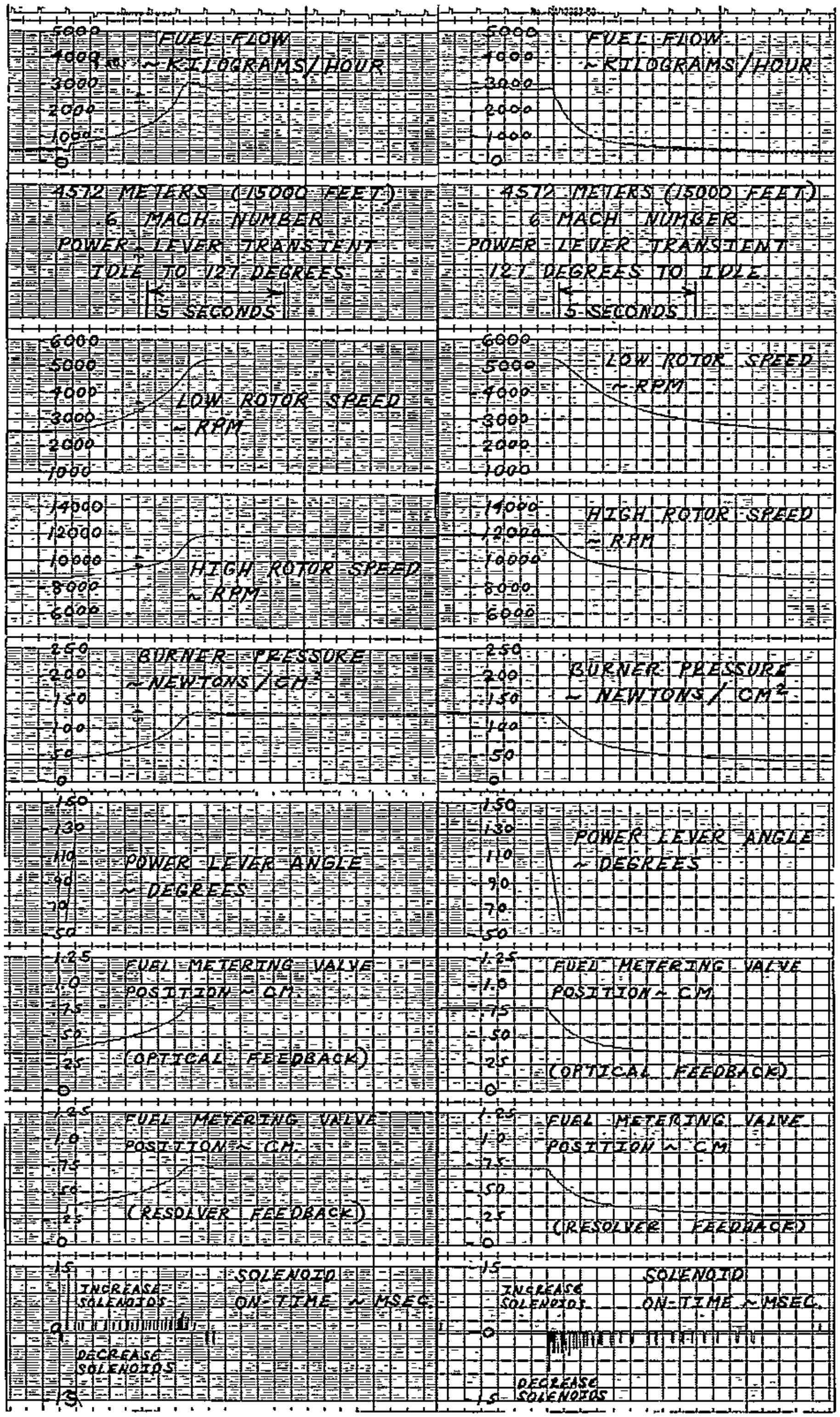


Figure 24 Large Power Lever Transients at 4572 meters (15,000 ft), 0.6 Mn

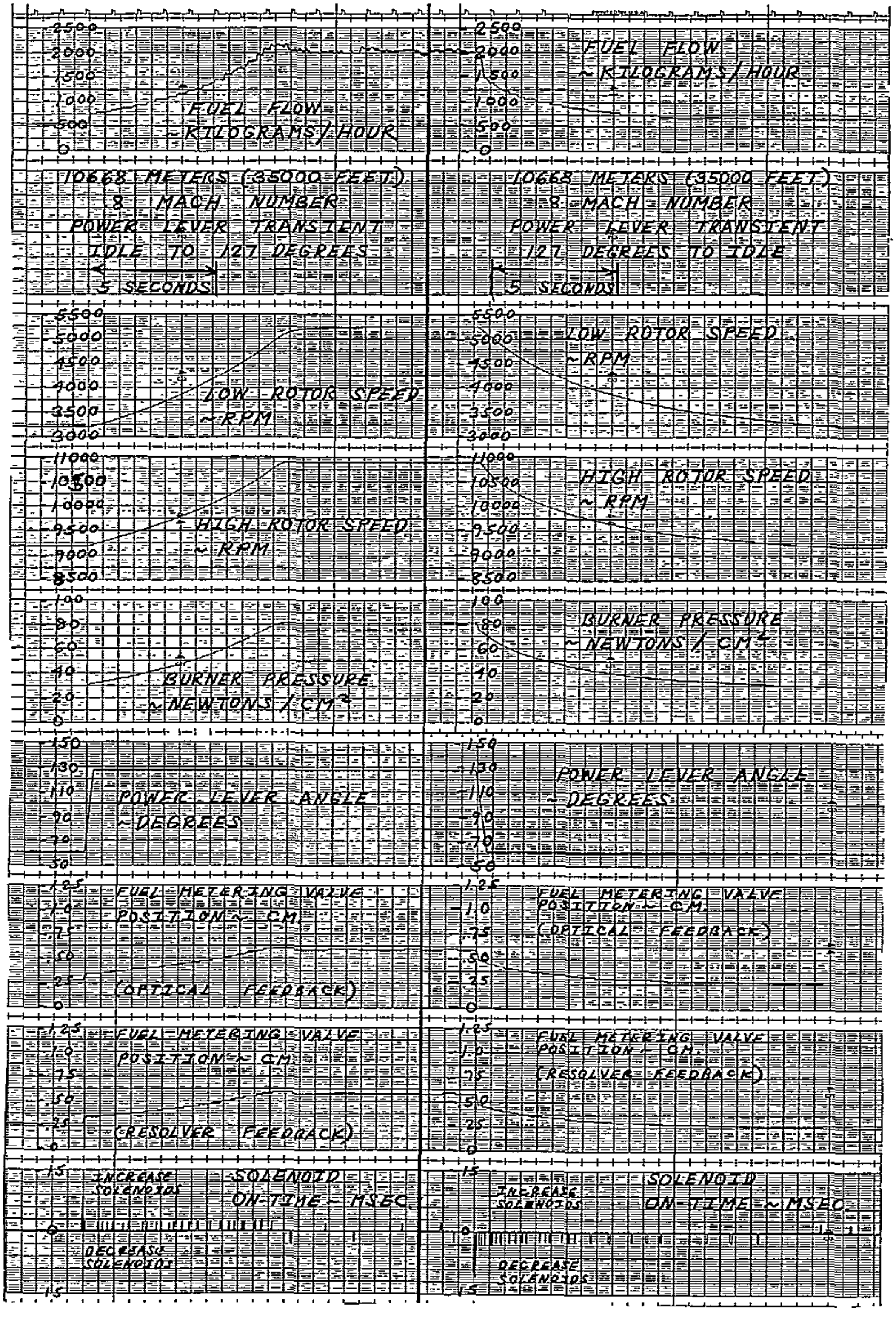


Figure 25 Large Power Lever Transients at 10,668 Meters (35,000 ft), 0.8 Mn

ORIGINAL PAGE IS
OF POOR QUALITY

Failsafe Demonstration Tests

This testing included simulated failures of the digital effector solenoids, the optical fuel metering valve position feedback, and the interface circuits. The failures were simulated by flipping the appropriate console program switches on the minicomputer. Failures were simulated during steady-state operation, and also prior to and during accelerations and decelerations at three flight conditions.

Simulated Solenoid Failures - The four solenoids were "failed" one at a time in the closed position and then in the open position. Steady-state failures were simulated at three power settings at three flight conditions.

