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REPORT NO. AP-68-4540

HYPERSONIC RESEARCH ENGINE PROJECT - PHASE IIA
CONTROL SYSTEM DEVELOPMENT
TERMINAL SUMMARY REPORT
3 APRIL 1967 THROUGH 3 SEPTEMBER 1968

DATA ITEM NO. 55-6.06
NASA CONTRACT NO. NAS1-6666

AP-68-4540 16 April 1969

NO. OF PAGES 350

DATE 16 April 1969

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FOREWORD

This Terminal Summary Report on the Control System Development is submitted to the NASA Langley Research Center by the AiResearch Manufacturing Company, Los Angeles, California. The document was prepared in compliance with the guidelines established for the partial termination of NASA Contract No. NAS1-6666.

Part I of this report summarizes the entire Control System Development effort expended under the Hypersonic Research Engine Project, which encompasses the period of 3 April 1967 through 3 September 1968. Part II presents a detailed discussion of the remaining effort not previously covered in an Interim Technical Data Report.

ACKNOWLEDGEMENTS

Acknowledgements for the completion of this document are extended to the following contributors:

W. T. Curran	Technical Supervision and Integration of Report Contents
T. Colwill and M. Mormino	Dynamic Analyses and Simulation Program Studies
R. Towner	Digital Computer Program Definition
H. Bellamy and D. Parker	Design of Digital Computer Interface Equipment
K. Hamilton	Input/Output System Analog Interface Design
B. Paquette, H. Marthinussen and T. Redfern	Temperature Control Hardware and Power Supply Design Effort.

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NOMENCLATURE

A	valve area
C	controller input
G	transfer function
G_{HO}	zero order hold
Ki	controller gain
Kss	steady-state gain
N	constriction factor; turbopump shaft speed
P	pressure
ΔP	incremental pressure change; pressure rise across turbopump
R	controller output; pressure disturbance input
S	laplace operator
T	sampling period; temperature
τ	time constant
τ_s	settling time
W	injector flow
ΔW	incremental flow change
(+)	positive slope region of $\Delta P/N^2$ curve
(0)	zero slope region of $\Delta P/N^2$ curve
(-)	negative slope region of $\Delta P/N^2$ curve

PART I

SUMMARY OF TASK

1. PROBLEM STATEMENT

A control system is required to provide positive and safe control during ground and flight testing of a hydrogen fueled, regeneratively cooled, hypersonic ramjet engine. The control system must (1) schedule the fuel flow to the engine combustion chamber in accordance with programmed instructions to vary the fuel-to-air (equivalence) ratio as a function of certain flight parameters, (2) schedule the total fuel flow to the engine to provide adequate structural cooling, and (3) provide appropriate signals in response to indications of hazardous conditions. The control system must perform these functions over a wide range of environmental conditions consistent with ground testing and flight testing onboard the X-15-2 aircraft. The objective of the control system development program is the design and development of such an engine subsystem.

2. TOPICAL BACKGROUND

The engine design developed in accordance with the NASA Langley Statement of Work L-4947-B must utilize supersonic combustion at freestream Mach numbers from 6 to 8. In the freestream Mach number range from 3 to 6, the combustion mode may be subsonic in order to yield the best performance. In addition, means must be provided for inlet flow starting and initiation of combustion, including at least one restart, after engine shutoff at any speed from Mach 3 to 8. It is the function of the control system to schedule engine fuel flow, in accordance with the computed freestream Mach number, and to establish, transfer, and maintain the desired combustion mode consistent with programmed instructions.

To achieve reliable operation over the intended hypersonic flight regime, major portions of the ramjet engine structure must be regeneratively cooled by the hydrogen fuel. The hydrogen fuel/coolant flow must be adequate under all engine operating and nonoperating conditions to limit metal temperatures and temperature differences compatible with sound structural design. In some engine nonoperating conditions and some operating conditions, there is insufficient fuel flow to the engine combustor to provide the necessary cooling. The fuel system, therefore, will include an overboard dump valve to permit fuel flow in excess of engine combustion requirements. It is the function of the control system to sense the critical structural temperatures and to initiate and maintain coolant flow as necessary.

To permit operation of the engine over the Mach number range from 3 to 8, it is necessary that the inlet spike be translated to various positions. It is the function of the control system to compute the freestream Mach number based on sensed flight parameters, to determine the appropriate spike position, and to signal the spike actuation system.

The control system is to be housed within the engine nozzle cavity. Accordingly, size and packaging limitations are governing factors in the design. Further, the need for access and replacement of components in the field must be kept to a minimum consistent with the research nature of the program.

3. OVERALL APPROACH

3.1 CONTROL SYSTEM OPERATION

The control system has two prime functions: (1) to control the inlet geometry and the fuel flow to the combustors during engine operation, and (2) to provide safe operation and automatic precautionary control as conditions dictate, for all phases of the flight environment.

In general, the control system operates automatically under the control of stored program data. It receives various stimuli from sensors in the system and only in a few instances will it be subject to the influence of manually initiated discrete commands.

The fuel delivery and the inlet spike actuator are controlled directly through the digital computer program. The temperature control functions as an analog control device with sampled data inputs. Its operating modes are determined by the digital computer.

3.1.1 Operating Configurations

The practical application of this system to the operational engine test can be divided into four phases. These include (1) pre-flight, which is define here as the period starting with ground power "on" until the time the X-15 is dropped from the B-52; (2) the period from the time the X-15 is dropped until the beginning of the actual engine operating test at high altitude; (3) the engine test run; and (4) the return from high altitude, high speed flight conditions to a subsonic flight environment. The major operating configuration of the HRE control system during such a test flight are itemized briefly in Table 3.1-1, and these considerations provide the basis for the various modes of the overall control program.

TABLE 3.1-1

OPERATING CONFIGURATIONS

Pre-Flight	X-15 Release	Engine Test	Post Test Operation
Ground start up	Normal control system operating mode	Inlet start and control	Engine shut down
Automatic checkout phase, degradation testing	Energize pneumatic systems	Fuel flow and distribution	Cooling control continues
Switch to operating mode, pre-drop test	Cooling system purge and start up	Ignition	Final purge (external control only)

The control system will be powered and operated from the time ground power is applied. Automatic self-check begins immediately and semi-operational testing continues until a few minutes prior to X-15 release from the B-52. Prior to release, the operating mode is changed to the flight test configuration and automatic self-test in this mode confirms the "go" condition prior to the drop. Self-test and monitoring functions continue throughout the flight.

The control system is ready to operate the engine when the X-15 is released. At the appropriate command, a series of pre-conditioning sequences bring the engine to full operational status. The hydraulic and pneumatic systems are pressurized, the cooling system is purged with helium, and finally, the turbopump start-up cycle is initiated. These sequences are described in greater detail in Section 4.1.3 of the Fourth Control System TDR.

The pilot initiates engine test and a further sequence of operations takes place under computer control. The inlet geometry is set, and after aerodynamic starting is confirmed, fuel is delivered to the combustor, and ignition is provided. Fuel flow (and distribution in the supersonic mode) is controlled by a computer program based on various locally sensed data. The pilot may terminate the engine burn at any time, but normally the computer will shut the engine down after a predetermined interval.

At termination of engine burn, the inlet is closed and the control system regulates engine temperature until the cooling fluid is expended or the engine repurge takes place. The control system continues to monitor all temperature data until power is removed.

3.1.2 Ancillary Functions

In addition to the normal operating configurations, further capability to communicate with the control system is needed for purposes of in-flight data recording and ground test. The data recording function is primarily to provide information on the performance of the control system. This data would be analyzed after the flight and in conjunction with recorded engine performance data retrieved through the instrumentation subsystem. The ground test capability provides a means for control system checkout and a limited check on sensor calibration.

3.2 SYSTEM DEVELOPMENT

3.2.1 Basic Approach

The approach selected for this application utilizes a digital computer as the primary functional element in the control system. The fundamental reason for this approach is the high content of research and development in the basic engine development program. It was recognized that aerodynamic and thermodynamic testing would result in some changes to control methods and parameters as these data became available. Consequently, in order to accommodate this as a practical requirement, and to minimize effects of such changes on the physical hardware development, the digital approach was selected. Parameter values, stored functions and significant changes in the operating program can be made by software and executed as late in the program as the actual flight test phase with no effect whatever on the hardware. The addition of new sensed data can be accommodated, within limits prior to the contruction of the prototype engine control.

The decision to use a digital computer with its attending flexibility was influenced by the fact that suitable small computers with adequate memory capacity have become available as production items.

Subsequent expansion of the control system capabilities in the areas of self test, monitoring, communication, and control have substantiated the decision to go digital. There are, however, certain elements of the system which have been implemented in analog form because of their high data rate input requirements. These include the temperature control and the inlet (spike) position servo, both of which are unlikely to undergo any significant changes as the engine development progresses. Therefore, to the greatest extent possible the control system has been able to proceed with its hardware development largely independent of engine design changes.

It has been a major objective to avoid design work which presses the state of the art of circuit and component development in order to prevent dilution of the system development effort.

3.2.2 Physical Constraints

The flightweight control system is to be entirely contained within the nozzle cone of the engine innerbody. Structure and plumbing in this region limit the useable volume to less than 1/2 cu ft which must contain the necessary thermal protection and interconnecting electrical cables, connectors, and mounting hardware.

In very general terms, the major environmental objectives for the control system are -65° to +200°F operating, sea level to 100,000 ft, and 10 g vibration. Work to date indicates that some degradation in accuracy will be noticeable above 160°F. Heat transfer studies show that the temperature inside the nozzle cone can be maintained below 160°F during the engine flight test.

3.3 SYSTEM DESCRIPTION

The system block diagram, Figure 3.3-1, shows the data flow and identifies some of the major elements in the control system. The dashed lines shown in the diagram between the valves and the sensors indicate the feedback loops which are closed through the operating engine. Two functional elements omitted from the diagram, for simplicity, are the systems internal power supplies and the monitoring facility.

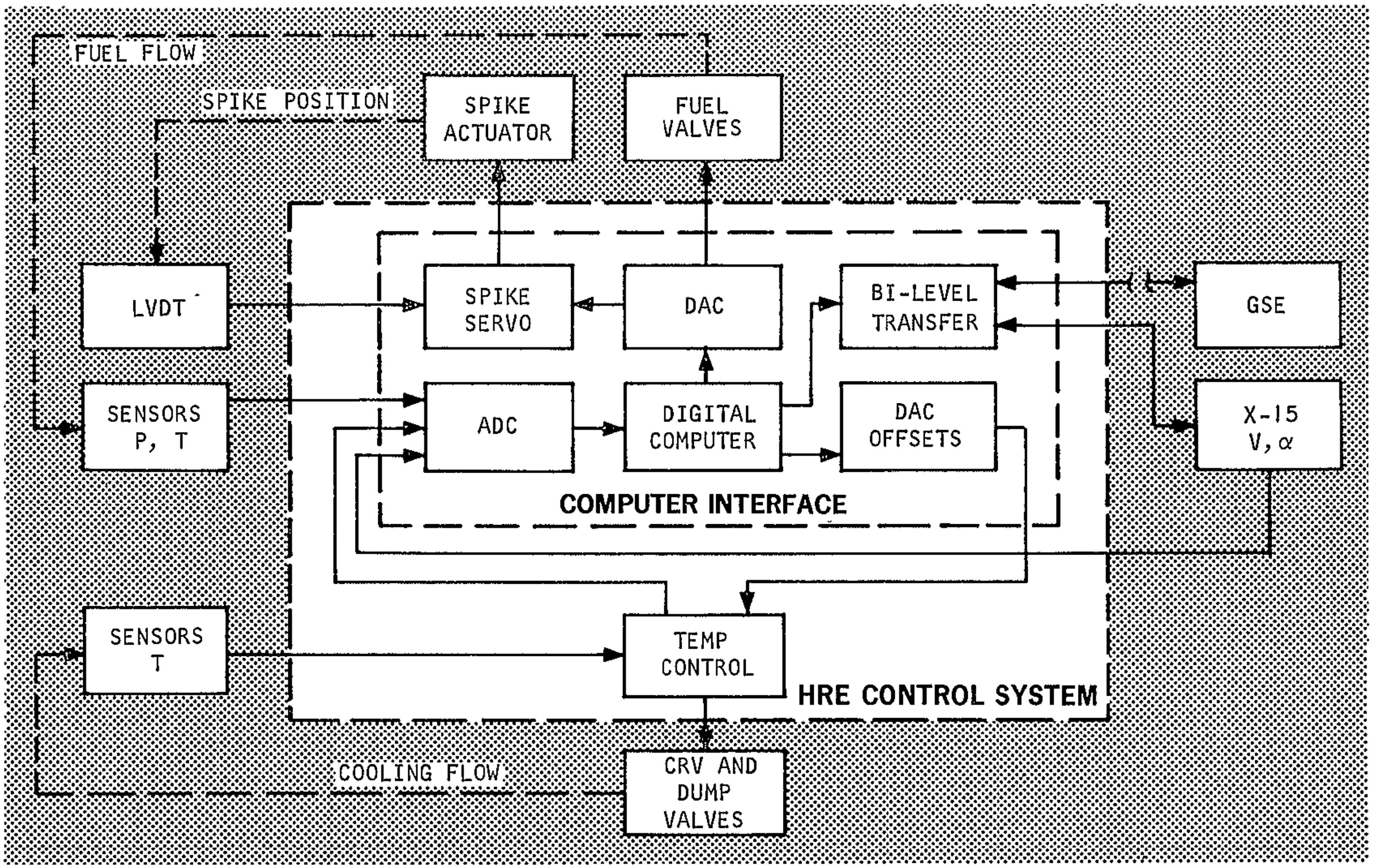

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Figure 3.3-1 Control System Block Diagram

3.3.1 Major Control Loops

3.3.1.1 Spike Loop

Based on data input from the X-15, the digital computer calculates Mach number for the engine flow field. Using this data and data relating to local angle-of-attack measurements, the computer calculates the required inlet configuration and generates position data as a command to the spike servo loop. A definitive discussion of the above computations are to be found in Section 4.2.1 of the Fifth Control System TDR (which superceded Section 4.3.3 of the Second Control System TDR).

The spike position command is modified slightly by a subroutine which provides temperature compensation for the LVDT (linear variable differential transformer) position transducer. This command is converted to analog form and is then compared directly with the measured position of the spike to provide the basic error signal for the servo loop. The computer generated command is up-dated at approximately 0.5 sec intervals and the last output command remains continuously available as an analog signal for the spike servo.

The servo electronics contained in the computer interface unit (CIU) generate the drive signal for the spike actuator hydraulic servo valve. A hydraulic ram is the prime mover for the spike. Smooth response of this subsystem is needed over a wide range of dynamic load conditions.

An in-depth performance analysis of the inlet control subsystem is given in Section 5.1 of the Third and Fourth Control System TDRs. By means of these studies, dynamic compensation for the control was defined. The details of the electronics circuitry used to implement the spike servo are given in Section 6.3.2.3 of the fourth TDR and Section 6.3.2 of the fifth TDR.

Inlet unstart and buzz conditions are detected by pressure sensors whose data input is processed in the digital computer as described in Section 4.3.4 of the Second Control System TDR. The system is programmed for one automatic restart sequence. The inlet must be aerodynamically "started" before fuel flow is initiated.

3.3.1.2 Fuel Loop

The required total fuel flow is proportional to the air mass flow entering the inlet. The fuel loop controls the fuel flow and, in addition, determines the mode for combustor operation.

Inlet air mass flow is not measured directly. A number of input variables from local sensors and from the X-15 are supplied to the digital computer which calculates the air flow. The computer then generates the fuel flow command. Another segment of the digital computer program measures the actual fuel flow delivered to the fuel injectors. The difference between the commanded flow and the "measured" flow becomes the basic error signal for the fuel valves.

The computer processes this signal even further. Compensation is provided so that stable and rapid response to the computer generated command is attained. The compensated error signal is then converted from digital to analog format and the low level signal from the converter is amplified to a level suitable for driving the respective fuel system servo valve.

There are two primary operating modes for the engine combustion process. When subsonic combustion is required, only the second injector is used to feed fuel. This occurs for nominal freestream Mach numbers of 3.0 to 6.0. For Mach numbers in the 6.0 to 8.0 region, the burning flow in the combustor is intended to be supersonic. The nature of the distribution of the fuel among the injection stations is the means for controlling the mode of combustion.

Proper supersonic combustion is also constrained by limiting combustor pressure ratios defined by a function of local Mach number and total temperature. These limits determine the maximum allowable fuel injection for Stations 1 and 2. The control criteria for fuel distribution are contained in the digital computer in the form of stored curve data. A detailed description of the distribution control is given in Sections 4.2.2 and 6.1.4 in the Fifth Control System TDR. An introductory discussion is provided in Section 4.3.2.2 in the second TDR.

Details of the air mass flow calculation used in the foregoing process are given in Section 4.2.1 in the fifth TDR. Calculation of the measured fuel flow is described in Section 6.1.2 in Part II of this document. The performance analyses of the fuel injection process and development of the compensation are given in Section 5.2.1 in the fifth TDR and in Section 5.1.1 in Part II of this document.

The above referenced processes supercede the corresponding write-up given in the second TDR (the superceded paragraphs in the second TDR include all of Section 4.3.1 and Section 4.3.2.3).

The calculations and program control for the entire fuel loop operation are embodied in the digital computer software. The software flow charts and listings for the engine control programs in Appendix G of Part II of this document. These listings are, in fact, the up-to-date mechanization of the engine control.

The hardware facility which collects the required inputs and delivers the valve commands to the servo valves is discussed as part of the CIU.

3.3.1.3 <u>Temperature Control Loop</u>

During high Mach flight operation, the HRE could not survive without provision for cooling most of its exposed surface. In addition, it is necessary to limit temperature differences between adjacent sections of the structure so that excessive stresses are not superimposed on the normal operating loads.

The temperature controller samples the temperature of the cooling fluid (gaseous hydrogen) at several locations. According to selected limits (programmable for anticipated flight test conditions) stored in the computer memory, the coolant is distributed through four main flow paths. The coolant is finally delivered to the fuel injectors. If the fuel flow required for combustion is insufficient to provide adequate cooling, the temperature control increases the coolant fuel flow and dumps the excess overboard, upstream of the fuel injector manifolds.

A detailed description of the temperature control function and its operating concepts is given in ,Section 4.3 of the Fifth Control System TDR. Hardware developments have been covered in Section 6.4 of each of the TDRs (the third and fourth TDRs show the basic circuit development). The mode control tie-in with the digital computer is done through the CIU, and the associated hardware is discussed in conjunction with CIU description.

The analyses associated with the performance of the HRE cooling system represents a major portion of the analytical effort for the control system development. It has encompassed large-scale analog and digital computer simulation programs. The analytical effort is contained in Section 5.2 of the Third through the Fifth Control System TDRs. All of Section 5 · in Part II of this document is devoted to analytical studies related to the fuel and cooling system performance. A block diagram of the cooling system is given in Section 5.2.2, Figure 19, in the third TDR and this section describes how the analog simulation is developed. A schematic of the up-dated plumbing is shown on page 5-18 in the fifth TDR. Hardware descriptions of the plumbing are to be found in the Structures and Fuel System TDRs.

3.3.2 Power Supply

The internal power supply circuitry accepts the aircraft prime power inputs and regenerates a variety of well regulated voltages suitable for use by the computer, the CIU, the temperature control, and the transducers. It also contains a system of internal failure monitors. The function of the supply, in addition to power distribution, is to protect the control system from undesirable power transients which may arise in the prime power system on the ground, or during flight with the B-52 or the X-15.

The design of the power supply has been predicated on size considerations and overall efficiency. A number of trade-offs have been made with this in mind and the resulting configuration is shown in Figure 3.3-2. This diagram shows the main power sources and the final destination of the regulated outputs.

The digital computer has certain peculiarities which are catered to by the internal supply. The prime concern here is to avoid conditions that in any way effect data stored in computer memory, such as improper voltage levels and electrical noise which might be mistaken for data pulses. Whenever a prime aircraft power interruption occurs, the computer input voltages are turned off and later turned on in a defined sequence so that the computer memory is retained intact. The sequence controller is contained within the power supply section of the control system.

Detailed discussion of the power supply design and its hardware development are provided in Section 6.2 of the Fourth and Fifth Control System TDRs and in Section 6.2 in Part II of this document.