Steady-state performance was not adversely affected by any simulated solenoid failures. A solenoid failed closed has no effect because the solenoids are closed more than 99% of the time in steady state. A solenoid failed open causes a fuel flow change which is quickly overridden by the electronic control sensing an error between the requested and measured fuel valve position and consequently energizing both solenoids on the opposite side of the fuel valve for approximately half the time. The effect on the simulated turbofan engine of an open failure is a small initial increase in low rotor speed (20-90 rpm, depending on flight condition and power setting) followed by a quick return to the original power level (1-2 seconds). An open failure and the resulting cycling of the two opposite solenoids increase the frequency of the steady-state fuel flow variation. This increases the frequency of the steady-state low rotor speed limit cycle, and in most cases decreases the magnitude of the limit cycle.

Test data for the simulated solenoid failures during steady-state at sea level static high, mid, and low power is shown in Figures 26-28. All four open failures and only one closed failure are shown for each power setting because the data is identical for all four closed failures. Solenoid failures at the two altitude flight conditions were similar to the failures at sea level static except at idle where an open failure of the #1 increase solenoid (I_1) caused a small steady-state power increase (60 rpm low rotor speed at 4572 meters [15,000 feet], .6 Mach number; and 80 rpm at 10, 668 meters [35,000 feet], .8 Mach number). The power increase occurs because the deceleration schedule in the electronic control is very close to the steady-state operating characteristic of the simulated engine. After the initial transient low rotor speed increase, the deceleration limit (which is the lower limit on the integrator, as shown in Figure 8) prevents the error between the requested and measured speed from decreasing the fuel valve position request. This keeps the simulated engine at the increased level of power.

The DOI is capable of accelerating or decelerating an engine with a failed solenoid. Testing showed a small increase in acceleration/deceleration time for a closed failure of the solenoid which changes fuel flow in the direction of the transient. No change in acceleration/deceleration time resulted from a closed failure of a solenoid which changes fuel flow in the opposite direction of the transient. Transients with solenoids failed open were faster than nominal if the failed solenoids were for the same direction of change in fuel flow as required for the transient, and slower than nominal if for the opposite direction. Transient response times with a failed solenoid are compared to nominal for three flight conditions in Table VI. Accelerations and decelerations at sea level static with failed solenoids are shown in Figure 29.

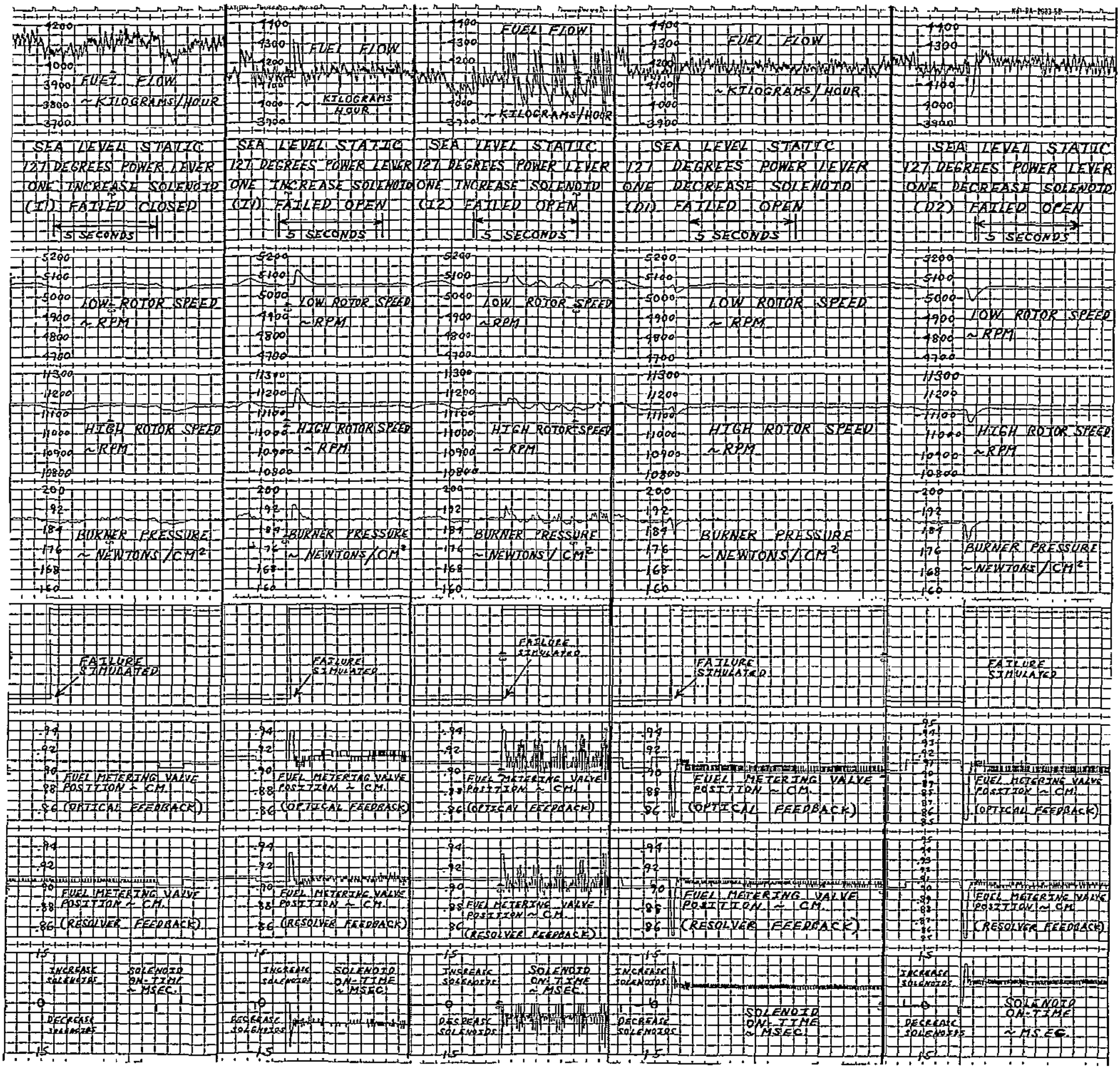


Figure 26 Simulated Solenoid Failures at Sea Level Static, High Power

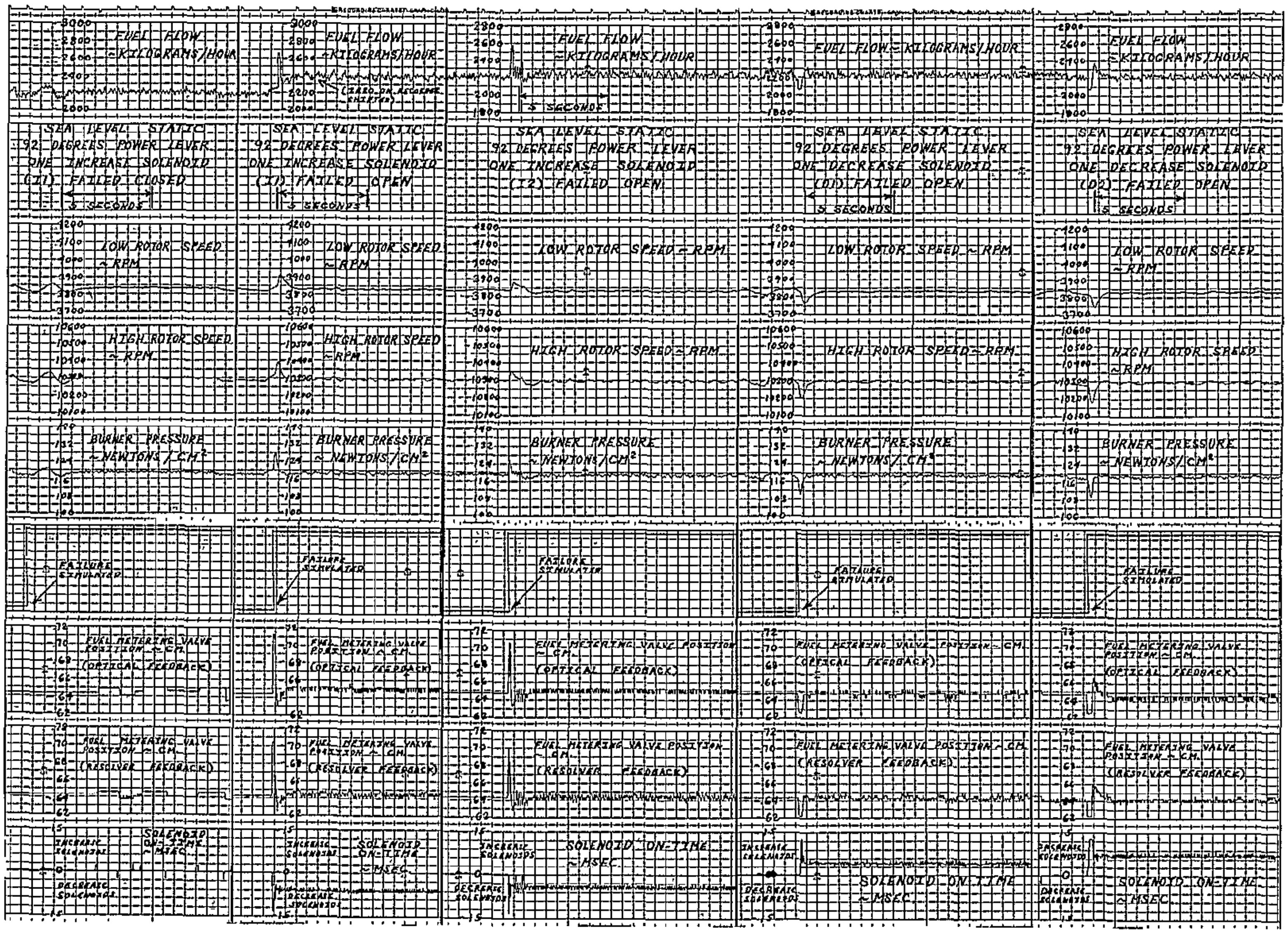


Figure 27 Simulated Solenoid Failures at Sea Level Static, Mid Power

ORIGINAL PAGE IS OF POOR QUALITY

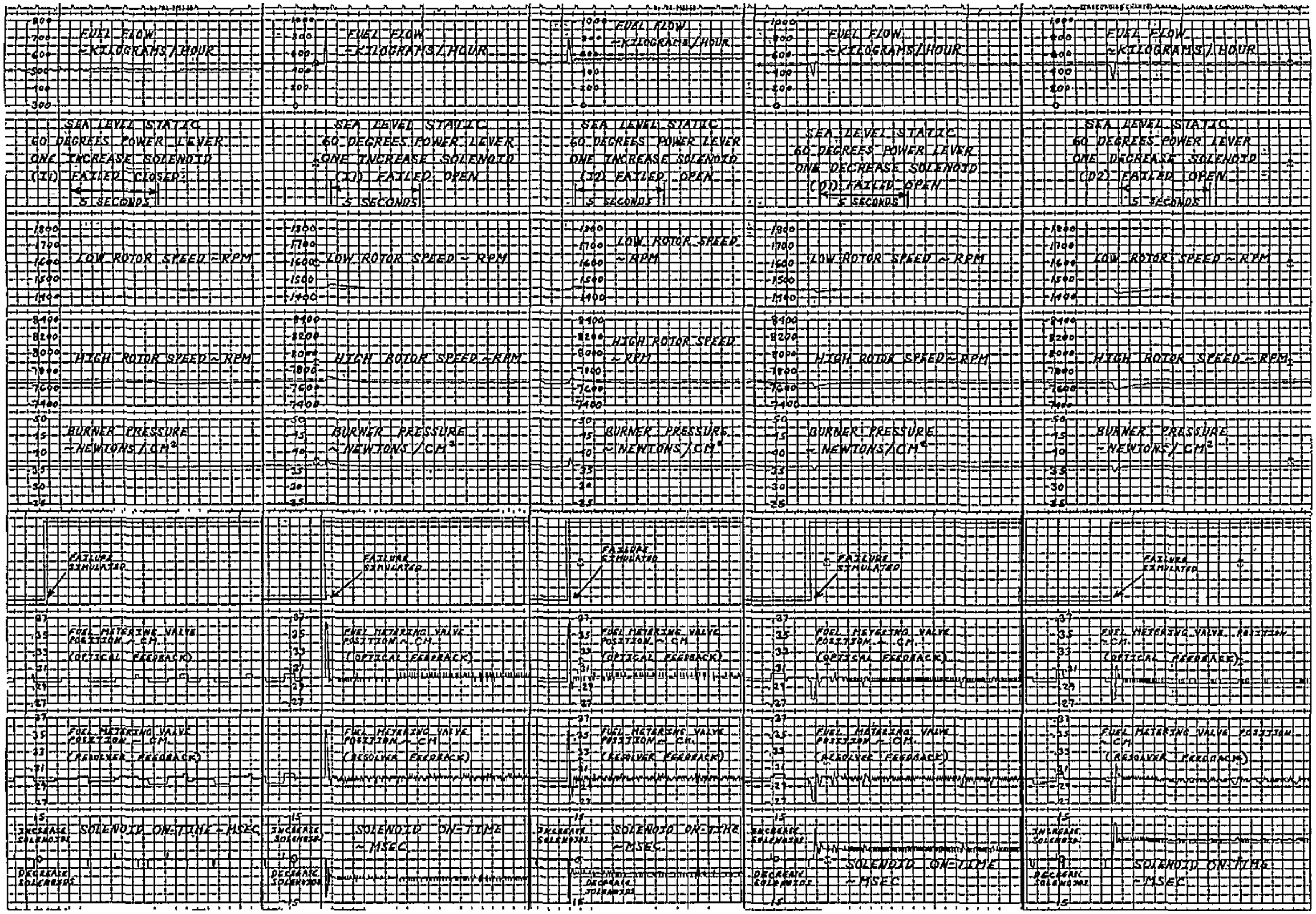


Figure 28 Simulated Solenoid Failures at Sea Level Static, Idle Power

TABLE VI

LARGE POWER LEVER TRANSIENT RESPONSE TIME WITH A FAILED SOLENOID

Flight Condition	Nominal	Acceleration Time(1) Seconds: I1(2) Failed Open	I1 Failed Closed	I2(3) Failed Open	I2 Failed Closed	D1(4) Failed Open	D1 Failed Closed	D2 Failed Open	D2 Failed Closed
Sea Level Static	5.5	3 75	5 75	3.75	5 75	6.5	5 5	7 5	5 5
4572 Meters (15,000 Feet), .6 Mach Number	5.0	3 25	5 25	3.75	5 0	6.0	5 0	7 5	5 0
10668 Meters (35,000	8 0	5 25	8 5	5 75	8 25	10.75	8 0	14 0	8 0

Flight Condition	Nominal	Deceleration Time(1) Seconds: I1 Failed Open	I1 Failed Closed	I2 Failed Open	I2 Failed Closed	D1 Failed Open	D1 Failed Closed	D2 Failed Open	D2 Failed Closed
Sea Level Static	7.5	16.25	7 5	10 25	7 5	5.5	8 0	5.0	8.0
4572 Meters (15,000 Feet), 6 Mach Number	10 0	13.75	10 0	14 0	10.0	5 5	10.5	5 0	10 5
10668 Meters (35,000 Feet), 8 Mach Number	12.0	21.0	12 0	19.0	12 0	6.75	13 75	5.75	13.75

(1) Acceleration/Deceleration time is the time to change the low rotor speed to within 100 rpm of the final steady-state value
(2) I1 is the #1 Increase Solenoid
(3) I2 is the #2 Increase Solenoid
(4) D1 is the #1 Decrease Solenoid
(5) D2 is the #2 Decrease Solenoid