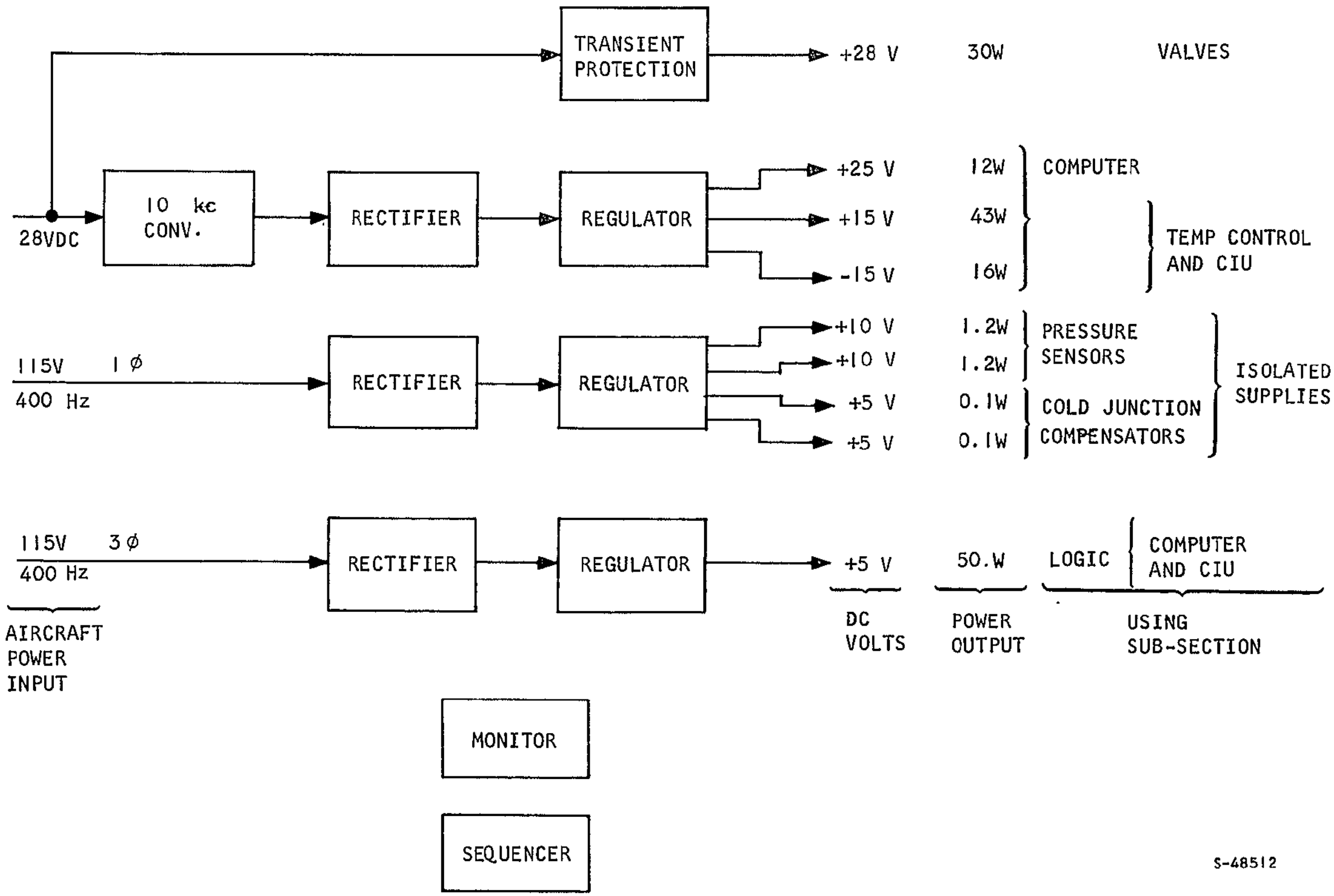

Figure 3.3-2. Power Supply Block Diagram

3.3.3 Self Test and Monitoring

The ability of the control system to thoroughly check itself before flight and during the engine test is of prime importance because there is no essential redundancy in the system. This approach was deemed acceptable because of the inherent reliability of the hardware design and the very short duration of the actual engine test run. Criteria defining safe operating conditions in terms of transducer inputs, discrete inputs, and computed data are stored in the digital program and provide the fundamental references for "go, no-go" decisions of the continuous self-test function. The system is subjected to a comprehensive, continuous check prior to the free-flight period. During the relatively short duration flight of the X-15, continuous monitoring and safety analysis is carried out.

The inherent digital computer capabilities make it possible to execute these activities with the necessary thoroughness. The data routing in a digital system is such that all information is available to interrogation and only a very small amount of additional hardware is directly attributable to the needs of testing. The reservations here are computer time and money capacity.

The test routines consist of hardware diagnostics, end-to-end performance checks of the control systems, and sensor validity tests. A detailed discussion of the monitoring and self-test concepts is given in Section 4.4 of the fourth TDR and these concepts are expanded and related to the hardware in Section 4.4 of the fifth TDR. The test routines for the engine control are described in Section 6.1.6.3 of Part II of this document.

3.3.4 Ancillary Functions

Data recording and communication with the teletype are accomplished through two different sections of the computer interface. The teletype has its own interface and all other data is transferred through two 12-bit registers which provide parallel input/output. The CIU contains buffers and line drivers for this data transfer. Additional discrete control lines are also provided.

3.3.4.1 In-Flight Recording

The interface design permits data to be dumped into the PCM (CT-77) recorder in the X-15. The data to be dumped will be selected through the computer software and can be altered to suit a given test flight data retrieval requirement. The recorder and digital computer operate asynchronously and if the existing access to the recorder is limited to one 9-bit channel in its digital interface, then a 9-bit data word plus a 9-bit address can be executed at approximately 100 samples per sec. More detail is given in Section 6.3.1.2 in Part II of this document.

The priorities on selected data and recording intervals have not yet been established. This is however, a software controlled facility and has not inhibited the interface hardware design.

The recording function is implemented through the external device interface logic and a detailed description is given in Section 6.3.1.2.4 and Section 6.3.1.4 in the Fifth Control System TDR.

3.3.4.2 Teletype Communication

The teletype has its own section of the interface in the CIU which provides a communication path between the typewriter and the digital computer when the B-52 is on the ground. This facility is used immediately prior to flight testing to input the meteorological data for the air mass flow computation. During ground test and calibration checks, the teletype provides test control and data print-out facility in hard copy and/or paper tape. Prior to flight testing, the final step (before disconnecting the teletype) would be read onto tape the total contents of the computer memory and to get a "go" from the control system self-test check. Before the flight is initiated, the memory contents tape would be checked for integrity against the master input tape.

3.3.4.3 Memory Loading

The optical reader is a practical method to read-in a complete memory tape. For example, 4000 words can be read in from paper tape in about 1 min as opposed to 1/2 hr using the teletype tape reader.

3.3.4.4 Ground Test and Calibration

Communication with external equipment for test, calibration, and other purposes can be readily accomplished through the 12-bit parallel input/output interface using the teletype as a control keyboard and print-out.

To accomplish this purpose, two other ingredients are required. One is the necessary software programming, and the other is the equipment interfacing which in this case would be part of the external hardware.

For HRE testing, when the engine is separated from the X-15, power must be supplied in conformance with the X-15 inputs. External-device inputs and the high-level analog channels may be used for additional data transfer and logic signals.

Although no extensive design work was done on automated external (ground test) equipment, it can be seen that there is ample scope with the present control system configuration to accommodate a fully automated ground support setup with hard-copy and tape-data records.

3.3.5 Input/Output Data Lines

Communication between the physical world of the operating engine and the electrical world of the control system is accomplished through four types of input and output transducers. Three basic input transducers are used for pressure, temperature, and position. The output transducer is in each case a torque motor device which controls a valve. The control system also inputs some high-level dc analog data from the X-15 which are used in the computation of Mach number. In addition, there are the discrete data transfer lines and prime electrical power connections between the HRE and the X-15 vehicle.

3.3.5.1 Input Transducers

All of the locally sensed engine data comes from three transducer types. The engine pressure measurements are made using a strain-gauge device. These are in effect resistance-ratio bridges that produce low-level signals on the order of ±15 mv full scale. The bridges are excited from an isolated power supply contained in the control system. Engine temperature measurements are made using chromel-constantan ungrounded thermocouples. These sensors will be used over a nominal 15 mv range and cover a much larger range by using a system of offsets. The cold junction compensation for all of the temperature sensors is contained in the control system CIU and has its own isolated power supply. Spike position is sensed using an LVDT. The LVDT is an ac-excited device and the necessary conditioning and compensation is contained in the CIU (see Section 6.3.2.2.6 of the Fifth Control System TDR).

3.3.5.2 High Level Analog Inputs

In addition to the local sensors, five high-level dc analog inputs come from the X-15. These data include inertial velocity components, angle of attack, and a dc reference voltage. They are in the 0 to 40 and 0 to 10 v range.

3.3.5.3 Output Transducers

There are nine valves in the system. Three control fuel injection, one controls the spike position, and five control the system cooling flow.

The fuel valves and the cooling system valves are servo valves which use gas as the control medium and control the flow of gaseous hydrogen. They are a vane-and-orifice device actuated by an electrical torque motor. Full-scale drive on the torque motor is approximately 2.7 watts. Control for the spike loop is a four-way hydraulic flow-control servo valve which feeds the main hydraulic actuator. The electrical power input to the valve torque motor is approximately 300 mw for full drive.

A discussion of the operating configurations for the control system valves is given in Section 4.1.2 in the Fourth Control System TDR.

3.3.5.4 Engine Mount Interface

The lines of cummunication and control are shown in gross terms in Figure 3.3-1. As presently configured, the total number wires passing through connections at the engine mounting interface is 55 (excluding spares). These lines, as represented on the block diagram, go to the two blocks on the right in Figure 3.3-1 and include the X-15 data lines, ground support equipment connection, and system prime power input. The number of wires including ground returns can be summarized as follows:

High level analog		7
Discrete data interface		41
Power		7
	Total	55

3.3.5.5 Control System Interface

The number of wires to and from the control system as a black box (within the engine) is presently estimated at 184 (excluding spares). These include shields, grounds, and sensor excitation lines and can be summarized as follows:

Engine internal lines		
Analog (sensors, valves)		123
Control discretes		6
Engine external lines		55
	Total	184

A complete line-by-line description of data lines to the digital computer is given in Appendix E in Part II of this document. This appendix does not include ground returns, aircraft power, temperature control sensor lines or spares.

3.4 PROGRAM PLAN AND STATUS SUMMARY

The activities discussed below are those encompassed by Phase IIA of the L-4947-B S.O.W., which is the basis for all work completed prior to September 1968. The end product in the control systems activity was the delivery of one flightweight prototype control system which would be used in the qualification testing with the first flightweight engine as part of Phase IIB of the contract.

The Phase IIA control system work was divided into two parts: the first consisted of producing a fully operative breadboard, and subsequently producing the flight engine prototype. The system engineering work overlapped the breadboard and the prototype activities. A generalized form of the control system development plan is shown in Figure 3.4-1. A stop order was instituted at the end of August 1968, and as shown on the chart, the breadboard system had not reached the stage where a fully integrated system was operative. However, integration of some of the subsystem groups had begun and intermediate development testing was well under way.

3.4.1 System Study

The disciplines of aerodynamics, thermodynamics structures, and controls were used in a cooperative effort to establish compatible control concepts.

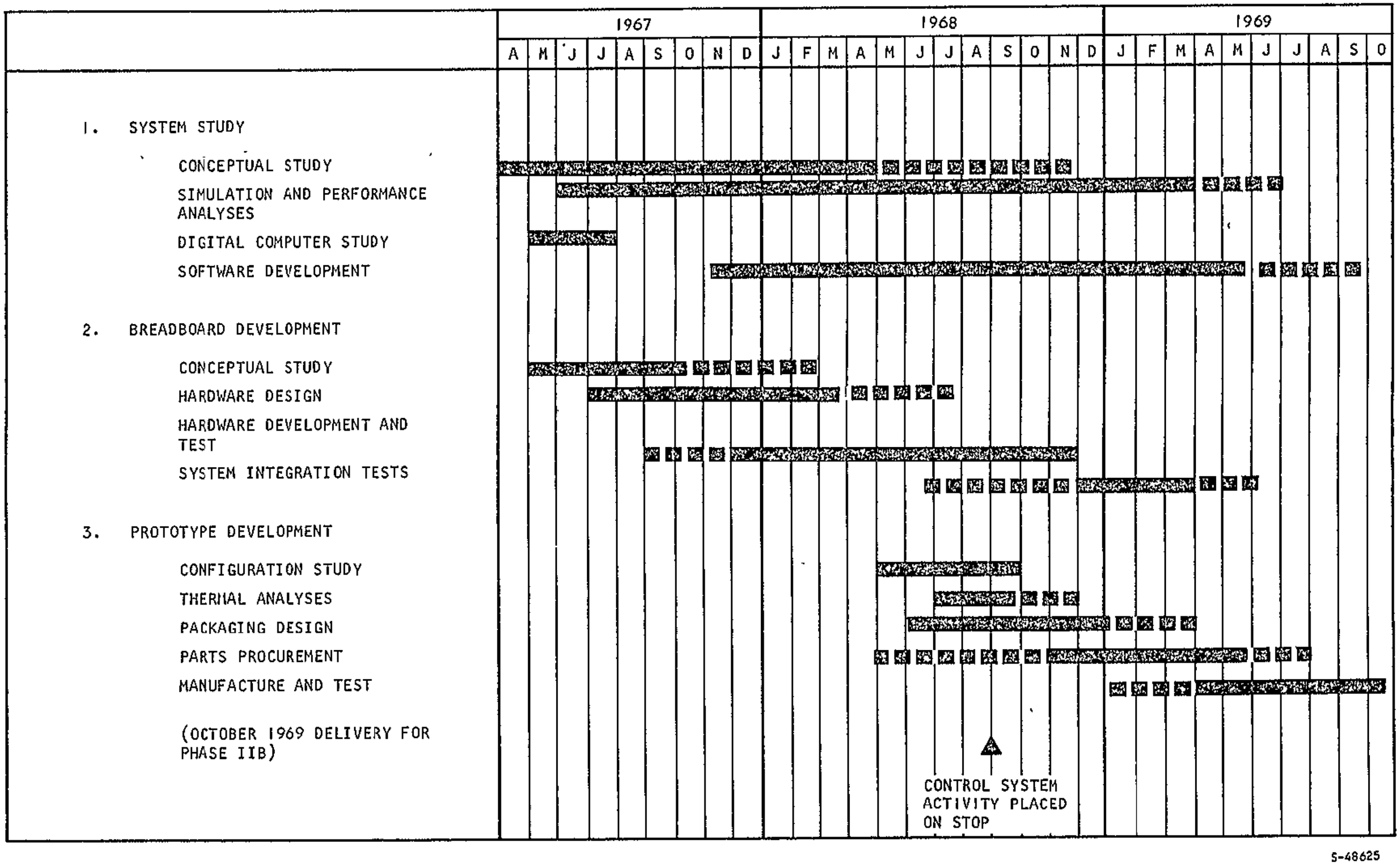

Figure 3.4-1. Control System Development Plan

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The development of large-scale simulations and associated performance analyses continued through most of the program. The digital computer software development began slowly and got seriously underway with the delivery of the computer itself in November 1967. The digital computer software development was also a continuing effort through the remainder of the program.

3.4.2 Breadboard Development

The breadboard system was to be a fully operating configuration which could be used in simulation studies and wind tunnel testing. No constraints on packaging were imposed and the breadboard is presently assembled in a 6-ft-high standard rack. Electrical access and front panel read-out capabilities are provided in all critical interfaces so that system operation can be easily analyzed. The final breadboard system console is shown in Figure 3.4-2.

Interface sub units were constructed and thoroughly tested by themselves before being coupled to other sections of the CIU and to the digital computer itself. The temperature control unit proceeded initially as an independent subsystem. All of this equipment was operated on laboratory power supplies. The breadboard power supply section with its protective circuitry was developed independently.

The progress of the breadboard work is discussed in Section 6 of the Control System TDRs, beginning with the third. This work was incorporated or rebuilt as required into the final breadboard format as soon as satisfactory results were obtained.

Figure 3.4-3 shows the final breadboard of the CIU extended from the console in a servicing position. Its normal location is behind the blank panel (shown in its closed position) at the lower center of Figure 3.4-2. One corner of the MICRO D digital computer is visible, mounted on the rear of the CIU drawer.

The temperature control final breadboard occupies the bottom section in the console. Its internal construction is incomplete. The final breadboard of the power supply is shown in incomplete form in Figure 3.4-4. All of the elements shown in Figure 3.4-4 are individually complete and tested as sub units.

An important element of the breadboard activity is the development of the digital computer software which embodies a major part of the engine control mechanization. This activity continues throughout the development program as a physically independent function but requires close coordination with the CIU logic design.