ORIGINAL PAGE IS
OF POOR QUALITY

PAGE IS
QUALITY

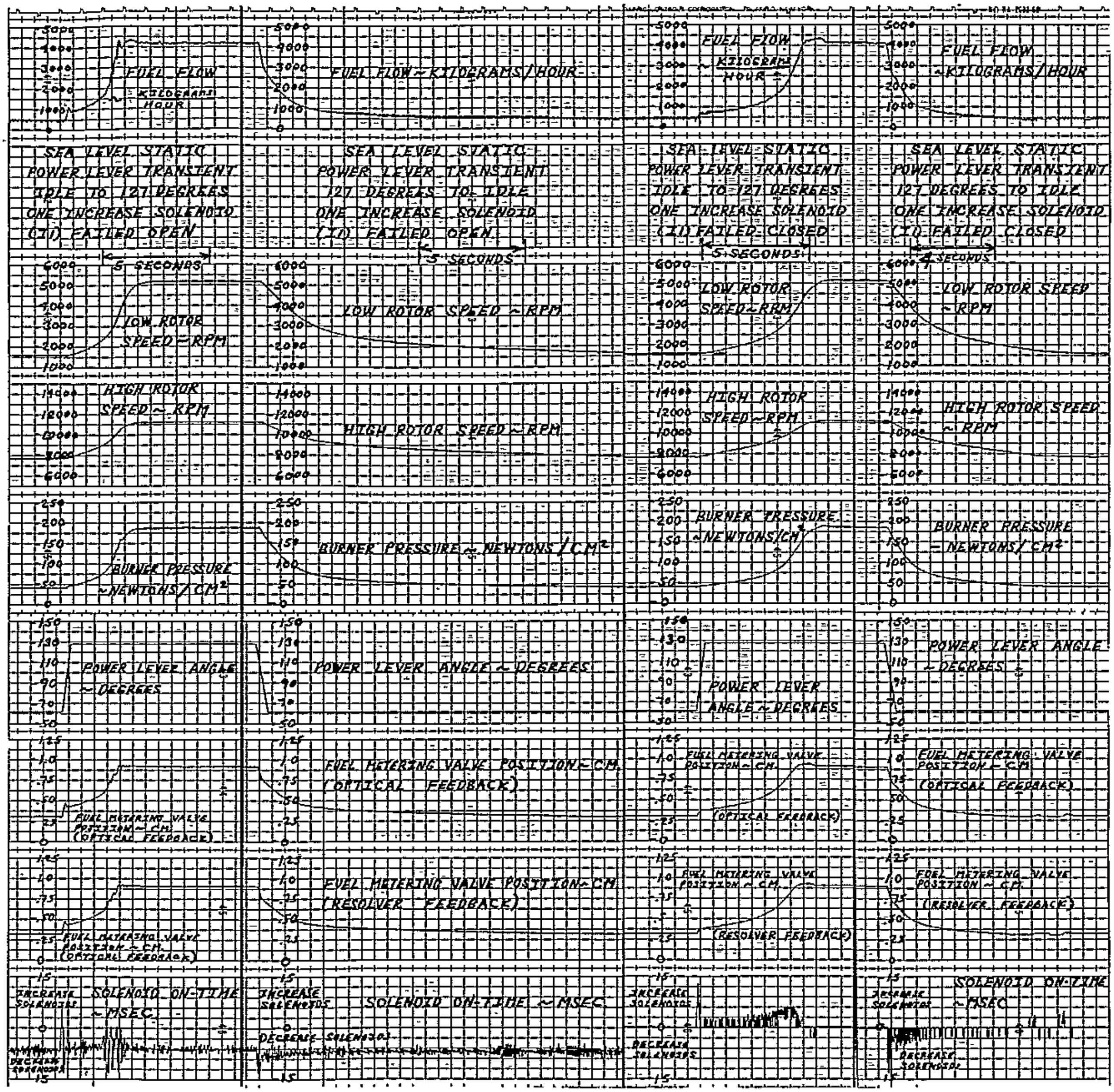


Figure 29 Large Power Lever Transients With Simulated Failures of the I_1 Solenoid, Sea Level Static

Simulated solenoid failures during accelerations and decelerations resulted in transient response times in between the nominal response time and the response time with the failure simulated before the start of the transient. No instability resulted from any solenoid failure during a transient. An example of accelerations and decelerations at sea level static with solenoid failures simulated during the transients is shown in Figure 30.

In summary, the DOI would provide slightly degraded but satisfactory "failsafe" performance with any single solenoid failure. Testing showed that transient response would only be slightly affected by a closed failure, and that an open failure would have a greater effect on transient response. Steady-state stability would not be affected by an open or closed failure, but an open failure would cause continuous cycling of one pair of solenoids.

Simulated Optical Position Feedback Failures - Failures of the optical position feedback signal (in Gray Code Format) were simulated by failing the least significant bit, most significant bit, an intermediate bit, and all eight bits in both the "on" and the "off" position. The electronic controller software included logic to test the optical feedback signal and close the fuel metering valve position control loop (Figure 8) with the resolver feedback signal when the optical feedback was detected to be failed. When the failure detection logic indicated no failure, the optical feedback would be used again after a time delay to control the valve position. A "range" test (feedback signal indicating valve position beyond the min. or max. range of valve travel) and a "rate" test (lagged difference between two successive feedback measurements 15 milliseconds apart indicating a rate of change of valve position faster than the maximum possible valve velocity) were used to determine a failed optical feedback signal.

A failure of the least significant bit (LSB) had a small effect on steady-state or transient performance. An "on" or and "off" failure of the LSB does not cause a range or rate failure indication, therefore, the optical feedback signal continues to provide closed-loop control.

A failure of an intermediate (fourth most significant) bit, or a failure of the most significant bit (MSB) would make the optical feedback incapable of controlling. An "on" failure at a steady-state condition where one of these bits is normally on (or an "off" failure where normally off) would have no immediate effect. However, a failure which changes the state of the bit caused a significant oscillation of the fuel flow and low rotor speed, and also caused excessive cycling of the solenoids as shown in Figure 31. The oscillation resulted because the logic in the electronic controller caused switching back and forth between the optical feedback and the resolver feedback. The failure was detected by the rate test which caused the resolver feedback to be selected; the system then returned to steady-state and the optical feedback no longer failed the rate test. The logic then selected the optical feedback, which caused a transient reset and made the optical feedback fail the rate test again, repeating the cycling. (For engine testing of the DOI hardware, it is recommended to not allow the optical feedback to be automatically switched back in once a failure is indicated and the resolver feedback is selected.) Acceleration and deceleration transients with a failure intermediate bit or a failed MSB showed significant acceleration/deceleration schedule overshoot/undershoot (Figure 32).

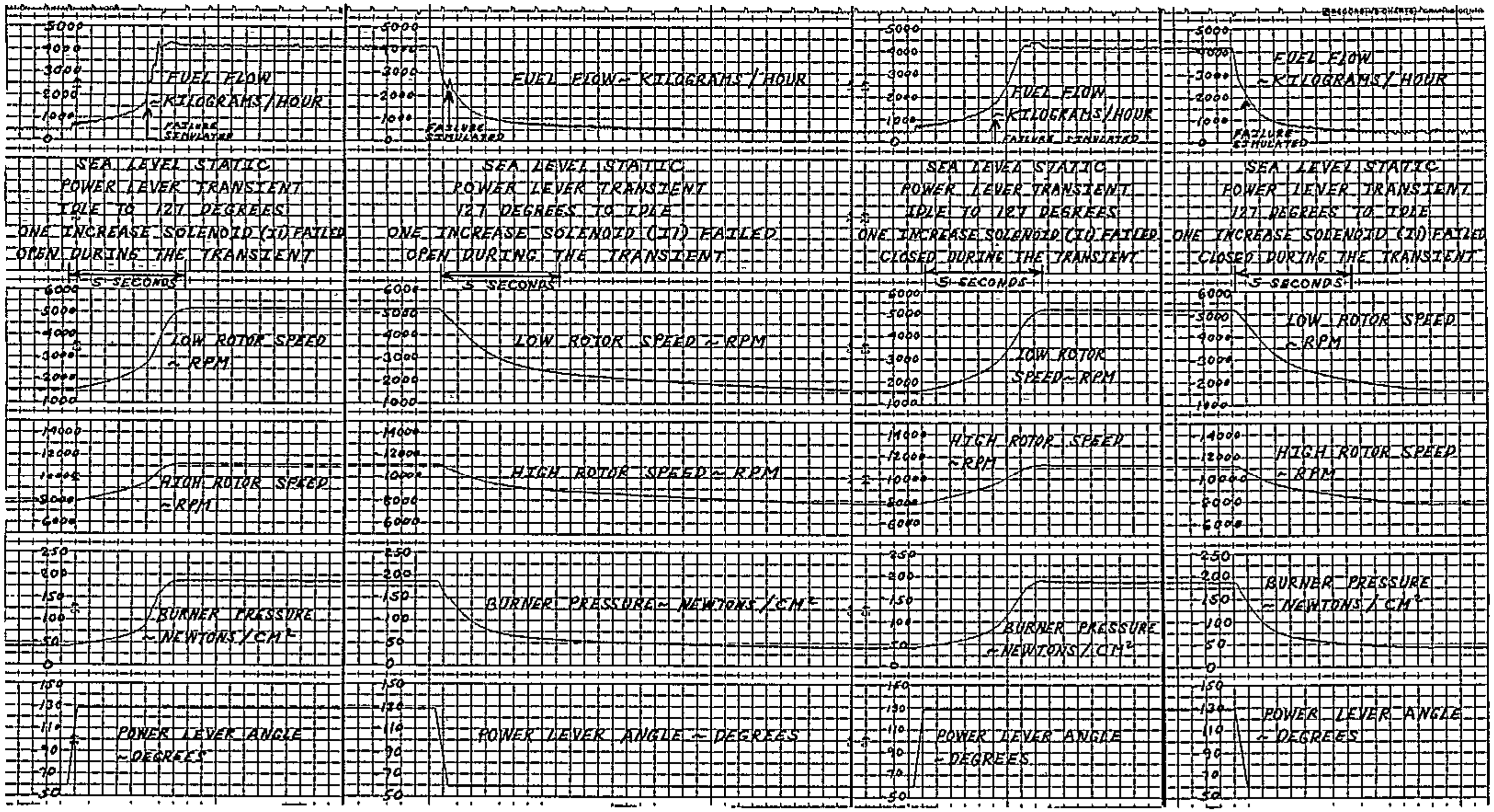


Figure 30 Large Power Lever Transients with the I_1 Solenoid Failed During the Transient