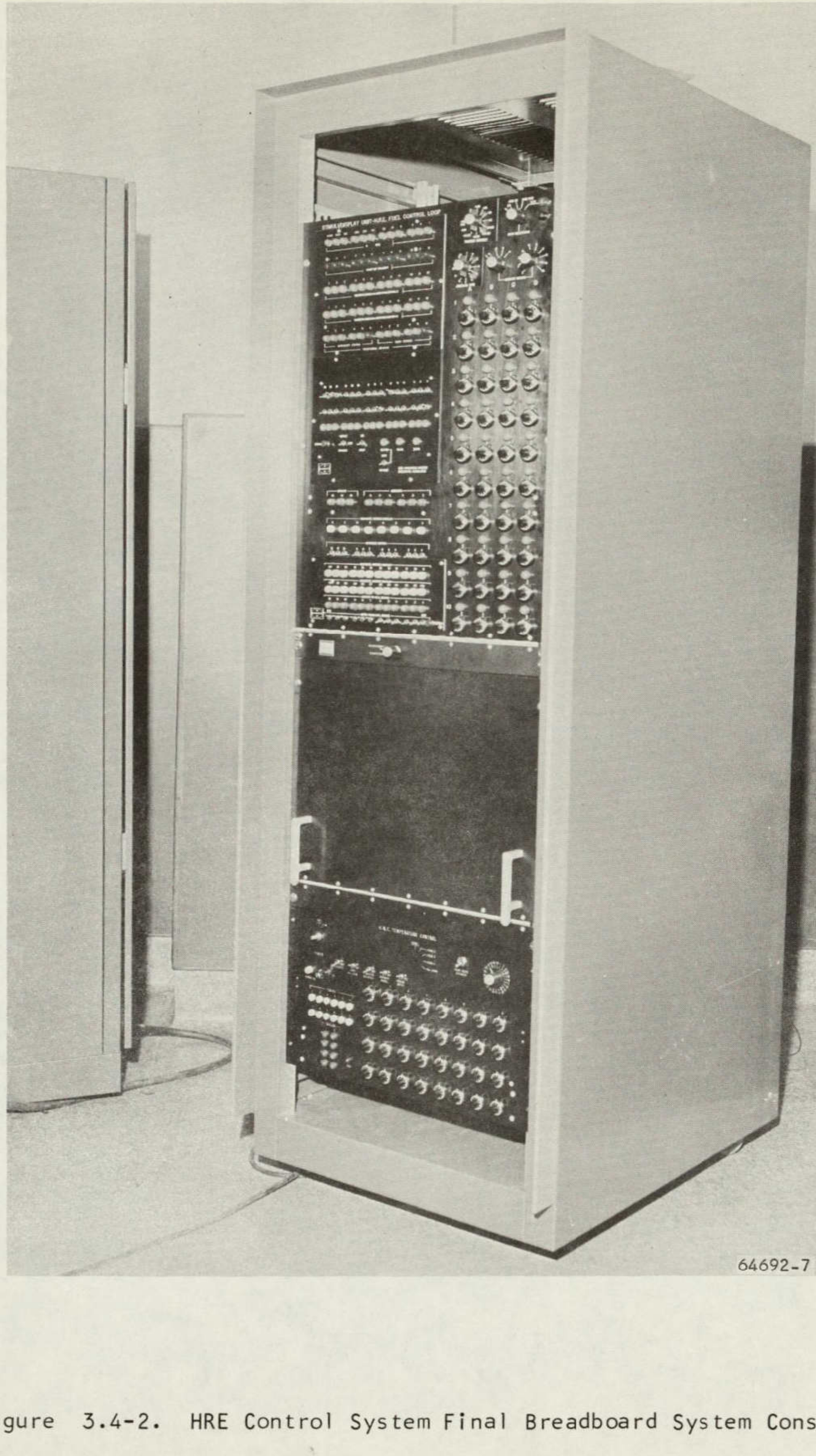

Figure 3.4-2. HRE Control System Final Breadboard System Console

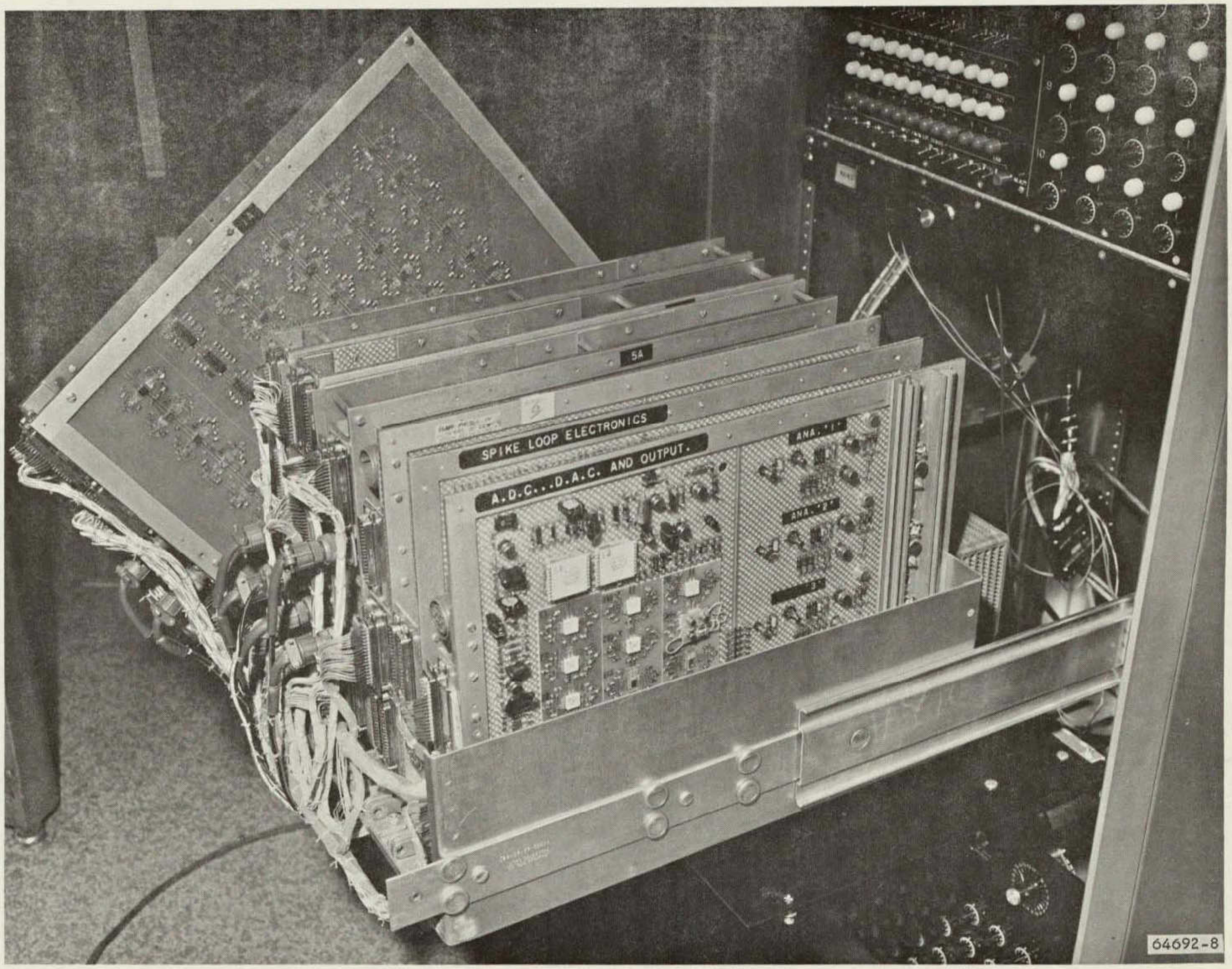

Figure 3.4-3. Final Breadboard Computer Interface Unit

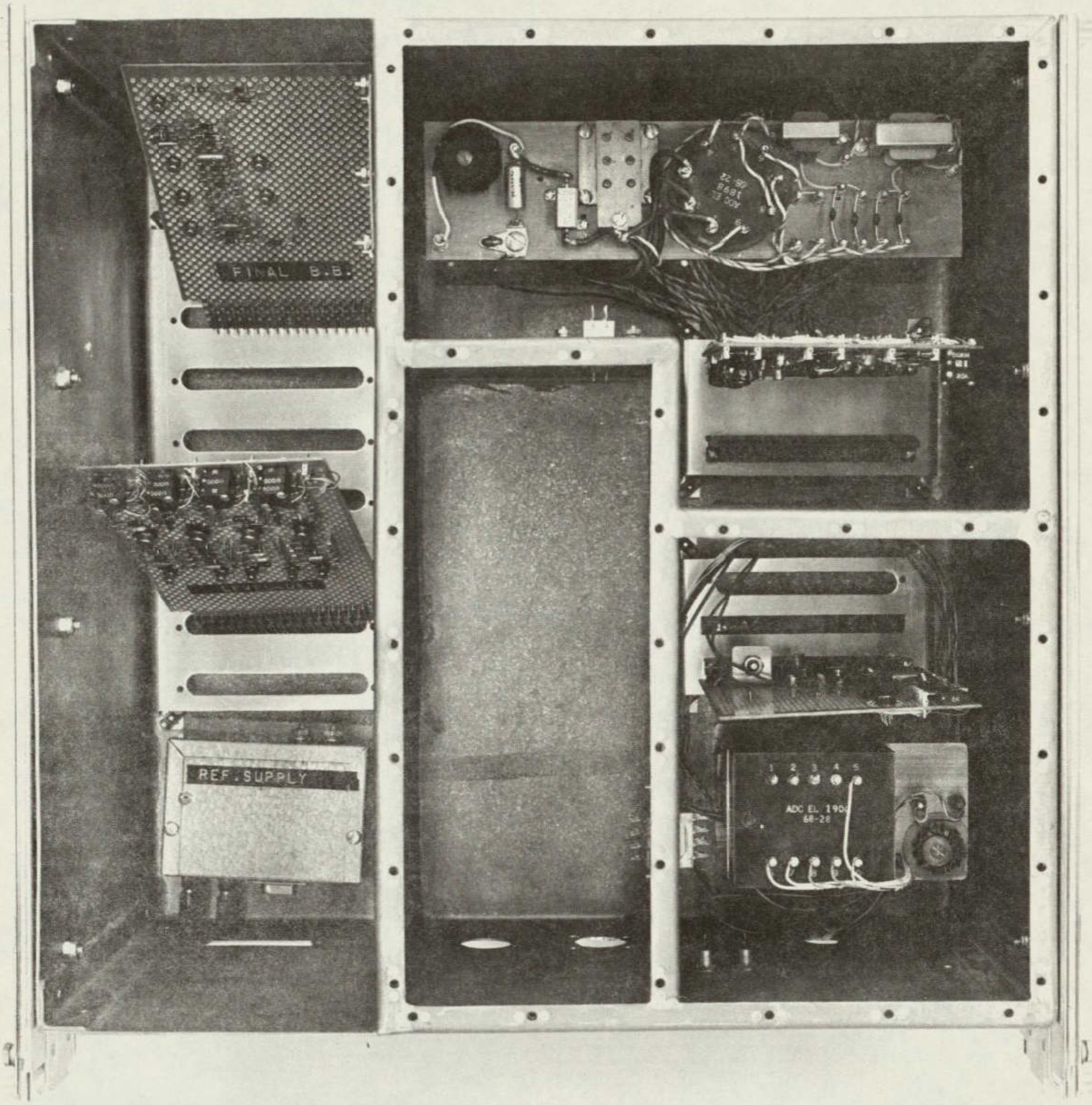

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Figure 3.4-4. Final Breadboard Power Supply Section

The present status of the software is as follows:

- Engine control programs - completed (to present control design) except for detailed parameter values. Programs detailed in Section 6.1 of the Fifth Control System TDR except where superceded by Section 6.1 of Part II of this report.

- Monitoring programs - inflight test monitoring programs flow-charted as detailed in Section 6.1 of Part II of this report and ready for coding. Remainder of inflight and ground monitoring to be produced.

- Temperature controller programs - flow charted and ready for coding as detailed in Section 6.1.5 of Part II of this report.

- CIU test programs - flow charted and coded ready for assembly and test as detailed in Section 6.1.7 of Part II of this report.

- Engineering software tools - in use as detailed in Appendix H of Part II of this report.

3.4.3 Prototype Control System

The dominant factors influencing the prototype hardware design are size and environment. The transition from the breadboard configuration must produce little or no change in electrical function, a fact which was duly considered during the breadboard circuit development.

In order to meet the space allotment within the engine nozzle, the circuit construction would be in hybrid form using medium scale integration (MSI), thick film, and some discrete components where necessary for power handling.

Heat dissipation is a serious problem and a thermal analysis is required to establish the limits of the control system operating environment for various ground and flight conditions. This phase of the work was just beginning at the time of the work stop order.

3.5 HRE CONTROL SYSTEM SYNOPSIS

The following paragraphs are descriptive highlights of the physical hardware and functional capabilities of the control system. Capsule statements indicate the structure of the analytical effort and provide specific estimates of system performance. The concluding paragraph illustrates some of the practical advantages in using a central digital processor.

The HRE control system is one of a few applications where the control problems are handled almost entirely by a central digital computer. The system exhibits a high degree of automation and maintains considerable flexibility for organization of control problem solutions. In this latter respect it presents a practical working tool to use in connection with an engine which is, itself, in a progressive stage of development.

Some general features of the system which are of particular interest include:

- Program flexibility (changes through software)
- Sophisticated monitoring and self test capability

One objective in the control system development was to avoid entanglement with basic component development. As a result, there is little to be shown in the way of unusual circuit design. However, there are features of the hardware which are interesting and seem worthy of review because of the rather extensive application of digital computer interfacing techniques.

3.5.1 Hardware Features

Points of interest and system features are listed below for the main areas of the hardware development.

- Fuel Control

  Central digital computer (sampled data system)

  High-speed random access multiplexing

  Shared, high-accuracy, fast-response signal conditioning (total settling time, 100 μsec per input)

  High-speed, high-accuracy analog-to-digital conversion (conversion time 8 μsec per bit)

  Communication between asynchronous sampling systems (temperature control, recorder, and GSE)

- Inlet Control

  High-load, high-accuracy position control (16,000 lbf; position accuracy better than 0.050 in. in 5.000 in. of travel)

  Fully damped response under extreme load fluctuations and wide variation of environmental conditions.

- Temperature Control

  Analog sampled data system

  Variable mode control directed by digital computer program

  Application of temperature-compensated substrates

  Application of MSI to multiplexer

- Power Supply

  Utilization of high-efficiency switching mode regulators

  Built-in monitoring functions

  Capable of meeting stringent MIL-STD-704A requirements

The foregoing comments relate primarily to functional aspects and other attributes of the hardware. A significant part of the control system development was involved in analytical effort.

3.5.2 Capsule of Analytical Effort

The analytical work included detailed mathematical model studies and extensive use of digital and analog simulation techniques. These studies have contributed substantially to the cooling system, the fuel control, and the spike actuator design efforts.

The fundamental features of these studies include

- Mathematical model development
- Component transfer function characterization
- Linear and nonlinear subsystem performance analyses
- Control system performance optimization

The performance analyses made direct use of Z transforms because of the sampled data nature of input variables. Extensive use was made of large scale digital and analog computer facilities both for data reduction and simulation studies. The practical use of several powerful analytical tools has been effectively demonstrated and their application is described in Section 5 of Part II of this document and Section 5 of previous TDRs.

3.5.3 System Performance Data

The analyses and testing carried out to date show that the control system performance will provide stable engine operation. The principle control functions of the system include control of the engine inlet, control of fuel flow and distribution, and the control of engine cooling.

3.5.3.1 Inlet Control

The inlet geometry is controlled through the spike actuator. This hydraulic servo controls spike position according to a computer generated value. Simulation runs have shown this loop to be overdamped (highly stable) with approximately a +30 db gain margin. Laboratory testing of the actuator system with the HRE breadboard electronic control showed small displacement responses of 5.0 Hz at 3.0 db down (includes inertial load but no air load simulation). These numbers imply a well-behaved control loop.

3.5.3.2 Fuel Control

The fuel injection system operates from a nearly constant plenum supply pressure of 550 psia. This control function is a closed loop through the digital computer with sensor data sampling and computation iterated at 10 samples per sec. It is mechanized as an integral control and operates with zero steady state error. The system settles out in less than 1 sec with a maximum of 2-percent overshoot. This data is derived from computer simulation runs.

3.5.3.3 Temperature Control

The temperature control is a high-rate, sampled-data analog subsystem which inputs sensor data at 40 samples per sec for each sensor. Although the analyses for this control element have not been completed, available data shows that open loop gains (32 db or more) should be realized.

The turbopump as a part of the closed loop control system interacts with the temperature control. Its effect is to produce a well-damped resonance in the flow response at about 10 cps. The turbopump itself can be described as a first order system, with its response predicated upon the rotor inertia. Interaction with the line dynamics and the turbine control valve produce the flow resonance.

Since the cooling system gain characteristic varies appreciably (for the plumbing and heat exchangers) over the operating range, it is not practical to state a specific overshoot. However, a minimum gain margin of +20 db is expected and the total error which includes overshoot and steady-state errors will be limited to 50°F or less. Settling times will vary from 1 to 2 sec, primarily due to the long time constants of the heat exchangers.

3.5.3.4 Performance Highlights

The following tabular listing indicates briefly the primary performance characteristics determined through tests and from the simulation studies:

- Spike Actuator

  Critically damped, no overshoots

  Response better than 5 Hz (small perturbations)

  Gain margin +30 db

- Fuel Injection

  Settling time less than 1 sec

  Less than 2-percent overshoot

  Zero steady-state error

- Temperature Control

  Skin temperature errors limited to 50°F

  Settling time 1 to 2 sec

  Gain margin +20db (estimate)

3.5.4 Special Features of the Digital Approach

In addition to flexibility in handling the normal control functions, there are other advantages accrued by use of a central digital computer. These are essentially linked with the ready accessibility of all data being handled in the control system. In theory, one can interrogate any sensor, any function, any operating condition of the system at any time for purposes of performance assessment and safety checks. In practice, there is a limit to the depth of this type of communication, because the time it consumes can interfere with the needs of the primary control program.

Since the necessary electronics interface does exist in the control system, the functions of monitoring, recording, and ground testing are accomplished through computer software development and can be tailored to suit the needs of a given situation without affecting the physical hardware. Thus, program composition may be changed even during the period of flight operations(after delivery of the hardware) without interfering with the hardware schedules. This highly desirable feature also applies to changes in parameters and functions of the engine control programs.

The computer interface unit has two digital input/output channels and associated control lines. These are the teletype interface and a 12-bit digital interface. In flight, the output section of the digital interface is fed to a PCM recorder on the X-15. On the ground, both input and output sections of the digital interface are used under control of the teletype keyboard which provides the hard-copy readout facility. The input section of the digital interface is used on the ground to load the digital computer memory with the operating program, using an optional paper-tape reader.

The digital interface can also be used in conjunction with external facilities to do calibration tests and other GSE functions in a fully automated fashion. In this case, the computer memory would be loaded with a separate program devoted entirely to the HRE ground testing requirements during periods when maintenance activities are taking place. Extensive automatic ground checkout with hard-copy and paper-tape records can be provided with a very modest cost penalty in GSE hardware.

Consequently, the self contained computer and its existing interface can serve as a tool for ground services as well as serving its intended function as an airborne control system.

4. HISTORICAL SUMMARY

This section presents a summary of the overall accomplishments of this task of the HRE Phase IIA development program.

4.1 PERIOD OF 3 APRIL 1967 THROUGH 2 JULY 1967

Preliminary design and analysis efforts were initiated for the control system in several areas. The digital vs analog system tradeoff study was completed and resulted in the choice of a digital-type control. This effort was followed by a detailed study of functional requirements for the digital system. Preliminary design of the computer input/output interface equipment was completed. Extensive activity also centered about math-model studies for the fuel system and inlet spike actuation system, using analog and digital simulations.

4.2 PERIOD OF 3 JULY 1967 THROUGH 2 OCTOBER 1967

During the second reporting period, design and analysis effort was expended in the following areas of control system development.

- Computer control
- Computer interface equipment
- Fuel control
- Temperature control
- Spike actuator control

As a result of changes in control system requirements, a review of the overall system concept was initiated. It was determined that the major hardware items would remain functionally intact, but detailed design features would be effected.

Mathematical model studies were initiated for the fuel injectors, turbopump, and heat exchangers.

Analytical studies of the temperature control function indicated the need for faster response than was originally estimated. Study of the loop stability showed a necessity for rate compensation andan increase in the temperature sensor sampling rate. The circuit design was changed to incorporate these features.

Actuator performance was analyzed to evaluate the effects of removing the hydraulic damper and providing other means of compensation.

4.3 PERIOD OF 3 OCTOBER 1967 THROUGH 2 JANUARY 1968

The control system development progressed from the analyses and design to the early stages of breadboard hardware. Functional testing of some primary circuits of the temperature control and the computer interface was begun.

Analytical work on the temperature control and inlet control was reinitiated in the latter part of this reporting period due to concept changes. These changes arose from the results of the preceding analyses and experimental test data originating in this and other areas of the HRE program.

Some changes were made in the configuration of the computer interface. These changes increased the system flexibility and improved hardware economy. Breadboard testing was initiated for the analog-to-digital converter (ADC) and input register.

Several temperature control breadboard elements were constructed and functionally tested. This activity was confined to those areas that would be least affected by results of the concurrent analytical activities. The physical hardware for the temperature control system was increased by approximately a factor of four due to the requirement for individual control in each of the four main coolant flow channels.

A study was begun which defined the interfacing circuitry for the sensors and valves of the computer interface and the temperature control.

4.4 PERIOD OF 3 JANUARY 1968 THROUGH 2 APRIL 1968

The control system development reached an advanced stage of breadboard hardware construction. Most of the existing circuitry was functionally tested and some of the circuits were tested over a wide range of temperatures.

Conceptual studies of failure modes directly influenced both the system design and the detailed electronics design activities.

Some areas of analytical design associated with auxiliary design communications (teletype, GSE, and recorder), and a small portion of the analog output section were still incomplete.

Simulation studies of the spike actuator dynamics were completed during this reporting period.

Simulation of the fuel and temperature control functions progressed to an operational stage in the analog computer facility. Heat exchanger characteristics were dealt with in detail. Cooling system simulation progressed to the point where usable design data were being provided for the temperature control electronics circuit development.

The Arma MICRO D digital computer, its operating console, and the teletype equipment were delivered early in this reporting period. This equipment was extensively operated in the laboratory and provided the necessary means for obtaining a practical working knowledge of the machine for both software and hardware engineering personnel. The equipment was used for preliminary verfication and testing of the software programs.

The control system power requirements were reviewed. Minor variation would be expected as design of the remaining electronics reached its final stages. Conceptual design of the several power supply sections was completed.

Engineering effort in computer interface is divided into two sections which are closely related from a functional standpoint. The two areas are the digital part of the interface, and the analog part; the distinction was made for the convenience in reporting the details of design activities.

4.5 PERIOD OF 3 APRIL 1968 THROUGH 2 JULY 1968

The control system activity during the fifth quarter was in three general areas. These included the analog simulation activity, the computer software generation, and the breadboard hardware development.

The analyses of the various major elements of the cooling and fuel distribution system were still being examined to a large extent as separate entities. These elements were the cooling system, the injectors, and the turbopump.

Control methods were devised and tested using simulation techniques. Compensation schemes used for temperature control circuits were derived as a result of work done in the simulation studies. Although some circuit parameters may change as engine development progresses, the form of the circuits should remain as they were reported in the Fifth Control System TDR. The fuel control configuration remained flexible since this area of control lies almost wholly in the realm of computer software. In the case of the injector control function, the analyses and simulation studies provided definition for computer software format.

The software activity during this reporting period can be put in two categories. The first category relates to timing constraints imposed by interface hardware on the programming structure. This area of study includes a close examination of trade-offs which were made to save computing time. The second category relates directly to the actual functions to be performed in engine control processes.

The air mass flow calculation equations were revised.

Design of the teletype section of the computer interface unit was completed. The data output section of the computer interface unit was revised during this quarter. The change was incurred as a result of the studies on digital computer program time economics.

4.6 PERIOD OF 3 JULY 1968 THROUGH 28 AUGUST 1968

Development engineering work was concentrated to a large extent on building and testing of sections of the final breadboard hardware. Some functional integration checks were initiated. The concept for mode control of the temperature loop was redesigned to be under direct control of software, but the associated hardware changes in the CIU were not completed. The overall system monitoring concept was established; however, the circuit design for the additional external hardware, namely the master monitor, was not initiated.

Computer memory storage estimates and iteration times were revised to reflect the latest design requirements and now include the monitoring programs. Some changes became necessary to the engine control programs during the sixth reporting period, with a new method of fuel flow measurement and a revision of combustor pressure limit computation.

All of the major components for the power supply were constructed and tested as units in final breadboard form. The supply itself has not been assembled as a whole.

Cooling system flow path cross coupling was analyzed using sampled data methods to determine the destabilizing effects. Compensation was derived for simple cross coupling in preparation for the fully coupled simulation study. The injector study determined the effects of sampling rate and gain on injector flow stability. A linearized analysis of the fuel system turbopump was carried out and the turbopump start-up study was completed.

Work on the control system was stopped on 28 August 1968.

PART II

TECHNICAL DATA REPORT ON REMAINING EFFORT NOT PREVIOUSLY COVERED

1. SUMMARY

The HRE control system activity was placed on stop on 26 August 1968, with plans to restart in some areas at a later date. The contents of this report cover the work performed since the Fifth Control System TDR and up to the end of August. This is the sixth and last of the quarterly reports to be submitted on the control system under the existing Statement of Work L-4947-B. A review of the program as a whole is given in Part I.

Details of the hardware of the CIU, the power supply, and the temperature control are given in Appendixes H, I, and L. These appendixes define the status of the equipment at the time work was stopped. Appendixes D through G list the completed software programs and other related products of this activity.

During the sixth reporting period, work on the control system proceeded as outlined in the fifth TDR. The breadboard hardware was on schedule when work was stopped and the concept of system monitoring, the last remaining major design effort, was established in detail. The development engineering effort during this period was concentrated in the area of building and testing of the breadboard hardware with system analysis as a continued support activity.

1.1 ANALYSES

The fuel injector study which began during the last reporting period has been completed. Satisfactory response to step flow commands was attained with the integral control technique. The study is carried out in two parts and these are covered in Section 5.1 of this report. Combustor limit control of fuel flow for the supersonic combustion configuration was yet to be examined; the basic control method is outlined in Section 6.1 of this report.

The study of the cooling system was completed to a point where the fully operational system may be simulated on the analog computer. Flow path interaction studies have been carried out on the mathematical model. Compensation for the control circuitry has been derived, treating the control as a sampled data system. The final perturbation studies (which would be run on the analog system simulator) were scheduled to verify the compensation developed and verify system performance requirements; however, this area of the work remains incomplete.

The turbopump studies conducted during this reporting period were directed to two objectives.

One is concerned with the pump as an operating element of the cooling system, and the other is primarily related to design of the device itself. The former study is an inseparable part of the math model studies of the cooling system. To study the turbopump as a component, a simulation was developed around a simple system with well defined characteristics. These subject areas are treated in detail in Sections 5.2 and 5.3 of this report.

The turbopump start-up study (Section 5.4) was conducted to assess the nature of the initial pressure and flow transients. The data derived here are the bases for calculations of available start-up power. The period of interest in this study is from fuel "turn on" to the point when the turbine begins to rotate, and as such is not related to the characteristics of the pump.

1.2 DIGITAL COMPUTER

The software activities have progressed in two areas: the computer programs associated with flight conditions, and programs used for laboratory testing of the breadboard hardware.

Programming has been developed for the proposed change in fuel flow measurement. The temperature control operating modes are now controlled by the digital computer, and software has been developed for this purpose. Sections 4.2 and 6.1.5 contain discussions concerning mode control and monitoring of the temperature control by the computer. Refinement of the engine control programs has continued during the period and revisions to previously presented routines are given in Sections 6.1.1 through 6.1.4.

A revised storage and iteration estimate as detailed in Section 6.1.7 indicates the need for a machine with larger than 4096 words of storage and preferably an increase in computer speed. Both of these requirements can be met by modifications to the MICRO D as specified in Section 6.1.7.

1.3 POWER SUPPLY

During the sixth reporting period, the test program for the power supply preliminary breadboards was completed. All final breadboard elements were fabricated and functional testing was started.

The circuit detail of the remaining sections of the control system power supply are given in Section 6.2 of this report. This includes the +5-vdc logic supply, the reference supplies, and the monitoring network. Design considerations and functional descriptions of the power supply elements are given in the text.

1.4 COMPUTER INTERFACE

The digital section of the interface hardware in final breadboard form is nearly complete. Of the three final breadboards in the analog section, two are built but not tested, and the third is about 60 percent through fabrication.

Definition of the overall system monitoring was established during this reporting period. The definition was evolved with due consideration for the functional requirements and for the practical impact on the control system hardware. Trade-off studies resulted in a multiple DAC configuration for the temperature control communications link and these are discussed in Sections 6.3.1 and 6.3.2 of this report. The final design configuration in this area of the CIU was not implemented in the existing breadboard hardware at the time of the work stop order.

Construction of the teletype interface final breadboard was completed and functional check-out was initiated prior to the work stoppage.

The final breadboards for the analog section were about 80 percent complete in manufacture, and consequently, the overall operation of the CIU was not functionally checked out in a completed operating system.

The spike control loop circuitry was fabricated as a separate unit and was used to operate the spike actuator assembly during its component evaluation testing. The control unit functioned satisfactorily and was capable of controlling spike position well within the specified accuracy.

Some minor modifications to the interface control logic have been made to give added programming flexibility.

1.5 TEMPERATURE CONTROL

Definition of the temperature control/computer communication link has been finalized in a form which accommodates the requirement for variable operating temperature levels.

The laboratory work included some modifications and further testing of existing breadboard circuits. The valve drivers were fabricated and checked out.

Discussion of this communication link is given in Section 4. and the hardware activity is covered in Section 6.4.

1.6 SYSTEM BREADBOARD

The console as shown in Figure 3.4-2 of Part I is the final breadboard configuration. Additional visual readout capability has been incorporated into the right-hand display panel during this reporting period. The temperature control drawer is shown directly below the blank panel. Most of the mechanical hardware for this drawer was completed. The chassis wiring had not been started at the time the effort was stopped.

Other system components which mount in the console are shown in Figures 3.4-3 and 3.4-4 of Part I. The bulk of the CIU is shown in Figure 3.4-3 (Part I) with the analog boards in the foreground and the digital section behind. One of the digital boards is shown in a servicing position. This drawer is mounted behind the blank panel shown in Figure 3.4-2 (Part I). The power supply drawer is shown in Figure 3.4-4 (Part I) with some of the completed sub units placed in their respective mounting locations. This drawer mounts from the rear of the console. The construction used for the power supply drawer, was dictated by EMI containment requirements.

2. PROBLEM STATEMENT

(Refer to Section 1 of Part I.)

3. TOPICAL BACKGROUND

(Refer to Section 2 of Part I.)

4. OVERALL APPROACH

The existing control system concepts have been described in Section 3 in Part I of this document. References for providing information at the detail level are included and the description summarily encompasses all the data provided in the following sections of this report. The hardware descriptions in Section 6 and its appendixes (Part II) provide a hardware physical summary.

During this reporting period, two changes have been incorporated. The first change is in the method of fuel flow measurement, and the other change provides for more flexibility in the operation of the temperature control.

4.1 FUEL FLOW MEASUREMENT

The flow measurement method described in Section 4.3.2.3 in the second TDR has been replaced by a method which is independent of fuel injector discharge characteristics. The new method makes use of venturis placed in sections of the main flow paths downstream of the fuel control valves. A detailed discussion of the design and application considerations is given in Section 5.4 of the Sixth Instrumentation TDR (Data Item No. 55-8.06, AiResearch Report No. AP-68-4273). The expression shown in this reference can be rewritten in the following form:

$$W_f = C_1 \left(\frac{P_2 \cdot \Delta P}{T_2} \right)^{1/2} = C_1 \frac{P_2}{\sqrt{T_2}} \cdot \left(\frac{\Delta P}{P_2} \right)^{1/2}$$

For purposes of flow calibration, the computation will take the form

$$W_f = C_2 \frac{P_T}{\sqrt{T_T}} \cdot f\left(\frac{\Delta P}{P_T} \right)$$

where P_T = total pressure

T_T = total temperature

ΔP = pressure drop between the venturi inlet and its throat

c = constant

$f\left(\frac{\Delta P}{T_T} \right)$ is derived from calibration tests

Due to the configuration of the hardware, two venturis are required for the number one injector flow measurement. The square law characteristic limits the flow measurement range from an accuracy standpoint and, as a consequence, a second sensor is used to cover the entire ΔP range for the third injector flow. Thus, the number of analog inputs to the computer, for fuel mass flow, include four P_T inputs, four T_T inputs, and five ΔP inputs for a total of 13 inputs.

The pressure and temperature sensor inputs to the system are consistent with existing signal conditioning in the CIU. The computation is a software task and is covered in Section 6.1.2.

4.2 COOLING SYSTEM MODE CONTROL

It has been planned to run the engine initially at somewhat lower skin temperatures than the anticipated final operating levels. It has also been recognized that some control over engine temperature differentials may be desirable in flight. These needs coupled with the existing requirements for engine start-up sequences, etc., make it an economical move to place the mode control and parameter selection (for operating levels of the temperature control) with the digital computer software, rather than expanding on temperature control hardware.

A further advantage of making this change is that all temperature control monitoring can be vested in the software program. This simplifies the temperature control and allows the related design to be firmed up by virtue of eliminating the need for hardware monitoring functions.

4.2.1 Temperature Control/Computer Interface

The temperature control function has been maintained separate from the digital computer because of the large number of steps required to process the data. Software studies have shown that more than 80 percent of the available computer time would be required to input the sensor data, process it, and service the valves. The sensor input data rate is 1280 analog inputs per sec (based on 32 sensors at 40 iterations per sec). As input to the digital computer, these analog inputs would have to be handled serially. Hence, the design was modified to use the computer to provide offset control at this rate and in order to minimize the computer's servicing time. Four separate DAC (digital-to-analog) converters will be used, each with its own digital register. Two things were accomplished by this redesign: first, a digital hold function was provided which improves overall accuracy; and second, the digital computer can service each register very quickly (no settling time delay involved as would be the case for servicing the analog sensor inputs).

Using the separate DACs, the synchronization problem between the CIU and temperature control clock is avoided. The digital hold capability means no drop in the output with time, and with this holding method, physically large discrete components are not required. Once the computer has serviced a register with the required temperature offset value, it is free to execute other tasks.

With regard to the monitoring task, it might at first glance be expected that a significant segment of computer time would be consumed because of the requirement to look at all the sensors. However, from a monitoring point of view, the sensor data need not be scanned at the same frequency necessary for control functions. It is anticipated that one iteration per sec will be adequate. Thus the entire time expenditure for the tasks of offset control and temperature control monitoring will be somewhat less than 20 percent of the total computer time available. A detailed discussion on this subject is given in Section 6.1.5 (using four channels with ten sensors per channel as a basis for the calculations).

The trade-off on total number of components for this change is in favor of the new approach, but more work is required in the software production. A considerable advance in control flexibility has been achieved and the hardware construction is now free of any constraints imposed by development of the monitoring and self-test philosophy.

4.3 FUEL SYSTEM SYNOPSIS

A review of the fuel system is presented here for the purpose of continuity. The fuel system includes the cooling system which is controlled by the temperature control, and the fuel injection system which is controlled by a part of the digital computer program. The turbopump and its control valve operate independently.

Figure 4.3-1 is an elementary schematic which includes all the primary flow paths of the fuel system. The temperature control receives temperature data from the four coolant flow paths and it operates the four CRV (coolant regulator valves) and the DV (dump valve). The diagram shows this connection for one flow path only (innerbody), for the purpose of simplicity. The fuel injection system is controlled through the digital computer. It receives sensor data from four venturis as described in Section 4.1 above, and operates the three FCVs (fuel control valve). Again, the connection is shown in Figure 4.3-1 for only one injector.

Hydrogen is supplied to the system under a pressure of about 50 psi. This pressure is increased to between 600 and 1100 psi by a bootstrap turbopump. By the time the hydrogen has passed through the cooling jackets and reached the main fuel plenum, its pressure has dropped to about 550 psi and its temperature has risen from about 100^0R to 1500^0R.

The turbine control valve (TCV) maintains the pressure in the main fuel plenum at a constant 550 psi. This is done to ensure adequate fuel pressure for injection into the combustor.

Before combustion, the hydrogen fuel is passed through the double-walled shell of the engine to act as a coolant. There are four distinct paths for the coolant: (1) the movable centerbody, (2) the innerbody, (3) the forward outerbody, and (4) the aft outerbody. After passing through the cooling jackets, the hydrogen collects in the main fuel plenum from where it goes to the combustors. The coolant flow system is shown in Figure 4.3-1. Each

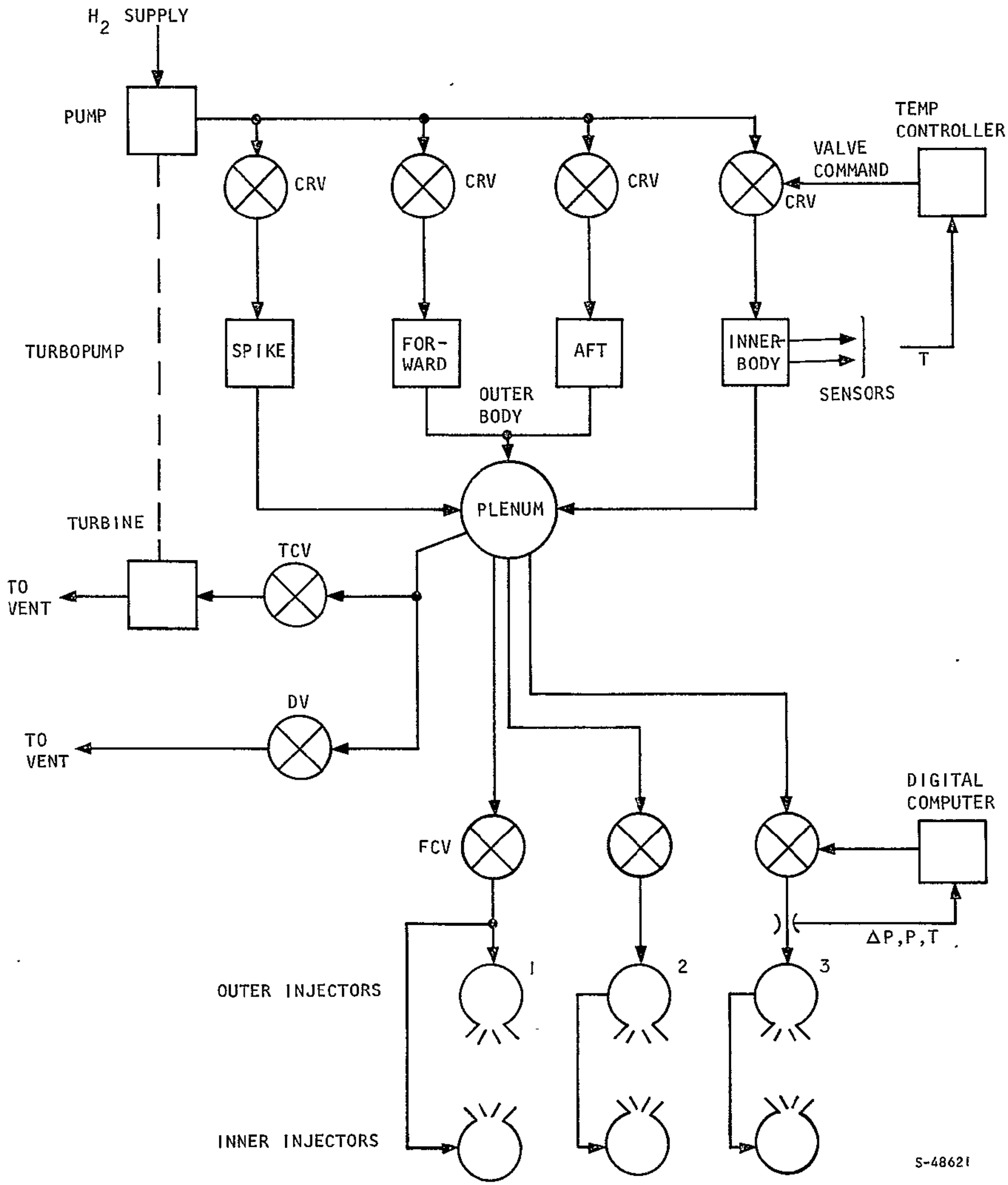

Figure 4.3-1. Fuel System Diagram

of the four flow paths has its own coolant regulating valve (CRV). If the cooling system requires more total fuel flow than is needed for combustion, the dump valve (DV) opens and this increases the coolant flow.

There are between six and eight temperature sensors in each cooling jacket for sensing coolant temperature. The signals from the sensors are multiplexed into a select-highest circuit. The highest temperature deviation signal is used to control the coolant regulating valve in each channel. If the temperature control commands a valve opening in excess of that which the coolant regulating valve can provide, then the excess error signal is used to open the dump valve. A detailed discussion of this operation is given in Section 4.3 of the fifth TDR.

If the dump valve is closed, then more fuel is being used for combustion than is required for cooling. In this case, one or more of the coolant paths would be overcooled. Each coolant regulating valve has a minimum valve area, sized so that if all four valves are at their minimum, the turbopump will always be able to supply sufficient hydrogen for combustion.

An elementary schematic of the plumbing for the injector system is shown in the lower half of Figure 4.3-1. The inner and outer sections of the number one injector are fed in parallel. For injectors number two and three the plumbing is somewhat different. The inner sections of these injectors are fed in series with the outer injection manifolds. Further discussion and analyses are given in Section 5.1.2 of this report.

5. ANALYTICAL EFFORT

5.1 INTRODUCTION

The analytical effort for this reporting period was concentrated in four specific areas: (1) fuel injector studies, (2) turbopump studies, (3) temperature control studies, and (4) a turbopump start-up study.

The fuel injector studies indluded the analog computer analysis and also a digital computer Z-transform analysis. The analog computer study of injectors 2 and 3 was completed. The study indicated that the second and third injectors will respond more slowly than injector 1 (e.g., settling times of 0.8 sec as opposed to 0.5 sec), and also that wide variations in coolant temperature (1600^0 to 800^0R) will cause a further increase in settling time (to about 1.0 sec). The analysis of the first injector was completed on the digital computer. The study verified the analog computer results (by producing a compensation scheme similar to a digital integrator), and also provided a check run for software to be used in more complex analyses.

The study of the turbopump included analog model studies and a brief linearized analysis. The purpose of this analysis was to evalute the reaction of the turbopump as a pressure control device, when coupled with the regenerative cooling system.

The temperature control study has used an integrated "analog computer/digital computer" approach. The complete analog model (including turbopump) was frequency response tested to provide information for the digital computer analysis. The digital analysis was completed.

The purpose of the start-up study was to determine the time required for the turbopump to start up after the opening of the purge valve. The study indicated that the start-up time would be about 0.2 sec.

The analog simulation of the first injector was reported in the Fifth Control System TDR. Since then, the second and third injectors have been studied, and the results are presented in Section 5.1.2.

5.1.1 Fuel Injector Study

The fuel injector analytical study consisted of the following sequential steps: (1) an analysis was made of the basic dynamics of the uncompensated system, (2) an analysis was made of the effect of sampling rate, and (3) a digital compensation scheme was designed.

5.1.1.1 Linear Model

The basic fuel injector system consists of valves, manifolds, and lines which behave in a nonlinear manner. The system is therefore characterized by a set of nonlinear equations which do not lend themselves to analysis. It was therefore necessary to initiate the analysis with the development of a linear model. This was accomplished by observing the step response of a nonlinear analog model and making a linear fit to that response. The transfer function of the linear model is shown in Equation (5-1).

$$W/A = \frac{62.690}{(S + 9.45)\ (S + 49.02)} \quad K_{ss} = 135.3 \qquad (5\text{-}1)$$

5.1.1.2 Analysis of Basic Dynamics

As can be seen from Equation (5-1) the basic dynamics consist of two first order lags, the larger lag ($\tau = 0.106$) being due to the valve and the smaller ($\tau = 0.020$) being due to the plumbing. In addition to the valve and plumbing, the complete system includes a zero order hold circuit and a digital compensator. The complete system is shown in Figure 5.1-1. The dynamics of the uncompensated system were analyzed by first performing an S to Z transformation of the the system (with $\tau = 0.10$ sec) and then constructing a Z-plane root locus. (Both operations were accomplished with existing digital computer programs.)

The result of the S to Z transformation is presented below in transfer function form and is shown in Figure 5.1-2 in graphical form.

$$G_{ho}(Z)G(Z) = \frac{70.5\ (Z + 0.166)}{(Z - 0.3886)(Z - 0.0074)}$$

The effect of increasing gain on the uncompensated closed loop poles is illustrated in Figure 5.1-2. As the gain is increased, the two aperiodic poles move toward each other, meet, and breakaway to form a complex pair. As the gain is further increased, the complex pair move in a circular manner about the left-half plane zero. At very large gains, the complex pair become aperiodic, one approaching the zero, the other approaching negative infinity. The marginal gain (the gain at which the locus crosses the unit circle) is approximately 0.025, which is equivalent to an overall system steady-state gain of 0.025 x 135.3 = 3.4. If a damping ratio of 70 percent is desired, then the gain would obviously yield unacceptable performance and thus more than simple gain adjustment is called for.

5.1.1.3 Effect of Sampling Rate

It has been shown that acceptable performance can not be realized by simple gain adjustment. In this section, the possibility of improving performance by adjusting the sampling rate will be discussed.