ORIGINAL PAGE IS OF POOR QUALITY

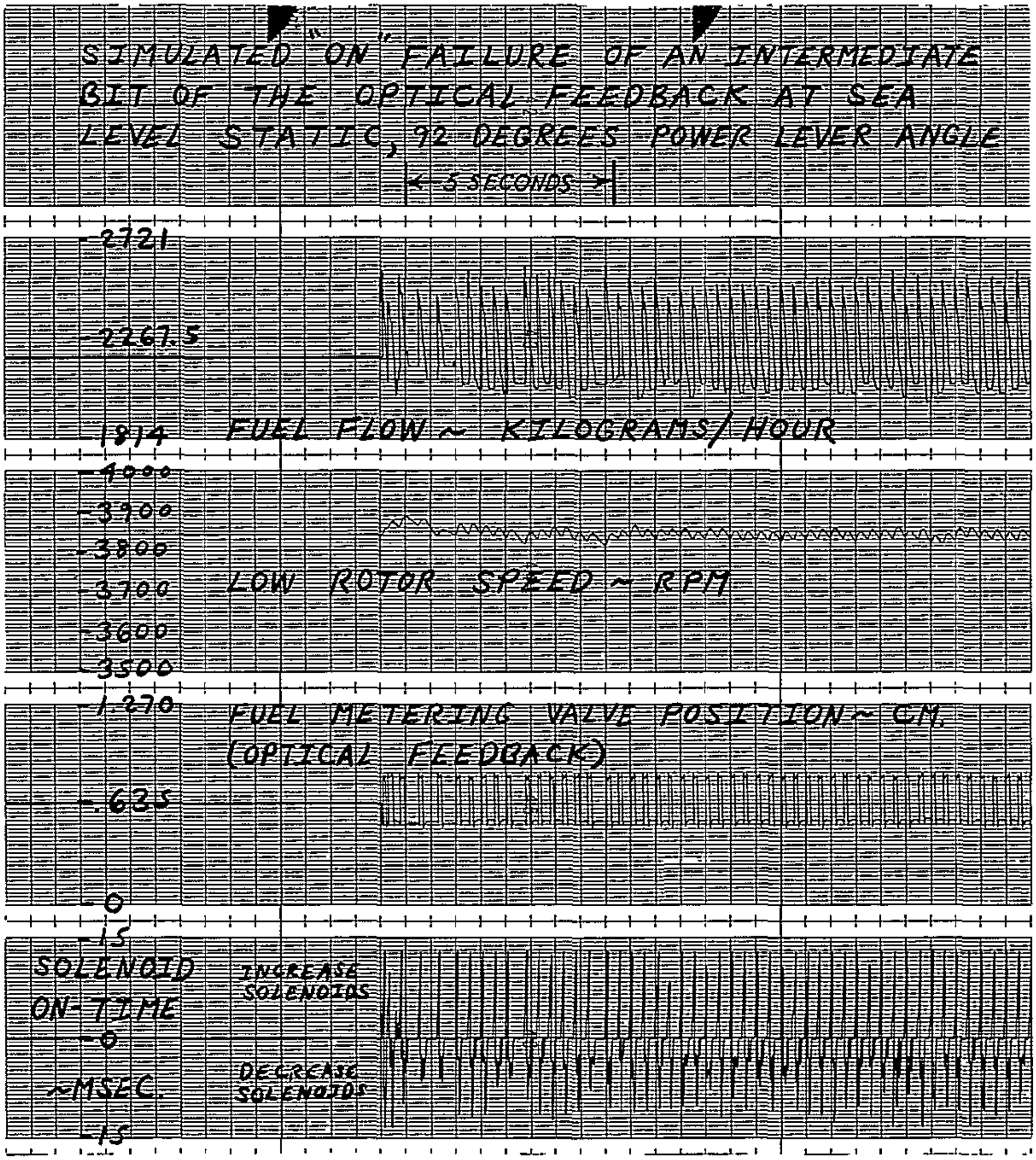


Figure 31 *Simulated "On" Failure of an Intermediate Bit of the Optical Feedback at Sea Level Static, 92° Power Lever Angle*

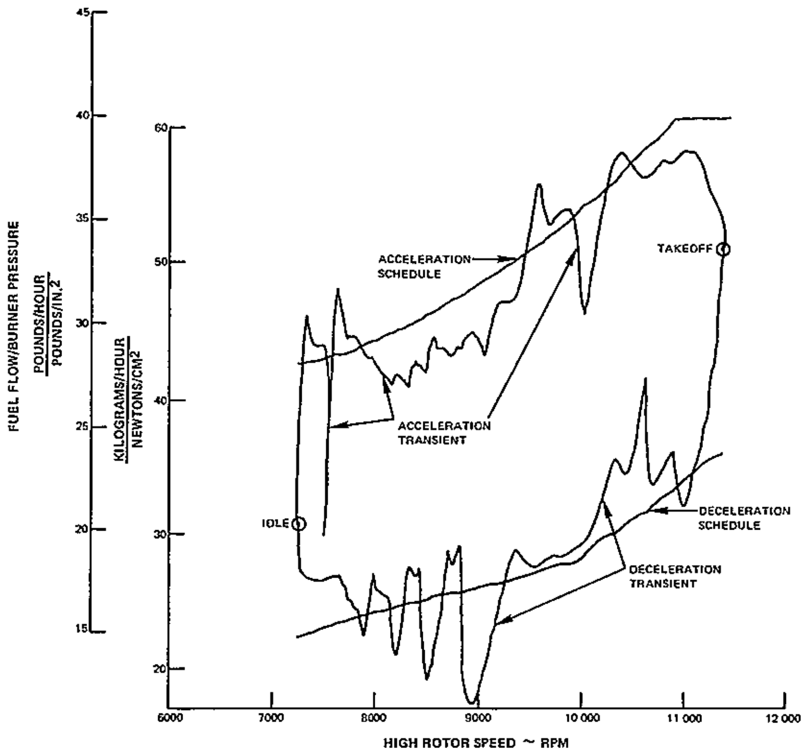
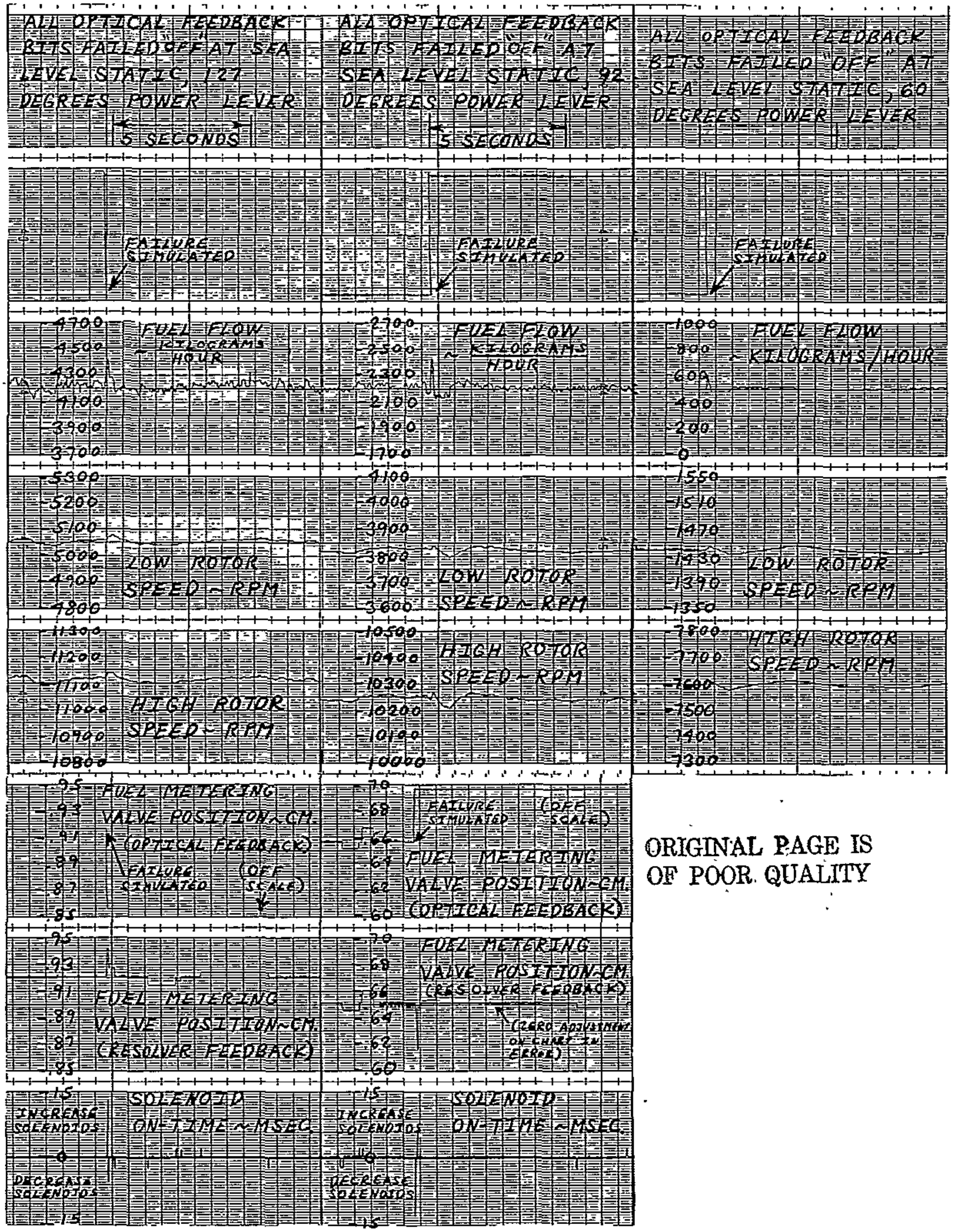