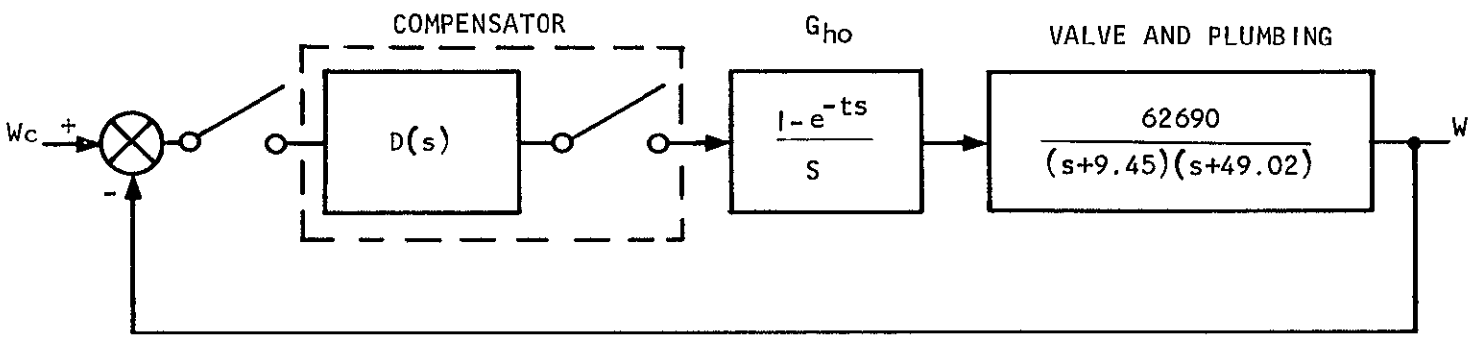

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Figure 5.1-1. Fuel Injector System Block Diagram

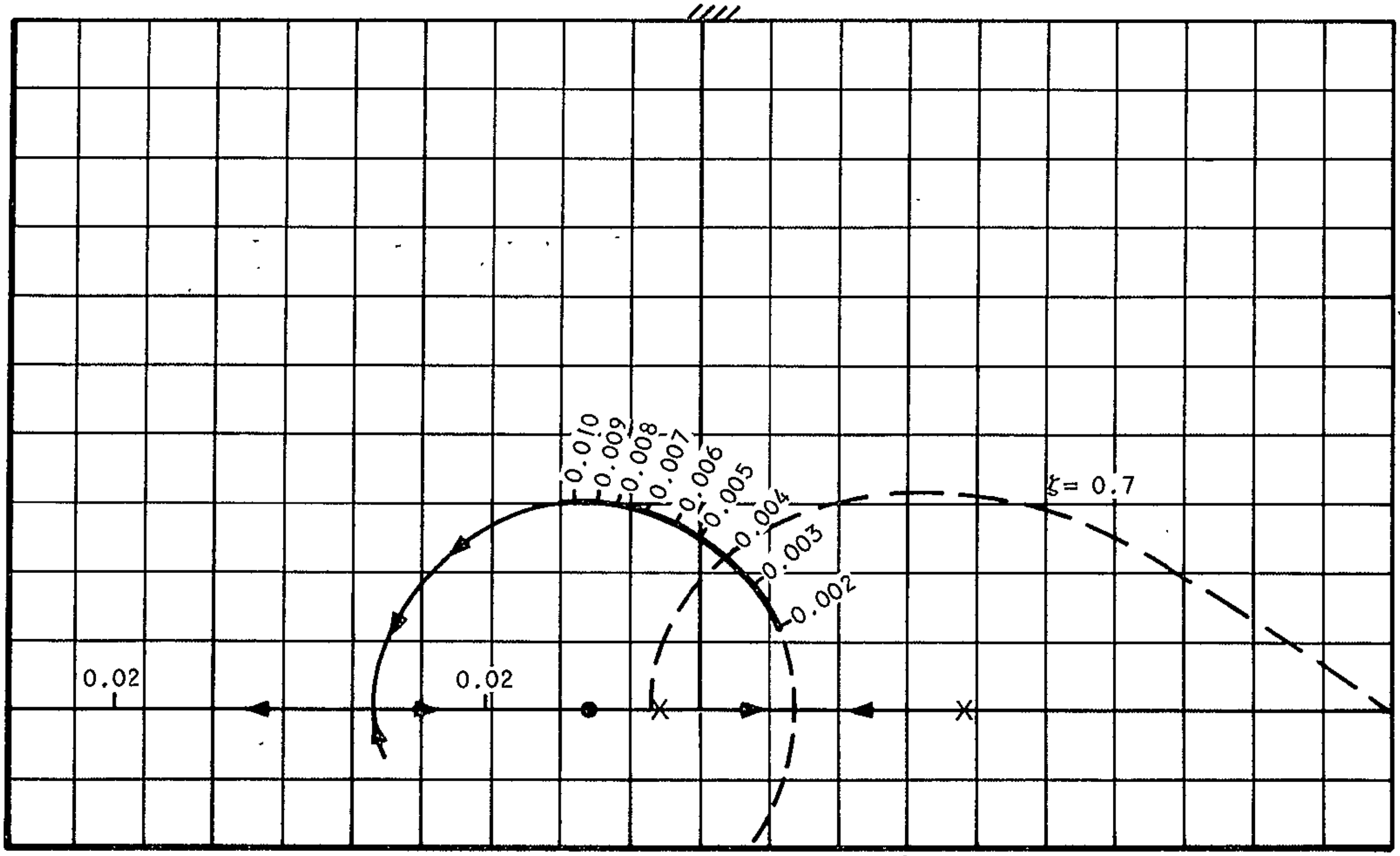

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Figure 5.1-2. HRE Fuel Injectors Basic Dynamics

The effect of sampling rate was assessed by first performing an S to Z transformation on the open loop transfer function for various values of the sampling rate, and then constructing a root locus on the resulting Z-plane transfer functions. A summary of the results is presented in Figure 5.1-3 as a plot of maximum stable gain vs sampling period. As can be seen from Figure 5.1-3, the increase in allowable gain with increasing sampling rate is small until the sampling rate is increased to 100 samples/sec. Thereafter, the increase is dramatic. In summary then, it can be stated that there would be little reason to burden the computer with increased sampling unless 100 or more samples/sec could be accomplished.

5.1.1.4 Design of Compensation

No criteria (such as natural frequency, damping ratio, setting time, ripple factor, etc.) have been established for the performance of the fuel injector control system. Thus, the compensator cannot truly be synthesized but rather must be selected somewhat arbitrarily. An examination of the root locus of the fuel injector system basic dynamics indicates that the frequency at the point the locus crosses the 70-percent damping ratio line is adequate (approximately 2 Hz), but that the gain is much too low. Intuitively, one feels that if the gain could be increased significantly, while maintaining the frequency and damping ratio, the system performance would be accepatable.

The compensation selected to achieve the above goals was a first-order lag configuration of the following form:

$$D(Z) = \frac{0.0349\ (Z - 0.429)}{(Z - 0.98)} \quad K_{ss} = 1.0$$

The effect of increasing gain on the compensated fuel injector closed loop poles is shown in Figure 5.1-4. As can be seen by comparing Figures 5.1-4 and 5.1-2, the addition of the open loop compensator pole and zero have not significantly altered the shape of the loci, but have greatly increased the gain at the point where the locus crosses the 70-percent damping ratio line. The increase in gain at this point is approximately a factor of 60 (0.004 to 0.25) while the frequency is about the same (2 Hz). This system should yield satisfactory performance. If significantly higher performance is required, an increase in the sampling rate, and/or a more complex form of compensation, would probably be required.

5.1.2 Injectors 2 and 3 - Analog Study

A diagram of the plumbing for the injector system is shown in the lower half of Figure 4.3-1. The inner and outer sections of injector 1 are fed in parallel. For injectors 2 and 3 the inner sections are fed in series with outer injection manifolds. For the use of this study, it is assumed that the fuel is supplied from the main fuel plenum at 500 psi and 1600^{0}R. Fuel flow into the injector manifolds is controlled by a servo valve whose dynamic response can be described by a first-order time constant. The fuel is treated as a compressible fluid. It is further assumed that fuel flow is measured at the injectors, so that measured fuel flow and actual fuel flow are essentially identical.

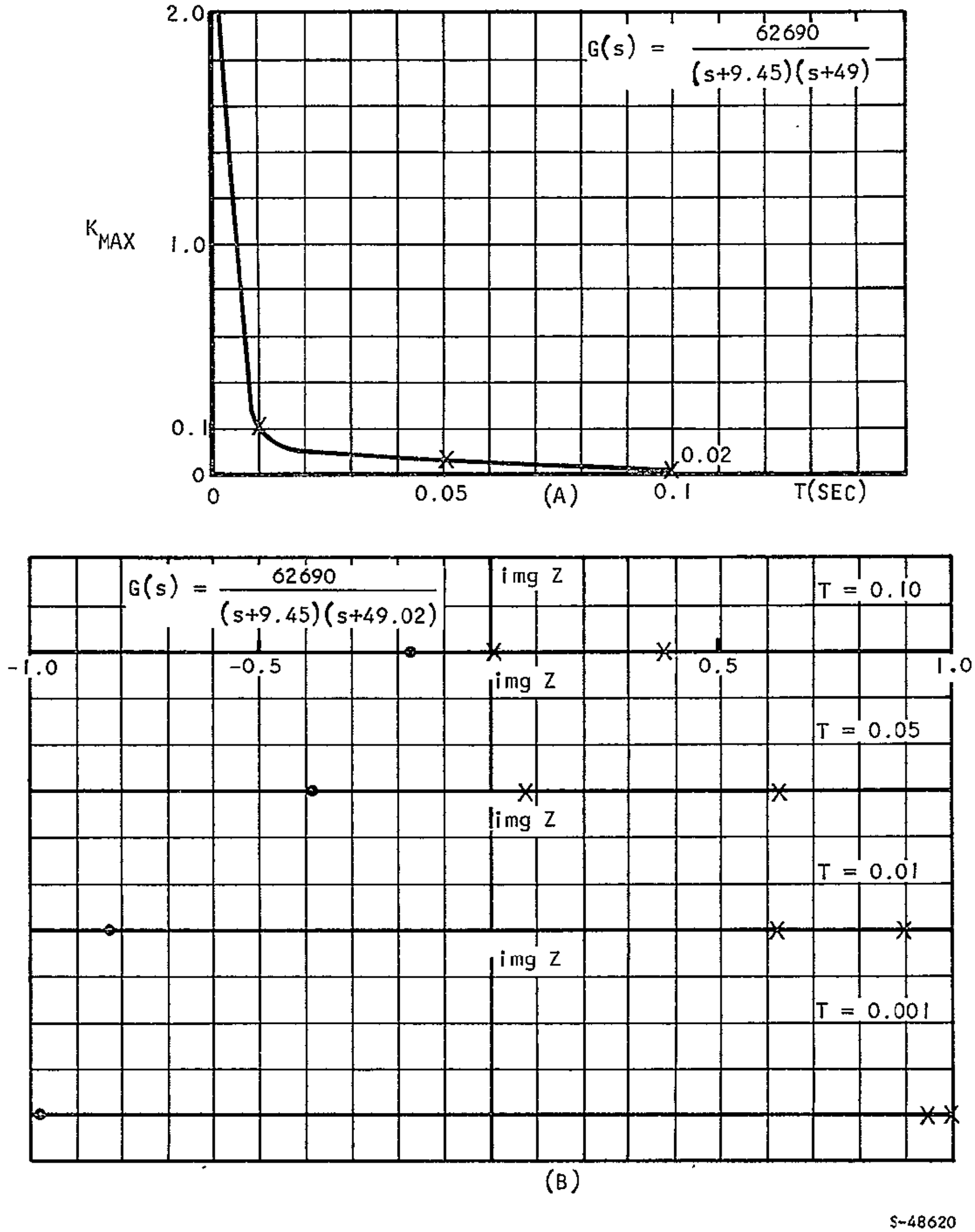

Figure 5.1-3. HRE Fuel Injectors

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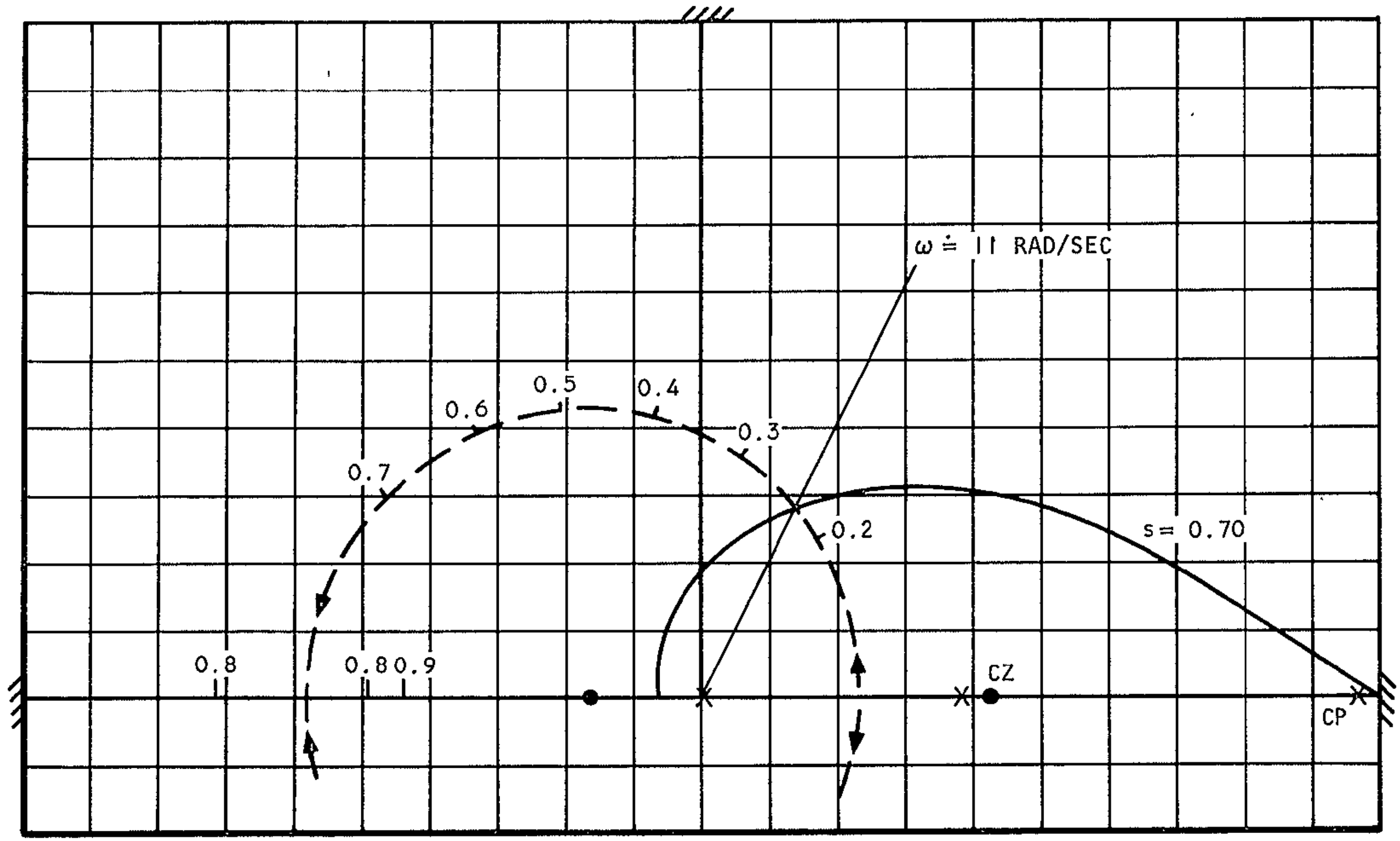

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Figure 5.1-4. HRE Fuel Injectors Basic Dynamics and Phase-Lag

The injector system as a whole is in series with the cooling system as indicated in Figure 4.3-1.

Injectors 2 and 3 have the same mechanical simulation although with different sizes, flows, pressures, etc. The same analog model was therefore used for both injectors but with different values. The same assumptions were made as for injector 1 (q.v.) with the exception that although fuel temperature was assumed constant throughout the system, two different temperatures were studied.

From the physical system a simplified mechanical drawing was produced and a set of equations describing the system were derived. The drawing for injector 3 is shown in Figure 5.1-5, and the equations in Table 5.1-1. The data for injector 2 is identical except that all suffixes (with the exception of P_{21} and T_{21} are decreased by 10. (e.g.: Line 31 and P_{32} would be Line 21 and P_{22}).

The next step was to construct a mathematical model of the system which is shown in Figure 5.1-6. The loop closing computer is not shown on this diagram. The inboard flow, W_{32}, was measured and fed back to the controller which positioned the valve. Therefore, the demanded flow had to be equal to the desired inboard flow, since in the steady state the ratio of inboard to outboard flow is a constant.

The scaling of the problem and the analog computer mechanization are given in Appendix A.

The steady-state values of parameters were compared to hand calculated values and total agreement was achieved. Only one control system was studied, namely the digital integrator system which was found to be successful with injector 1. The desired transfer function of the controller was

$$\frac{R}{C} = \frac{k_I}{s}$$

where C is the controller input and R the response. This may be written as

$$sR = k_I C$$

The following approximation was then made--where the suffixes (t_1) and (t_2) denote sampling periods, (t_2) being the sample immediately following (t_1):

$$\frac{R(t_2) - R(t_1)}{T_s} = k_I \; C(t_2)$$

T_s is the sampling period. Thus,

$$R(t_2) = T_s k_I \; C(t_2) + R(t_1)$$

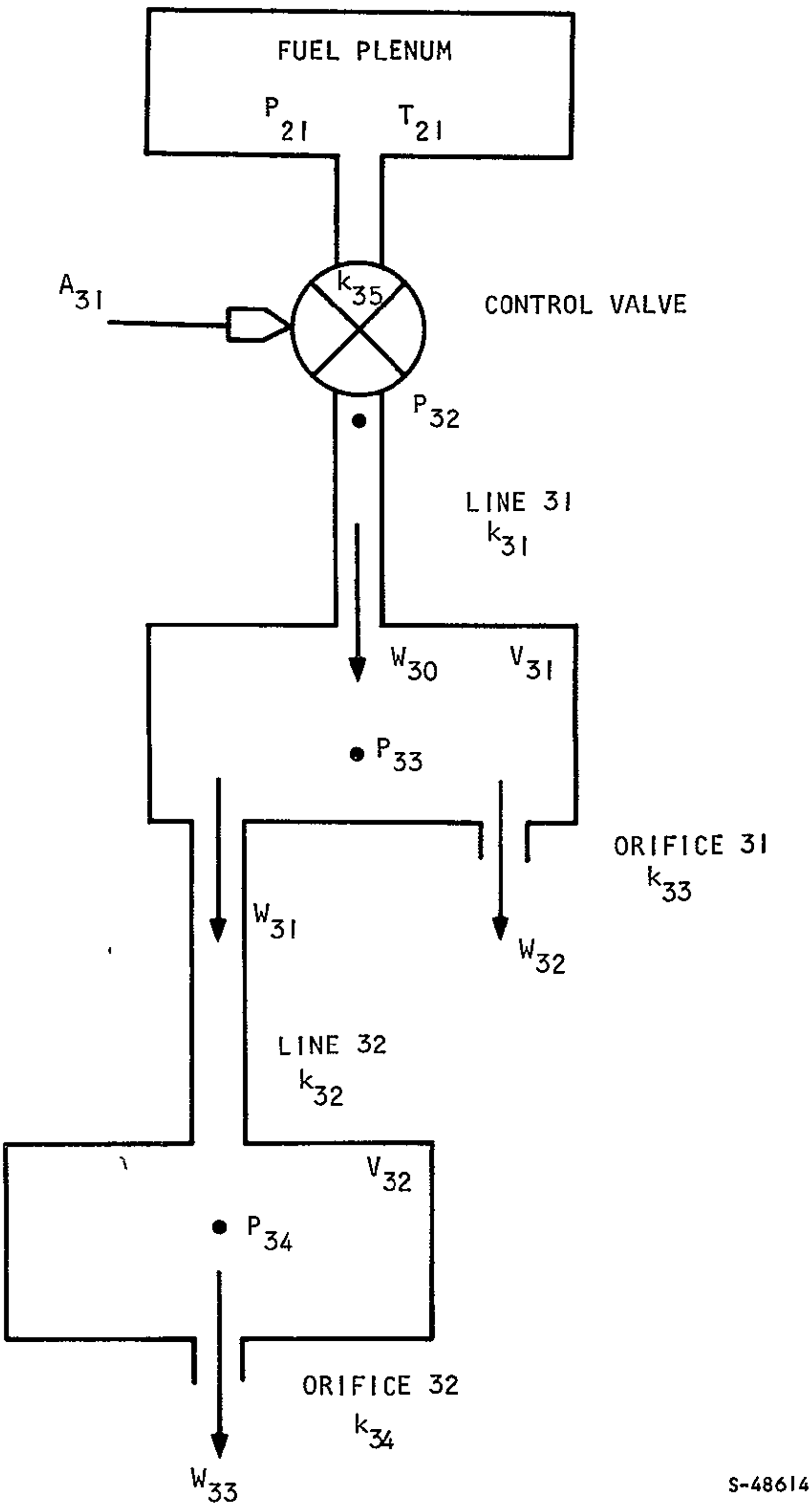


Figure 5.1-5. Injector No. 3

TABLE 5.1-1

EQUATIONS

Control Valve

$$W30 = \frac{k_{35}\ C}{\sqrt{T_{21}}} \cdot A_{31} \cdot N \cdot P_{21}$$

$$N = f\left(\frac{P_{32}}{P_{21}}\right)$$

Line 31

$$P_{32} = \sqrt{\frac{W_{30}^{2}}{k_{31}^{2}} + P_{33}^{2}}$$

Line 32

$$W_{31} = k_{32}\sqrt{P_{33}^{2} - P_{34}^{2}}$$

Manifold 31

$$P_{33} = \frac{RT_{31}}{V_{31}} \int (W_{30} - W_{31} - W_{32})\ dt$$

Manifold 32

$$P_{34} = \frac{RT_{21}}{V_{31}} \int (W_{31} - W_{33})\ dt$$

Orifice 31

$$W_{32} = k_{33}\ P_{33}$$

Orifice 32

$$W_{33} = k_{34}\ P_{34}$$

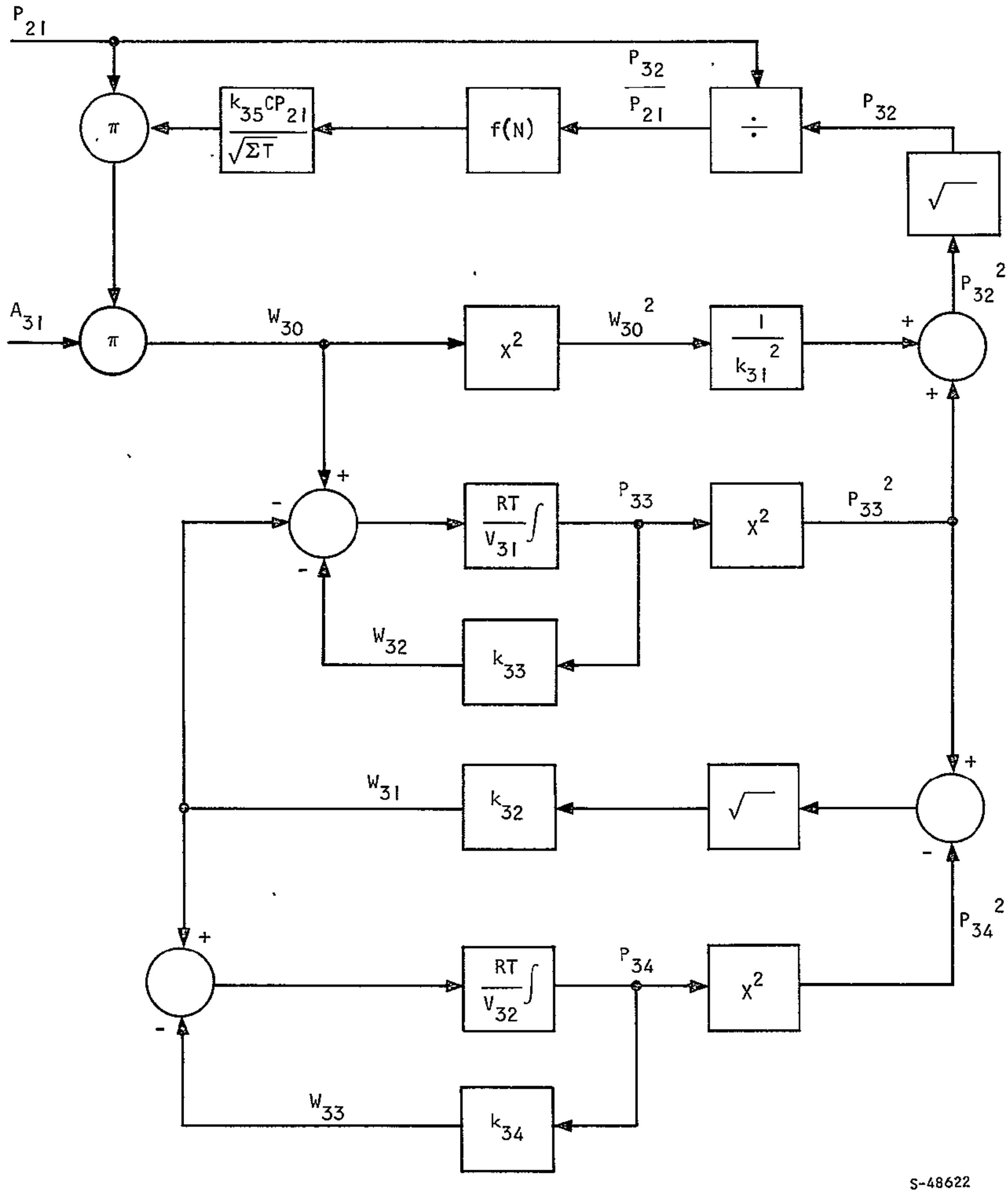


Figure 5.1-6. Mathematical Model Injector No. 2

A delay was also built into the controller to simulate the time which the HRE computer takes to calculate fuel flow.

5.1.2.1 Results, Injector 2.

The conditions below and above Mach 6 were studied. In each case a flow of 0.4434 lb/sec was commanded. This gives an outboard flow of 0.5 lb/sec responses were measured on the outboard flow. The parameter k below equals $T_s k_1$.

Below Mach 6, the sampling rate was 30 samples/sec and the computation delay 12 msec. At each of two temperatures, the value of k was found which gave a 2-percent overshoot. The settling time is τ_s.

$T = 740^0R$

1. k = 0.023 Overshoot = 2 percent τ_s = 0.86 sec

$T = 1600^0R$

2. k = 0.023 Overdamped τ_s = 1.8 sec

3. k = 0.043 Overshoot = 2 percent τ_s = 0.63 sec

$T = 740^0R$

4. k = 0.045 Overshoot = 16 percent τ_s = 0.91 sec

The responses for trials 1 and 3 are shown in Figure 5.1-7 and 5.1-8, respectively.

The effect of varying valve dynamics was also studied. The assumed 2 Hz valve was replaced by one of 1 Hz and one of 5 Hz. The results are shown below.

$T = 740^0R$

k = 0.023

2 Hz valve	Overshoot = 2 percent	τ_s = 0.86 sec
1 Hz valve	Overshoot = 10 percent	τ_s = 1.68 sec
5 Hz valve	Overdamped	τ_s = 1.02 sec

The same series of tests was then conducted at the above Mach 6 conditions. In this case, the sampling rate was 20 samples/sec and the compute time was 33 msec.

$T = 740^0R$

k = 0.031 Overshoot = 2 percent τ_s = 0.9 sec

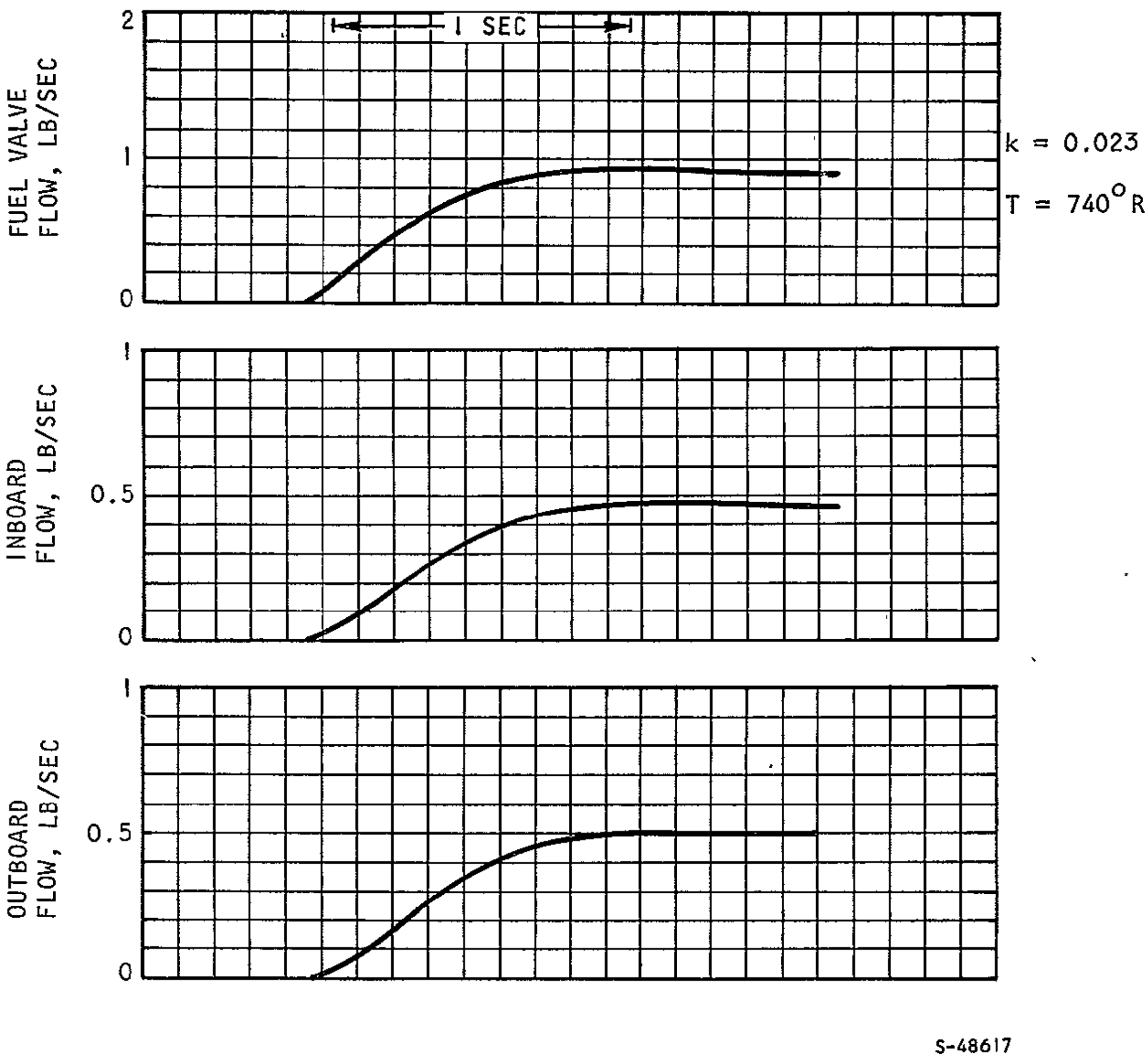


Figure 5.1-7. Flow Responses

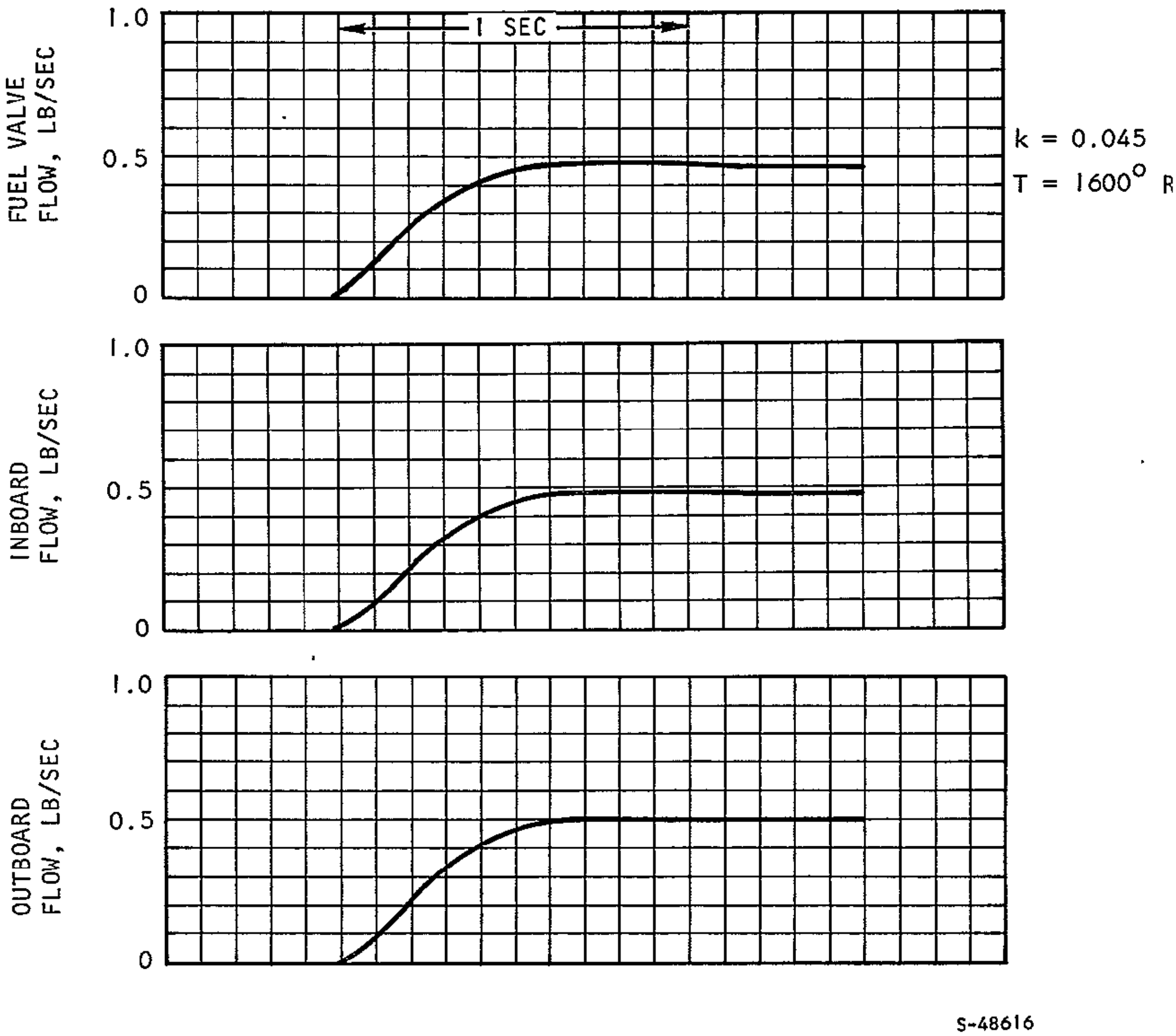


Figure 5.1-8. Flow Responses

T = 1600°R

k = 0.031 Overdamped τ_s = 2.0 sec

k = 0.060 Overshoot = 2 percent τ_s = 0.7 sec

T = 740°R

k = 0.05 Overshoot = 21 percent τ_s = 1.53 sec

k =0.031

1 Hz valve Overshoot = 9 percent τ_s = 1.82 sec

5 Hz valve Overshoot = 0.0 percent τ_s = 1.1 sec

The effect of valve dynamics on responses are shown in Figure 5.1-9 for the greater than Mach 6 conditions.

5.1.2.2 Results, Injector 3

Injector 3 is only operational above Mach 6 and therefore, only this condition had to be studied. An inboard flow of 0.2681 lb/sec was commanded, which gave an outboard steady-state flow of 0.3 lb/sec. The sampling rate was 20 samples/sec and the compute time 22 msec.

T = 990°R

k = 0.1175 Overshoot = 2 percent τ_s = 0.74 sec

T = 1600°R

k = 0.1175 Overdamped τ_s = 1.15 sec

k = 0.1685 Overshoot = 2 percent τ_s = 0.62 sec

T = 990°R

k = 0.1685 Overshoot = 10 percent τ_s = 1.0 sec

k = 0.1175

1 Hz valve Overshoot = 11 percent τ_s = 1.68 sec

5 Hz valve Overshoot = 0.0 percent τ_s = 0.98 sec

The responses for Trials 1, 3, 5, and 6 are shown in Figure 5.1-10.

5.1.2.3 Conclusions

The tests on injectors 2 and 3 proved the suitability of the digital integrator control system in each case. For a given temperature and

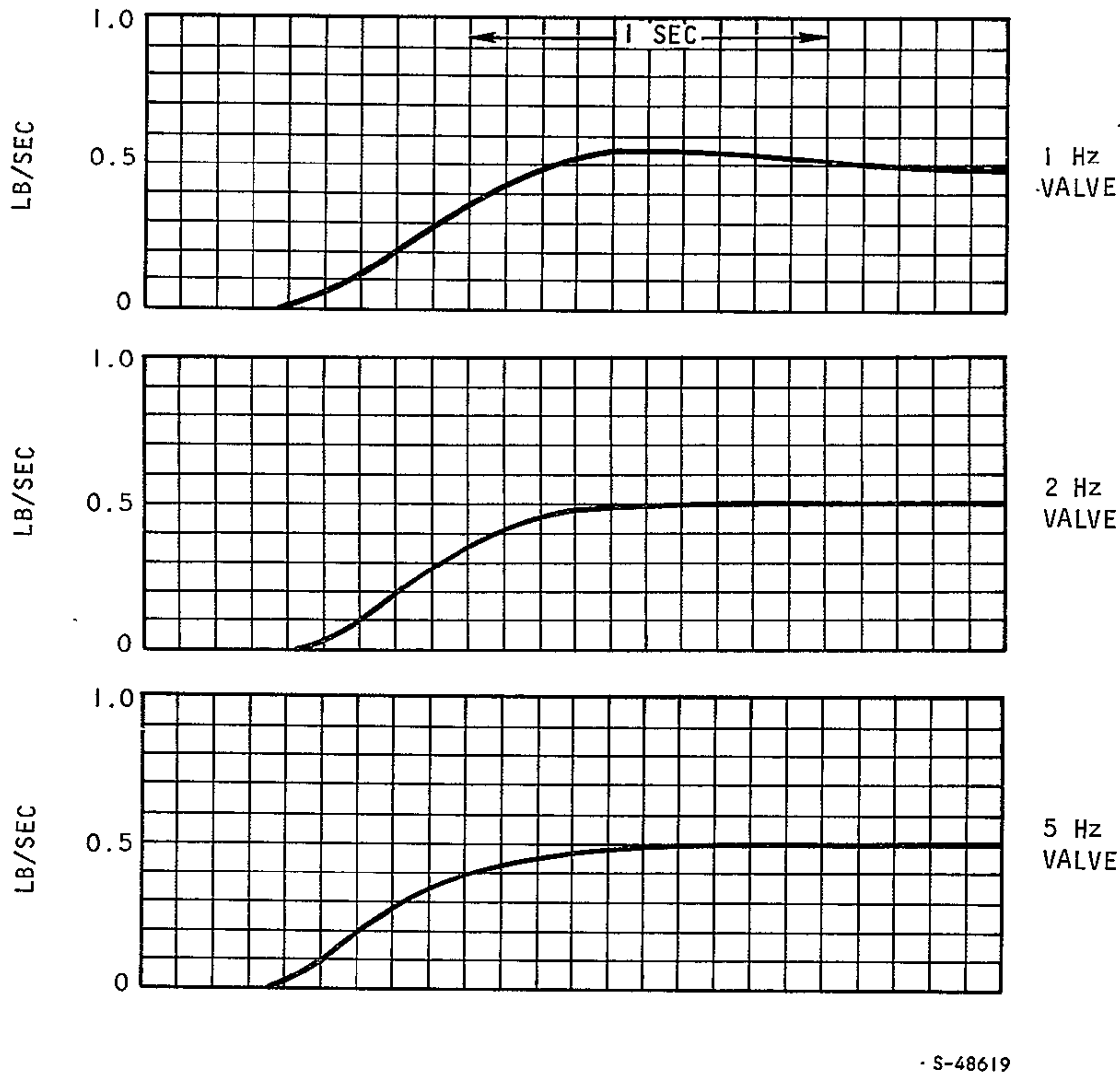


Figure 5.1-9. Outboard Fuel Flows

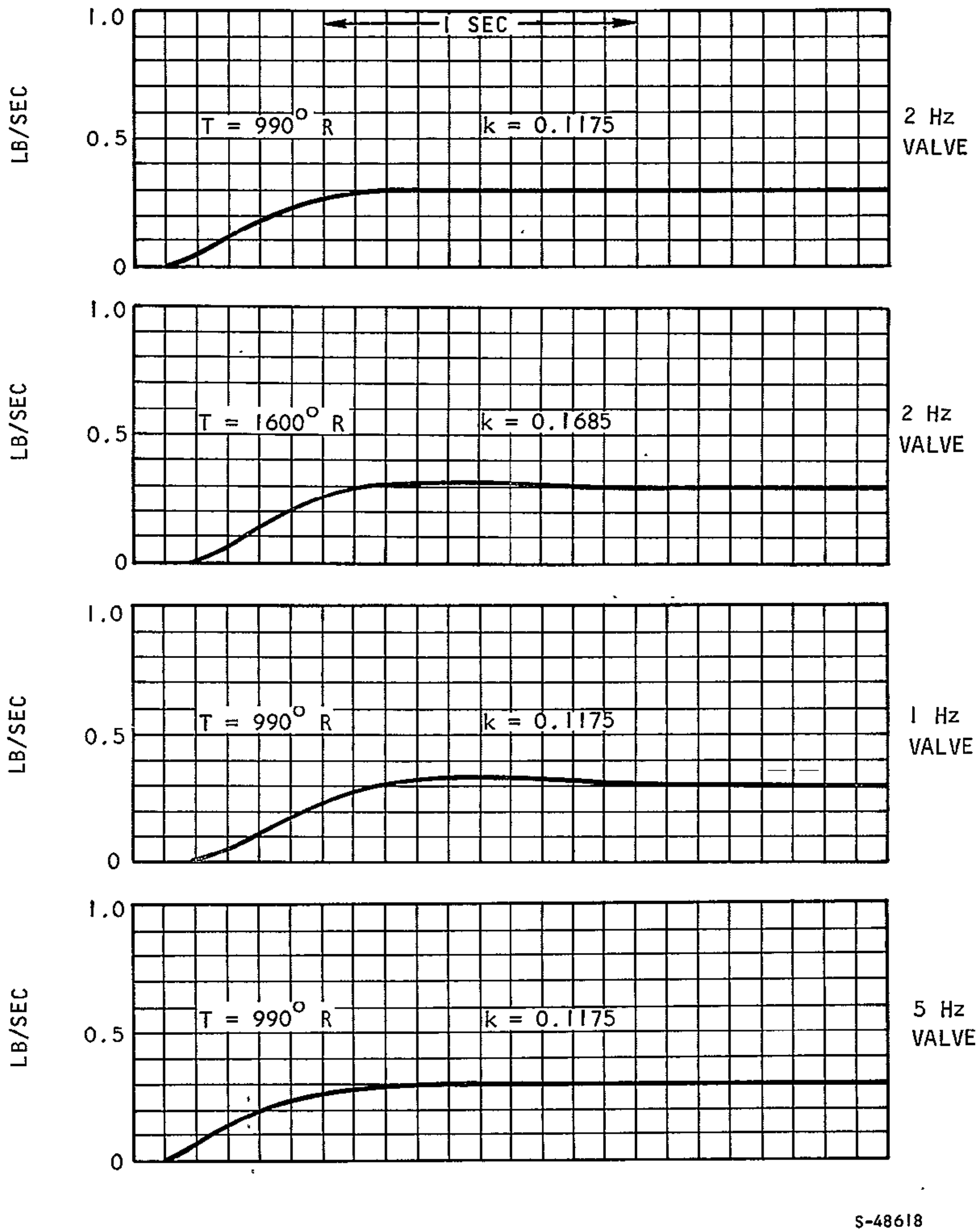


Figure 5.1-10 Outboard Flows, Injector No. 3

computation delay, there is a unique value, k, which will give any desired response in terms of dampening and settling time. If it is found that varying k is an impracticable approach to compensate for temperature and/or computation delay variations, then a value will have to be found which will give acceptable results under all conditions.