Figure 32 *Acceleration and Deceleration Schedule Transients at Sea Level Static With an Intermediate Bit of the Optical Feedback Failed Always Off*

An "on" or "off" failure of all the bits of the optical feedback signal was always detected as a failure by the range test which caused the resolver feedback to be substituted for the failed optical signal. A failure of all the optical feedback bits causes a very slight transient followed by good steady-state stability with the resolver feedback as shown in Figure 33. The resolver feedback provides good acceleration/deceleration response as shown in Figure 34.

Simulated Interface Circuit Failures - The solenoid drive circuit and the optical-electronic interface circuit were simulated failed at sea level static, high power by shutting off electircal power to the electronic interface suitcase. No change of the fuel flow or the low rotor speed of the simulated engine occurred. No transients were possible in this failed condition because the digital effector solenoids are closed and cannot be energized to change the fuel flow level. If the interfacing circuits failed during an engine test, no transients would be possible, and it would be necessary to shut down the engine by energizing the shut-off solenoid of the DOI flow box.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 33 Steady State Failures of all Bits of the Optical Feedback at Sea Level Static

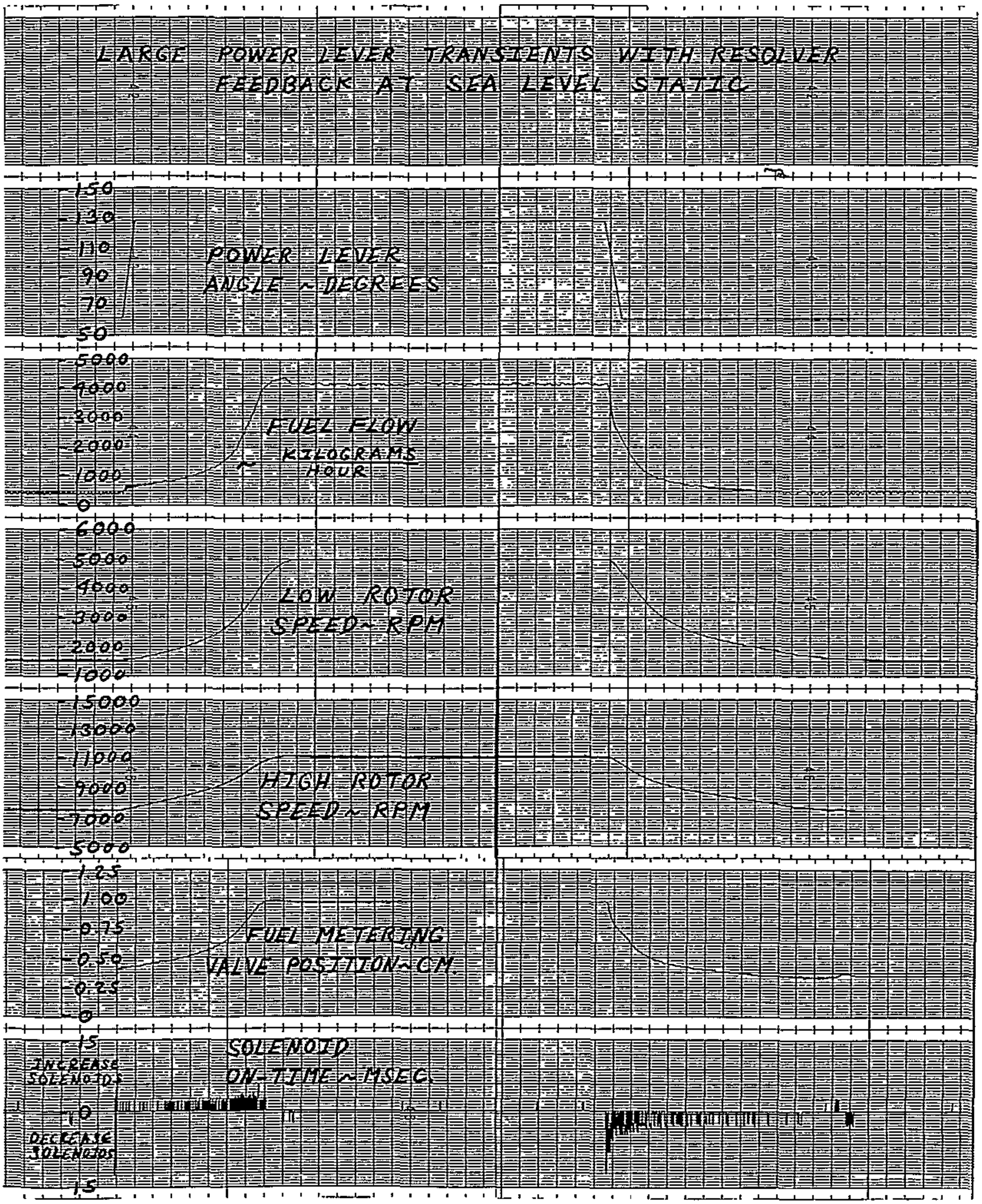


Figure 34 *Large Power Lever Transients with Resolver Feedback at Sea Level Static*

ORIGINAL PAGE IS
OF POOR QUALITY

ENDURANCE TEST

An endurance test was run on the same closed loop flow bench used for the performance test. The test consisted of the following simulated flight cycle:

- accelerate from idle to takeoff, stabilize for five (5) minutes, record data
- set climb power (115 degrees power lever angle), hold for 55 minutes, record data
- set cruise power (105 degrees power lever angle), hold for 60 minutes, record data
- decelerate to idle, hold for 60 minutes, record data

The cycle was repeated continuously to operate the DOI sixteen (16) hours per day. The following data was recorded at each test point in the flight cycle: date, time, power lever angle, pressure at DOI inlet, pressure downstream of the DOI, metering valve pressure drop, optical position feedback and resolver feedback signals. Every sixteen (16) hours, a calibration was taken at five steady-state power settings at sea level static conditions to record fuel flow, rotor speeds and burner pressure of the simulated turbofan engine, optical and resolver feedback, DOI inlet and downstream pressure, metering valve pressure drop, and the total number of cycles for each of the four digital effector solenoids.

The test was terminated after 342 hours. During this period, the DOI performed with no degradation and experienced no failures.

POST-TEST INSPECTION AND RECALIBRATION

The DOI was disassembled and inspected after the endurance test. The metering valve, pressure regulating valve, minimum pressurizing valve, and optical encoder assembly were inspected and the four solenoid valves were taken apart and examined under a microscope. The optical encoder assembly is shown on Figure 35.

The metering valve, pressure regulating valve, and the minimum pressurizing valve showed no visible signs of wear. None of the solenoids showed any significant wear. The two decrease solenoids were cycled 2¼ million times and showed slight wear on the pintle. The two increase solenoids were cycled one million times and showed no wear on the pintle other than a slight discoloration on one of them. All four solenoids showed small scratches in the metal of the seat.

The decrease solenoids were cycled more than twice as many times as the increase solenoids and consequently showed more wear than the increase solenoids, although no solenoids showed any significant wearing. A summary of the inspection of each solenoid is shown in Table VII. A photograph of the decrease solenoid valve pintle with the most wear is shown in Figure 36.