5.2 TURBOPUMP STUDY

5.2.1 Approach

This study can be separated into four phases: (1) development of a model; (2) verification of the model; (3) analysis of the turbopump with the simplified system; and (4) analysis of the turbopump with the controlled system.

Model development resulted in a pair of transfer functions which described the response of the turbopump discharge pressure to changes in controlled pressure or to changes in turbopump flow. These transfer functions were verified by comparison with frequency response data that was obtained from the analog computer model.

The simplified system is shown schematically in Figure 5.2-1. By using this system as a proxy for the regenerative cooling system, it is possible to perform relatively simple analyses, and establish rough standards of performance for the turbopump.

The test phase of the analysis would be the determination of the frequency response characteristics of the regeneratively cooling system with the temperature controls. This information would be used to set values for turbine control valve gain and speed of response.

5.2.2 Linearized Turbopump Model

A block diagram for the linearized turbopump model is shown in Figure 5.2-2. G_1 is a transfer function which describes what would happen to turbopump discharge pressure (P_{40}) if the controlled pressure (P_{44}), is changed while turbopump flow (W_{40}) is held constant. G_2 determines what would happen to P_{40} if W_{40} was changed while P_{44} is held constant. The form of the transfer functions was found to be

$$G_1 = \frac{K(\tau S - 1)}{(\tau_1 S + 1)(\tau_2 S + 1)(\tau_3 S + 1)}$$

$$G_2 = \frac{K_1 (\tau_4 S + 1)}{\tau_3 S + 1}$$

G_1 has a zero in the right-half plane. This is due to controlled pressure also being the turbine control valve (TCV) upstream pressure. If this pressure

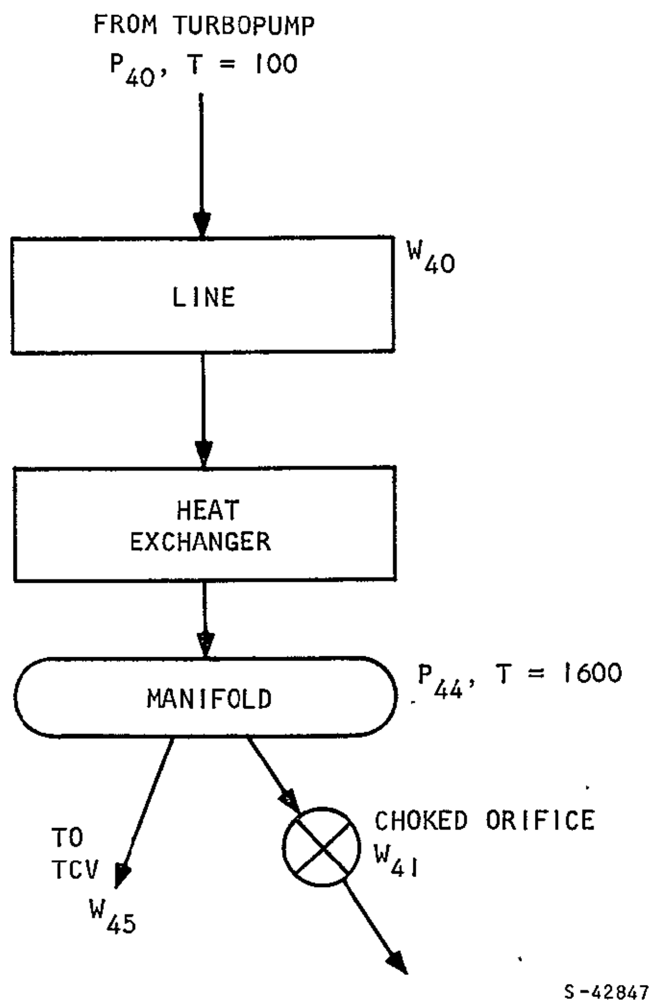
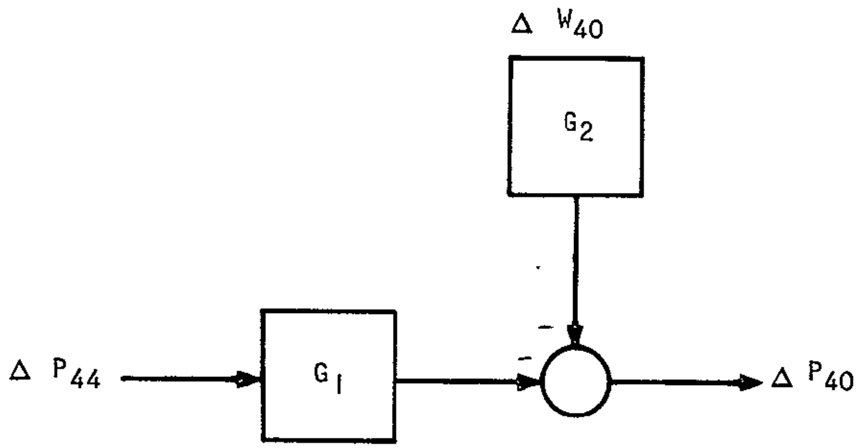


Figure 5.2-1. Simplified Turbine System



P_{40} - TURBOPUMP DISCHARGE PRESSURE

P_{44} - CONTROLLED PRESSURE

W_{40} - TURBOPUMP FLOW

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Figure 5.2-2. Turbopump Block Diagram

(P_{44}) increases, the immediate effect is to increase turbine flow. The valve senses the increased pressure, and subsequently decreases the valve area, so that TCV flow is decreased. Thus, an increase in P_{44} causes an immediate increase but an eventual decrease in TCV flow. This effect shows up in the linearized model as a right-half plane zero. The time constant (τ) for this effect is quite small, and the zero is of little consequence.

The values of the gains and time constants for the Mach flight condition are

$$K = 25 \text{ psi/psi}$$

$$K_1 = 283 \text{ psi/lb/sec}$$

$$\tau = 1.58 \times 10^{-3} \text{ sec at 101 Hz}$$

$$\tau_1 = 1.44 \times 10^{-2} \text{ sec at 11 Hz}$$

$$\tau_2 = 4.69 \times 10^{-4} \text{ sec at 340 Hz}$$

$$\tau_3 = 2.74 \times 10^{-1} \text{ sec at 0.596 Hz}$$

$$\tau_4 = 3.46 \times 10^{-2} \text{ sec at 4.62 Hz}$$

The effects of τ and τ_2 occur at such high frequencies compared to the other terms that they can be neglected; i.e., the approximations

$$\tau \approx 0$$

$$\tau_2 \approx 0$$

can be made.

5.2.3 Analog Computer Tests

Frequency response tests were conducted on the analog computer to verify the calculated transfer functions G_1 and G_2. The gain frequency response of G_1 is shown in Figure 5.2-3. The linear model predicts that:

$$G_1 = \frac{25}{(0.0144\ S + 1)\ (0.274\ S + 1)}$$

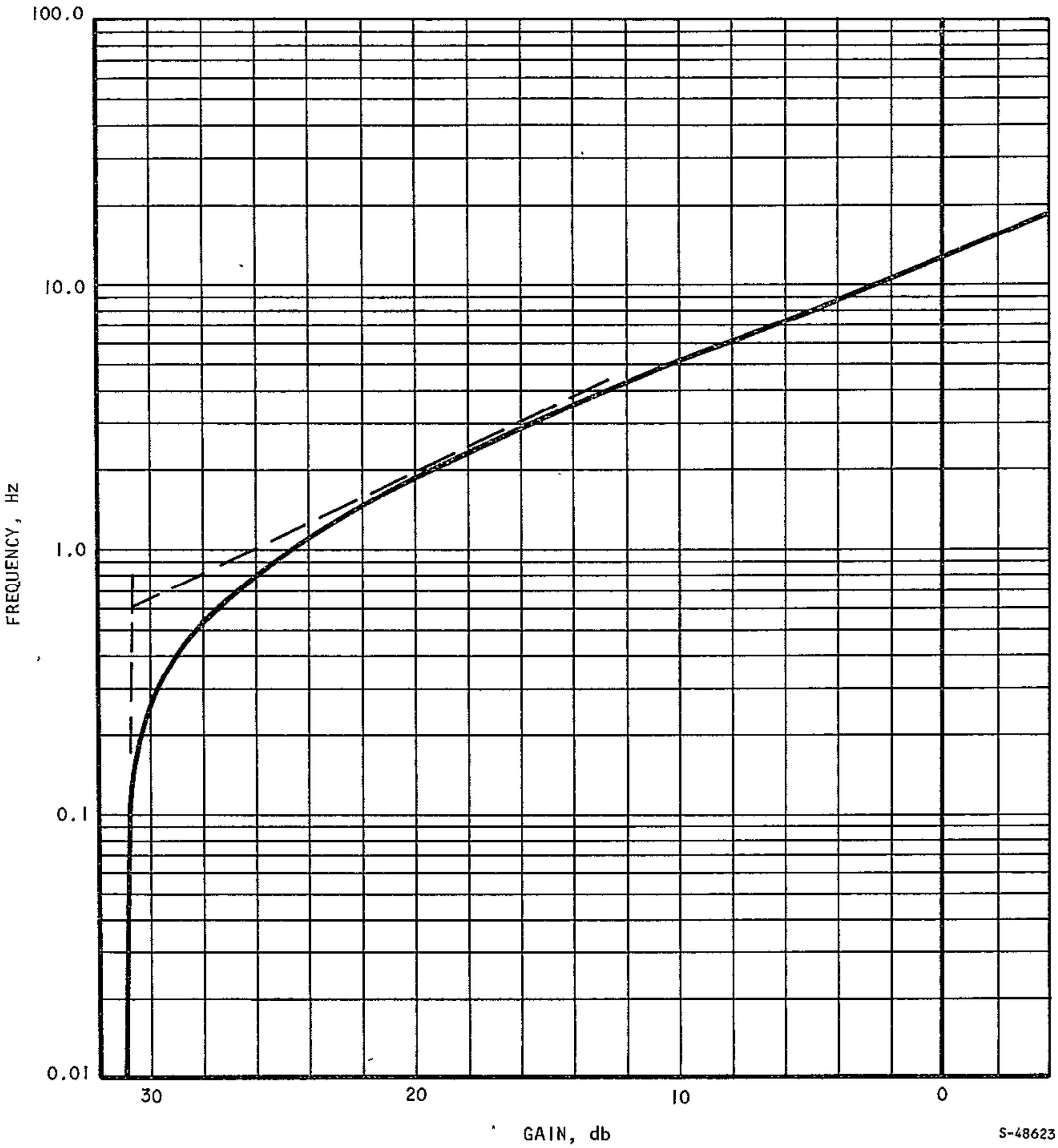

Figure 5.2-3. P_{40}/P_{44}; Analog Computer

The steady-state gain is 25 psi/psi. This corresponds to 28 db. The measured steady-state gain is 31 db, or a gain of about 35.2 psi/psi. This inconsistency has not been reconciled. The first-order breakpoint shown on the Bode plot occurs at 0.6 Hz. This is in close agreement with the predicted value.

The response of turbopump discharge pressure to changes in turbopump flow is shown in Figure 5.2-4. Both the gain and phase of the response were measured in this run. The predicted transfer function is

$$G_2 = \frac{283\ (0.0346\ S + 1)}{(0.274\ S + 1)}$$

Steady-state gain = 283

$$\text{High frequency gain} = \frac{283 \times 0.0346}{0.274} = 35.8$$

In comparing the low- and high-frequency gains with the analog computer results, the scaling of the computer variables must be taken into account. The gain which was measured in the frequency response test is

$$\frac{\Delta P_{40}/2000}{\Delta W_{40}/10} = \frac{\Delta P_{40}}{\Delta W_{40}} \cdot \frac{1}{200}$$

Thus the measured gains are too small by a factor of 200, or about 46 decibels. The corrected gains are

	Decibels	Psi/Lb/Sec
Low-frequency	49	280
High-frequency	31	35.3

These gains are essentially identical to the calculated values. The calculated breakpoints of 0.6 and 4.62 Hz also agree with the measured transfer characteristic.

Figure 5.2-5 shows steady-state values of turbopump discharge pressure as a function of controlled pressure, for different fixed values of turbopump flows. This graph can be used to determine the value of K for different values of W_{40} and P_{40}. The graph shows distinctly that, as P_{40} and/or W_{40} is decreased, the gain of G_1 will increase greatly. This would indicate that the system stability would decrease for lower flow and pressure conditions.

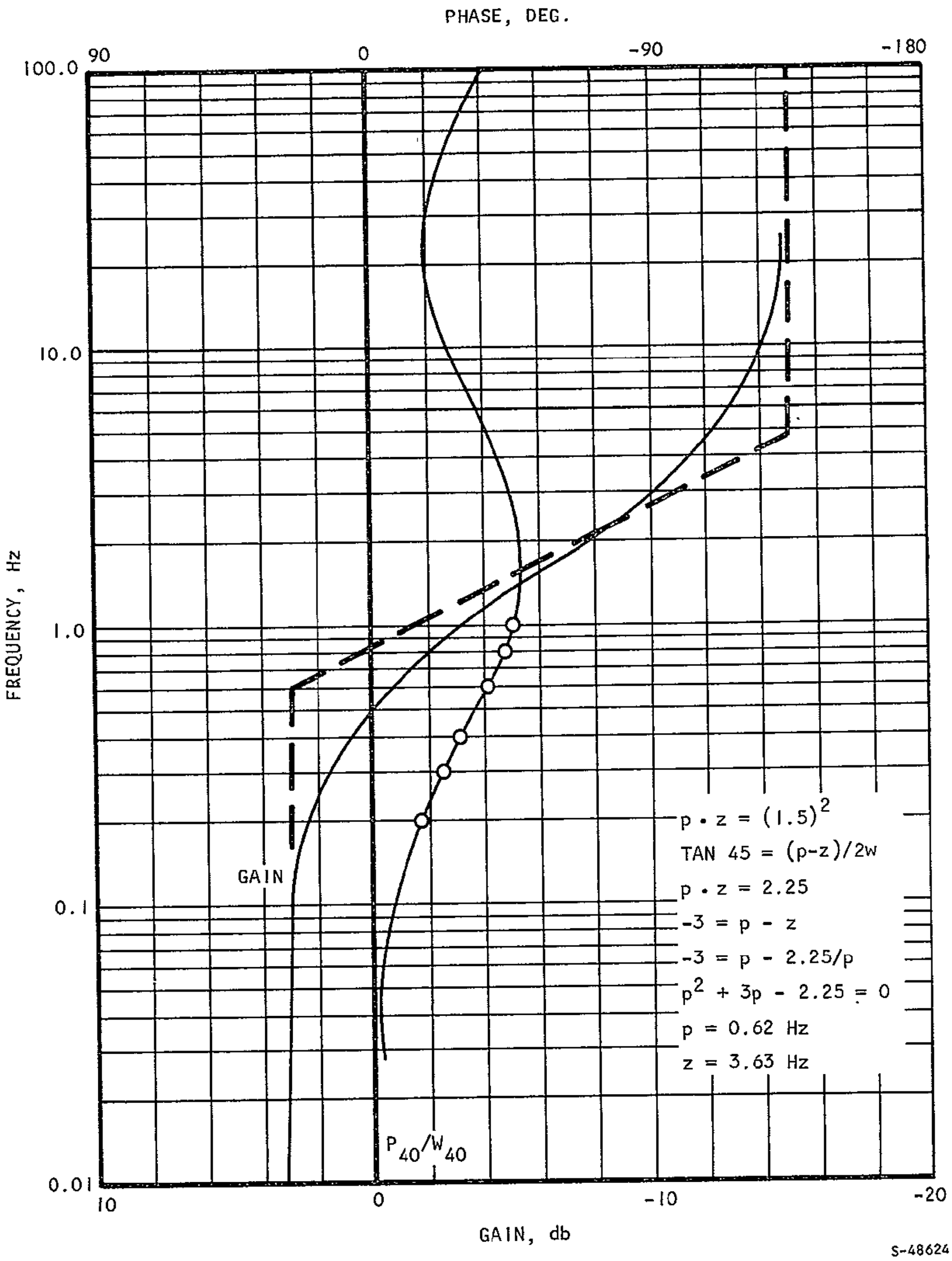

Figure 5.2-4. P_{40}/W_{40}; Analog Computer

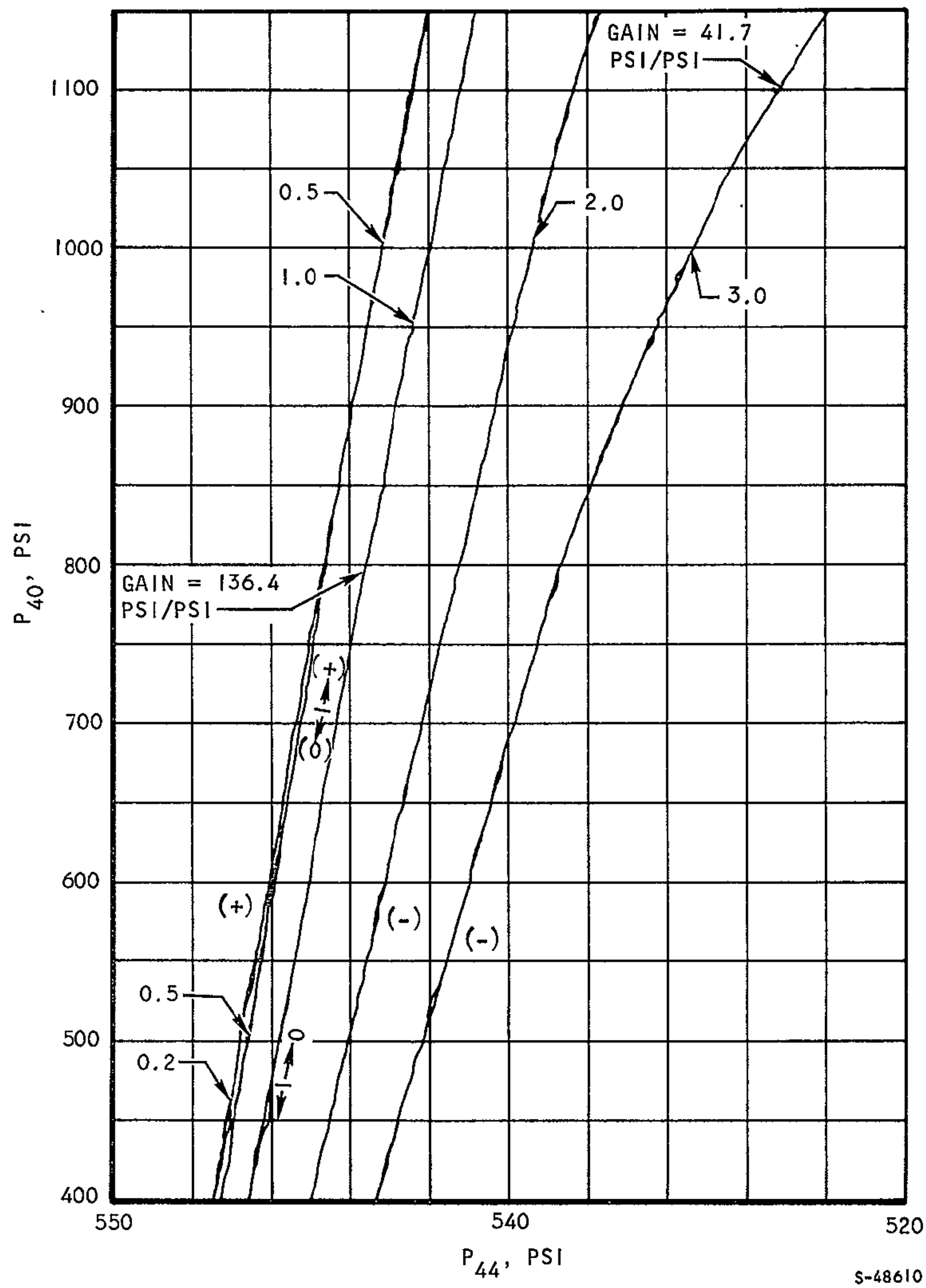

Figure 5.2-5. HRE Turbopump Steady-State Characteristic P_{40} vs P_{44} for Constant Turbopump Flow

The parenthetical symbols (+, -, 0) which mark each graph relate that graph to a region in a turbopump characteristic. That characteristic is the $\Delta P/N^2$ vs W_{40}/N curve, which is shown in Figure 5.2-6. This curve defines the relationship between turbopump pressure, flow, and shaft speed. The curve is shown divided into three regions: one of negative slope (-), one of approximately zero slope (0), and one region of positive slope (+).