Figure 35 Post Test Teardown of Optical Encoder Assembly

TABLE VII

POST-TEST INSPECTION OF DIGITAL EFFECTOR SOLENOIDS

Solenoid	Observations
Decrease Solenoid #1	Slight wear on pintle, small rub mark on core, small scratches on seat, no noticeable wear on springs
Decrease Solenoid #2	Very slight wear on pintle, small scratches on seat, no noticeable wear on springs or core.
Increase Solenoid #1	Slight discoloration but no other wear on pintle, small scratches on seat, no noticeable wear on springs or core.
Increase Solenoid #2	Copper-colored chip on the pintle below seating surface (possible fuel contamination), white powdery substance on inner spring, small scratches on seat, no noticeable wear on pintle or other spring.

Note:
Decrease Solenoid #1 showed the most wear.

ORIGINAL PAGE IS
OF POOR QUALITY

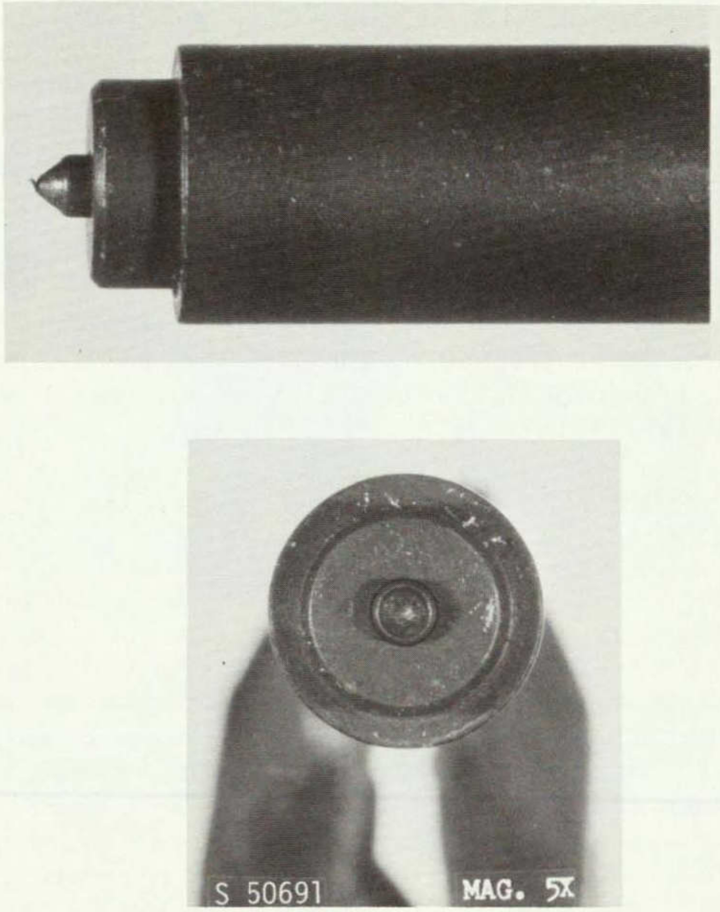


Figure 36 Decrease Solenoid Pintle With the Most Wear

After the inspection, the DOI was reassembled and reinstalled on the closed loop flow bench for a calibration. The calibrations of the optical feedback, resolver feedback, and fuel flow were acceptable. Steady-state stability of the low rotor speed was good at high, mid, and idle power, but at idle, the decrease solenoids cycled 8-9 times per second compared to .76 cycles per second during the closed loop performance testing. Response to small and large power lever changes, and response to simulated failures of the solenoids and optical position channels was similar to the results obtained during the closed loop bench testing.

The DOI was returned to Hamilton Standard and a throttle valve seal replaced. The system was installed on the closed loop bench for a recalibration. Solenoid cycling rates at idle were similar to the results obtained during the performance test (.43 cycles per second for the increase solenoids and .54 cycles per second for the decrease solenoids with the new seal). Solenoid cycling rates and steady-state stability at mid and high power, transient response, and steady-state calibration of the optical and resolver feedback signals were acceptable.

ORIGINAL PAGE IS
OF POOR QUALITY

RELIABILITY EVALUATION

A reliability evaluation was performed for those portions of the DOI system which would be part of a production version of a digital effector with optical feedback. These components are the optical position sensor, optical cable, optical transmitter and receiver, and the flow box excluding the resolver. A reliability prediction and a Failure Mode and Effects Analysis (FMEA) were performed on these components.

RELIABILITY PREDICTIONS

The predicted reliability of the electrical/optical section, which includes all optical position feedback elements and the solenoid drivers, is 15.946 failures per million hours (FPMH) or a mean time between failures (MTBF) of 62,712 hours. The predicted failure rate of the flow box is 21.452 FPMH or an MTBF of 46,616 hours. The entire DOI system would have a failure rate of 37.398 FPMH or an MTBF of 26,739 hours.

Electrical/Optical Section

The predicted reliability of the electrical/optical section was based on MIL Handbook 217B, Reliability Prediction of Electronic Equipment, considering an uninhabited airborne environment. The fuel control circuitry is assumed to be affected by cooling fuel at a temperature of 361°K (190°F) in the following manner: Integrated circuits junction temperature of 388°K (238°F), diode case temperatures 383°K (229°F), transistor case temperatures 388°K (238°F) and passive components at 379°K (222°F). All components were assumed at 100% duty cycle with a 10% steady state electrical stress. The following component quality levels were assumed: integrated circuits, screen class B (MIL-M-38510), S quality for capacitors; R quality for resistors; and JANTX level for semiconductors. The optic cable and encoder were estimated to have a failure rate of 3.0 FPMH, which is a representative conservative estimate similar to other feedback devices. Substantiated data for this specific device is not available. Predicted reliability of the electrical/optical section is tabulated in Table VIII.

DOI Flow Package

The reliability predictions for the DOI flow package are based on Hamilton Standard's predictions for the flow package components and based on Hamilton Standard's experience of over 200 million hours with the JFC-25 and JFC-60 commercial fuel controls. The DOI flow package reliability is tabulated in Table IX. Further evaluation of the reliability and durability of the digital effector solenoids is required.

FAILURE MODE AND EFFECTS ANALYSIS

A failure mode and effects analysis (FMEA) was performed on the electrical/optical section and the DOI flow box. No single solenoid or driver circuit failure could result in a loss of control because the digital effector is designed with a pair of solenoids to move the fuel valve in either direction. A solenoid failure reduces the maximum fuel valve velocity by half in one direction. A failure of the optical feedback signal, or of an individual bit of the feedback would make the feedback inoperative (with the exception of a failure of one of the least significant bits). Therefore, some form of redundancy is required for a production system. In the DOI system tested, a resolver was used to provide fuel metering valve position feedback redundancy. The FMEA of the optical/electrical section is included in Appendix A.

TABLE VIII

PREDICTED RELIABILITY OF ELECTRICAL/OPTICAL SECTION

Subsystem	Failure Rate - Failure per Million Hours	Mean Time Between Failures - Hours
Optic Cable and Encorder	3.0	333,333
Solenoid Driver Circuit	1.915	522,357
Optic Sensor Transmitter	3.135	318,979
Optic Sensor Reccivor	7.896	126,645
Total	15.946	62,712

TABLE IX

PREDICTED RELIABILITY OF THE DOI FLOW BOX

Component	Quantity	Failure Rate - Failures Per Million Hrs.	Mean Time Between Failures - Hours
Pressure Regulating Valve	1	.611	1,636,661
Mn Pressue and Shutoff Valve	1	4.340	230,415
Filter	1	.650	1,538,462
Metering Valve	1	2.051	487,567
Shutoff Solenoid	1	4.085	244,798
Digital Effector Solenoids	4	9.180	108,932
Orifices	3	.483	2,070,393
Links	4	.052	19,230,769
Total		21.452	46,616

CONCLUSIONS

The objective of this program was to pursue the development of an innovative digital output interface (DOI) which shows promise of improving the reliability and maintainability required of future digital electronic controls for aircraft propulsion systems. The objective has been met by fabricating a digital output interface, and testing and demonstrating its operation and performance under simulated engine operating conditions on a fuel flow bench, and by evaluating its reliability.

The DOI system selected for development uses a digital output effector with on-off solenoids driven directly by signals from a digital electronic controller. The DOI was designed to interface a digital electronic controller with a gas turbine fuel flow metering valve. The DOI also includes an optical feedback of the fuel metering valve position to the electronic controller.

Results of the DOI testing indicate that the digital effector with optical position feedback is a viable candidate, with further development, for future digital electronic gas turbine controls. The testing successfully demonstrated steady-state stability, transient response for small and large power lever changes, and the capability to tolerate a failure of any one of the DOI solenoids.

The testing successfully demonstrated the digital effector and optical feedback concepts, but also showed several unresolved problem areas which would have to be overcome in a final production configuration. Steady-state performance testing with a simulated turbofan engine showed a low rotor speed limit cycle of ± 15 rpm due to the resolution of the optical position feedback. An optical position sensor with more than 8 bits resolution on the fuel metering valve travel would improve steady-state performance.

Failures of the optical feedback channels (bits) would make the feedback incapable of controlling. For the brassboard DOI configuration tested, the resolver can be used if the optical feedback fails, but a production configuration would require some redundant measurement of the fuel metering valve position. An interesting feature of the DOI is that fuel valve position becomes fixed if solenoid interfacing electronics or the power to the electronics failed. Since fuel flow could not be changed, it would eventually be necessary to shut down an engine through the shut-off solenoid. Failed fixed may be an attractive feature in other servo system applications.

A reliability evaluation conducted for the DOI system predicts a failure rate of 37.398 failures per million hours or a mean time between failure 26,739 hours. Further evaluation of the reliability and durability of the digital effector solenoids is required.

APPENDIX A

FAILURE MODE AND EFFECTS ANALYSIS

OPTICAL/ELECTRICAL SECTION

ORIGINAL PAGE IS
OF POOR QUALITY

MODEL DOI
SYSTEM Digital Output Interface
ASSEMBLY Solenoid Drive Circuit (one of four identical circuits)

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY E.L. Harrington
DATE 1/78 PAGE 1 OF 5
REVISION NO DATE

Name and Identification No	Quant Per System	Function	Failure Mode	Failure Detection Method	Failure Effect	R/M Failure Mode Impact	Notes
Digital Line Driver, U1	2	Differential Line Driver, transfers computer command to solenoid drive circuit	Loss of output pulses	Redundant channels under software control with resolver backup	Computer command to energize or de-energize solenoid drive will not be received	None, no single driver failure can result in loss of control	Results in 1/2 gain in one direction
Noninverting Buffer, U2	1	Logic level conversion	Loss of output pulses	Same as above	Same as above	Same as above	
Voltage Divider Network, R1 & R2	4	Q1 bias	Open	Same as above	Q1 will not conduct as required	Same as above	
Transistor, Q1	4	Switch	Always on/always off	Same as above	Same as above	Same as above	
Emitter current resistor, R3	4	Stabilize Q1 emitter current	Open	Same as above	Q1 will not conduct as required	Same as above	
Bias resistor, R4	4	Q2 bias	Open	Same as above	Q2 will not conduct as required	Same as above	
Transistor, Q2	4	Switch	Always on/always off	Same as above	Same as above	Same as above	
Bias resistor, R5	4	Q3 bias	Open	Same as above	Q3 will not conduct as required	Same as above	
Transistor, Q3	4	Switch	Always on/always off	Same as above	Same as above	Same as above	

MODEL DOI
SYSTEM Digital Output Interface
ASSEMBLY Solenoid Drive Circuit (one of four identical circuits)

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY E.L. Harrington
DATE 1/78 PAGE 2 OF 5
REVISION NO DATE

Name and Identification No	Quant Per System	Function	Failure Mode	Failure Detection Method	Failure Effect	R/M Failure Mode Impact	Notes
Diode, CR1	4	Final Solenoid driver circuit switch	Open	Software program	Solenoid always energized	None, no single driver failure can result in loss of control	Results in 1/2 gain in one direction
			Short	Software program	Solenoid always de-energized	Same as above	

MODEL DOI
SYSTEM Digital Output Interface
ASSEMBLY Optic Position Sensor - Transmitter

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY E.L. Harrington
DATE 1/78 PAGE 3 OF 5
REVISION NO ______ DATE ______

Name and Identification No	Quant Per System	Function	Failure Mode	Failure Detection Method	Failure Effect	R/M Failure Mode Impact	Notes
IR Transmitter, CR2	1	Source of infrared radiation	Loss of IR radiation	Computer software	LED source inoperative, no feedback signal	Optic position feedback inoperative. Could result in engine shutdown. *Note:	*Note: For demonstration system, resolver could be used to provide feedback. Optic redundant system was not developed as a part of this program.
Thermistor, R11	1	Sense heat of LED	Open	Same as above	Stable current level required to maintain constant LED output	Same as above	
Strobe assembly	1	Limit LED duty cycle	Loss of output	Same as above	Same as above	Same as above	

ORIGINAL PAGE IS OF POOR QUALITY

MODEL DOI

SYSTEM Digital Output Interface

ASSEMBLY Optic Position Sensor Receiver (one of eight identical channels)

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY E.L. Harrington

DATE 1/78 PAGE 4 OF 5

REVISION NO ______ DATE ______

Name and Identification No	Quant Per System	Function	Failure Mode	Failure Detection Method	Failure Effect	R/M Failure Mode Impact	Notes
Photo Diode assembly	8	Detector element	Loss of detection	Computer software	LED detection inoperative, no feedback signal, data bit error	Optic position feedback inoperative; could result in engine shutdown. *Note:	*Note: for demonstration system, resolver could be used to provide feedback. Optic redundant system has not been developed as a part of this program.
OP-Amp, U1	2	Current to voltage converter	Loss of sense function	Same as above	False data	Same as above	
Voltage comparator, U4	2	Signal to reference comparison	Loss of feedback	Same as above	Same as above	Same as above	
Signal shaper, U6 & U8	2	Signal presentation to computer	Loss of feedback	Same as above	Same as above	Same as above	

MODEL DOI
SYSTEM Digital Output Interface
ASSEMBLY Optic Position Sensor & Optic Cable

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY E.L. Harrington
DATE 1/78 PAGE 5 OF 5
REVISION NO ______ DATE ______

Name and Identification No	Quant Per System	Function	Failure Mode	Failure Detection Method	Failure Effect	R/M Failure Mode Impact	Notes
Optic Position Sensor	1	Senses Fuel Flow Valve Position	Contamination of optic windows or breakage of fibers	Computer software	Position sense inoperative or with data bit errors	Optic position feedback in error; could result in engine shutdown.*Note	*Note: For demonstration system, resolver could be used to provide feedback. Optic redundant system was not developed as a part of this program.
Optic Cable	1	Transmits the optic signals to and from the position sensor	Same as above	Same as above	Same as above	Same as above	

ORIGINAL PAGE IS OF POOR QUALITY

DISTRIBUTION LIST

	No. of Copies
Bendix Energy Controls Division 717 North Bendix Drive South Bend, IN 46620	
Attn: Mr. J. Rupp	1
Mr. J. A. Bluish	1
Mr. A. J. Wetzel	
Mr. B. A. Barclay Naval Air Propulsion Test Center Trenton, NJ 08628	2
Mr. W. F. Ryan Airesearch Manufacturing Company of America Phoenix, AZ	1
Mr. F. W. Burcham, Jr. Dryden Flight Research Center National Aeronautics and Space Administration Box 273 Edwards, CA 93523	1
Boeing Aerospace Group P. O. Box 3999 Seattle, WA 98124	
Attn: Mr. L. Billig	1
Mr. C. Carlin	1
Mr. W. Hastings	1
Honeywell, Inc. Mr. Ross Schmidt GAPD 2600 Ridgeway Parkway Minneapolis, MN 55413	2
Moog, Inc. Mr. Paul Elwell East Aurora, NY 14052	1
Detroit Diesel Allison Mr. Eveene Ervin P. O. Box 894 Indianapolis, IN 46206	1
Sundstrand Aviation Mechanical Mr. Walter Kennedy 2421 Eleventh Street Rockford, IL 61101	

	No. of Copies
Mr. Leon Lewis Airesearch Manufacturing Co. 2525 West 190th Street Torrance, CA 90509	1
Mr. R. P. Wanger Advanced Control Systems Aircraft Engine Group General Electric Co. Cincinnati, OH 45215	3
Pratt & Whitney Aircraft Group Government Products Division West Palm Beach, FL 33402	
Attn: C. Borgmeyer	1
B. Suder	1
R. D. Hackney	1
C. B. Kunkle	1
R. J. Miller	1
NASA-Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135	
Attn: Mr. Leon M. Wenzel, MS 100-1	50
Rich Adams Systems Control, Inc. Champlain Technology Industries, Inc. 205 Datura Street West Palm Beach, FL 33401	1
Dr. Al Bellin General Electric, Mail Zone 24048 1000 Western Ave. Lynn, MA 01910	2

HAMILTON STANDARD – WINDSOR LOCKS

J. T. Sullivan	Bldg. 3	1
R. D. Porter	Bldg. 3	1
C. J. Bosco	Bldg. 3	1
A. N. Martin	Bldg. 3	1
Edward Fox	Bldg. 3	3
K. Linebrink	Bldg. 1A	1

PWA-CPD EAST HARTFORD

D. M. Newirth	ECS-3 Willgoos	30

ALL OTHER COPIES TO:

NASA STIF
Baltimore/Washington International Airport
(see Document Release Authorization Form for Address)