Since the operating points for the cooling system fall in all three of these regions, it would be of interest to know if the shape of this curve has any effect on the system characteristics. In the case of G_1, the shape of the curve seems to have little effect on the steady-state gain.

Figure 5.2-7 shows turbopump pressure as a function of turbopump flow. The most striking characteristic of this curve is that the sign of the gain changes in the positive slope region of the $\Delta P/N^2$ curve. In this region, an increase in turbopump flow will cause an increase in turbopump discharge pressure. This should have a destabilizing influence, although its exact effect has not yet been evaluated.

The discontinuous first derivative of this curve is due to the use of a digital function generator in the simulation of the $\Delta P/N^2$ characteristic.

5.2.4 Analysis With The Simplified System

A block diagram representing the turbopump and its interaction with the simplified system is shown in Figure 5.2-8. The simplified system consists of a line, a manifold, and a choked orifice. The line characteritics shows up in the block diagram as the constant K_1' and K_2'. K_1' describes how much flow will increase if upstream pressure increases slightly, and K_2' describes a flow rate decrease for an increase in downstream pressure. The manifold volume, and the manifold temperature decide the integrator gain, K'. Increasing temperature increases K', and increasing volume decreases K'. The orifice size determines the value of K_3', which relates increases in manifold pressure to increases in orifice flow. There are three blocks which describe the turbopump: G_1, G_2, and G_3. G_1 and G_2 have been discussed in previous sections. G_3 relates increases in manifold pressure to increases in turbine flow. Since turbine flow is small compared to turbopump flow (0.2 lb/sec vs 3.0 lb/sec), this effect has been ignored in the following discussions. This approximation will not be valid for flight conditions which call for very small turbopump flows.

A reduced block diagram is shown in Figure 5.2-9. The relevance of this block diagram is that it identifies the data that will be needed for the analysis of the complete system. The three blocks are K_1', K_2', and G_4. To analyze the complete system three frequency response tests on the regenerative cooling model would be made. The tests would be (1) the response

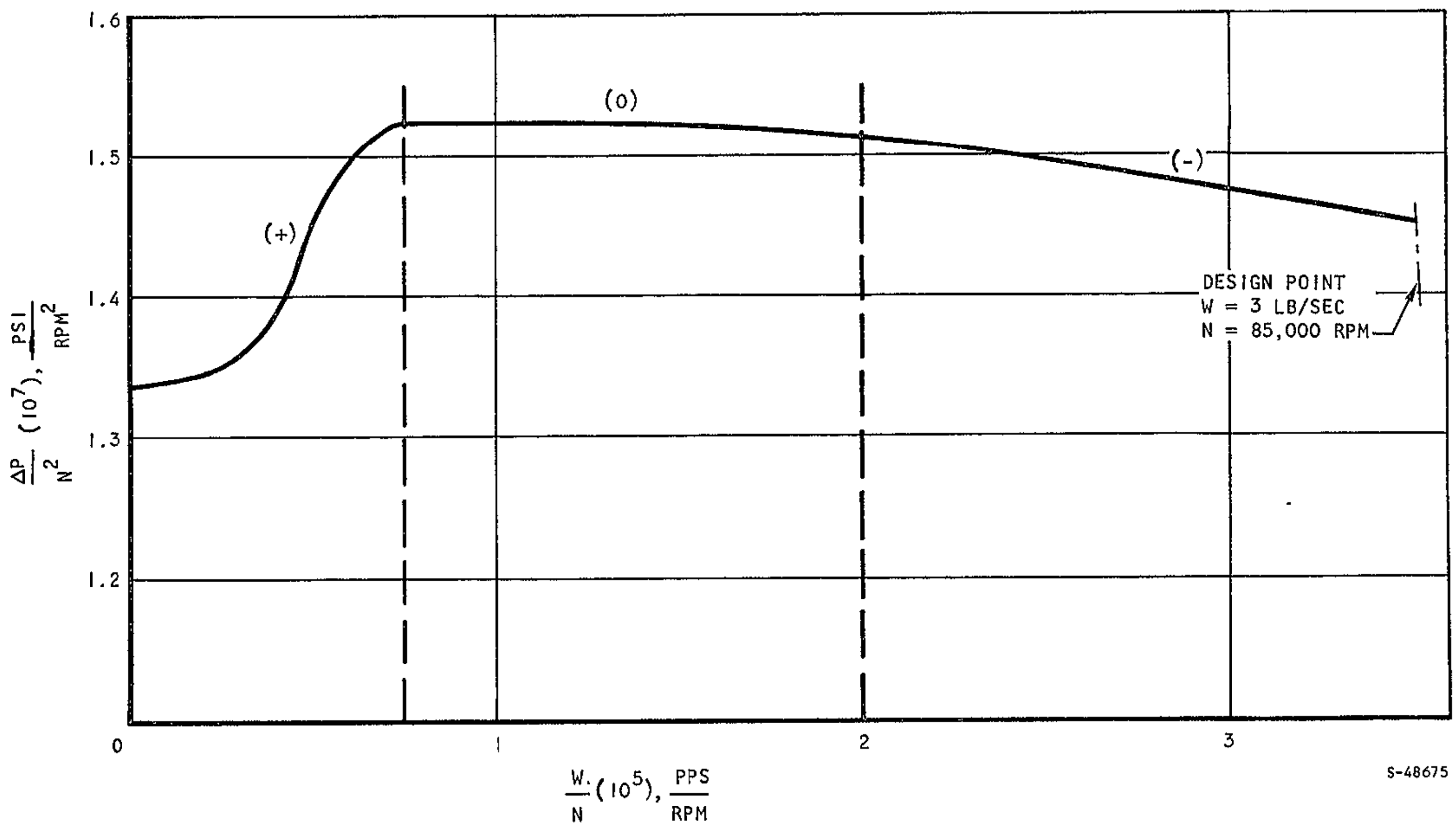

Figure 5-2.6. HRE Fuel Pump Performance

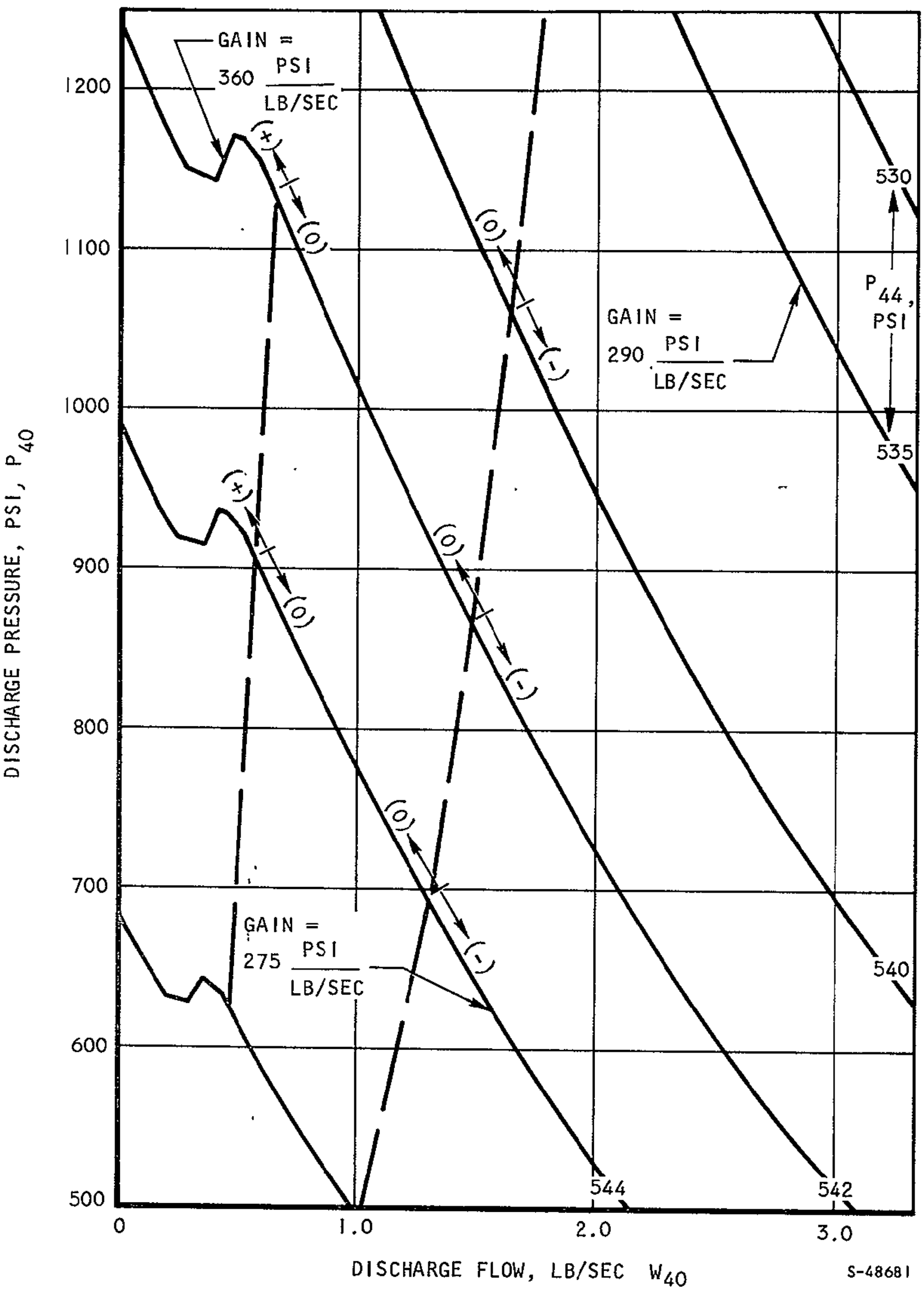

Figure 5.2-7. HRE Turbopump Steady-State Characteristic Discharge Pressure vs Discharge Flow Parameterized by TCV Inlet Pressure

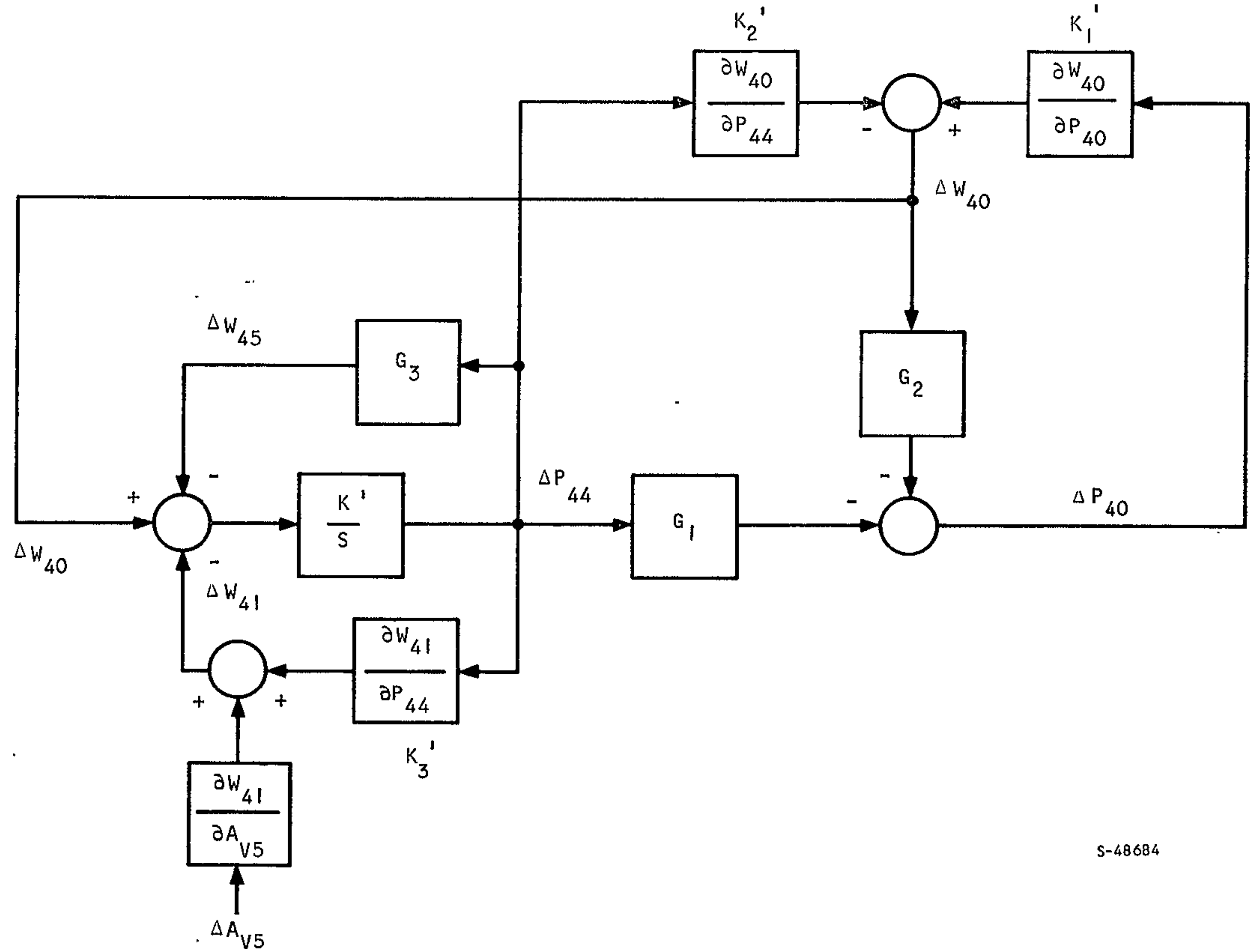

Figure 5.2-8. Turbopump with Simplified System Block Diagram

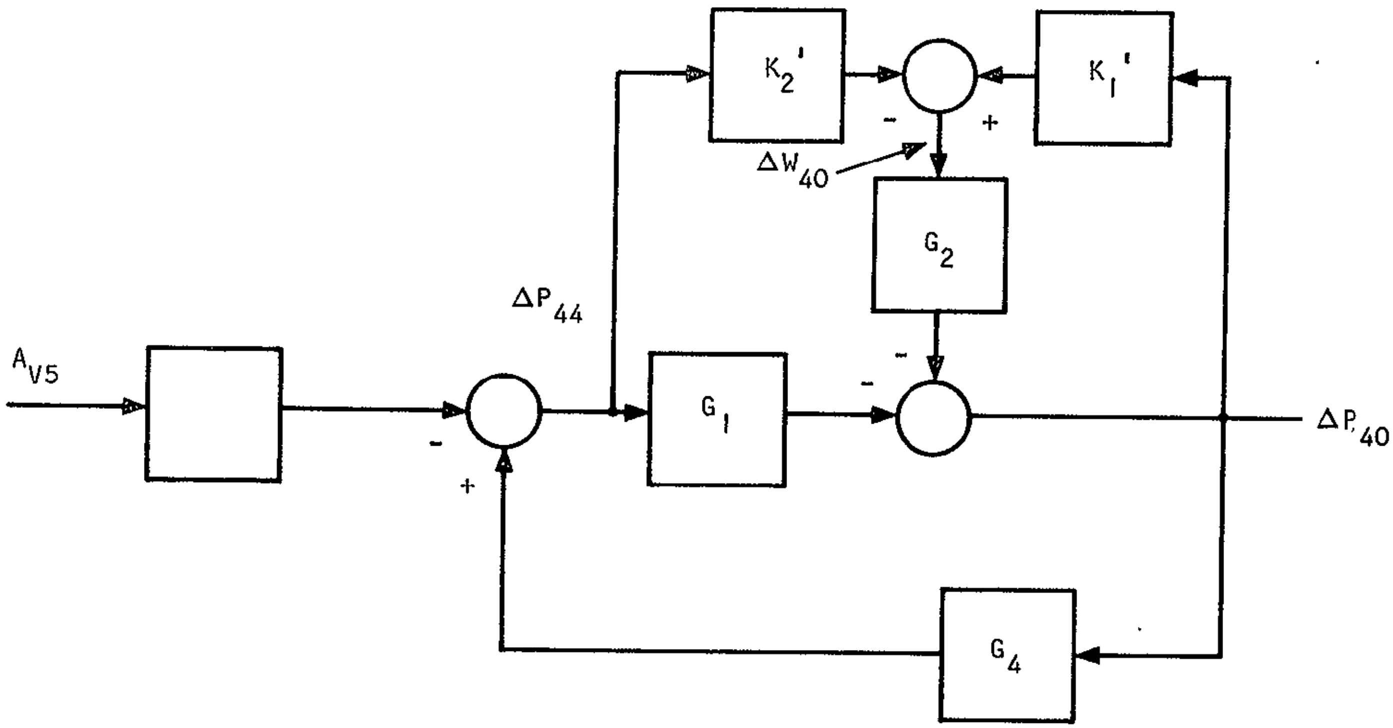

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Figure 5.2-9. Reduced Block Diagram

of W_{40} to changes in P_{40} (corresponding to K_1'); (2) the response of W_{40} to P_{44} (corresponding to K_2'); and (3) the response of P_{44} to changes in P_{40} (corresponding to G_4). The block determining the response of P_{44} to changes in the dump valve area is not specified, since it does not affect stability.

The final block diagram is shown in Figure 5.2-10. The dump valve tends to disturb the fuel plenum pressure, P_{44}. This disturbance is called R. The closed loop transfer function of the system is

$$\Delta P_{44} = \frac{R}{1 + G_5}$$

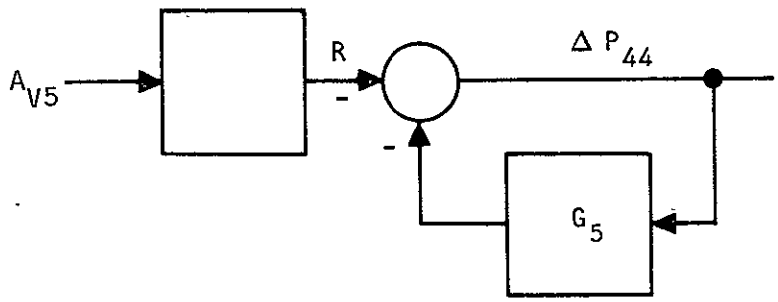
The object of the control is to minimize variations in P_{44}. This can be accomplished by making G_5 as large as possible.

The transfer function, G_5, has three time constants, τ_1, τ_7, and τ_8. τ_1 is the time constant associated with the turbine control valve. τ_7 is not identical to the turbopump rotor-inertia time constant, but is derived from it. That is, an increase or decrease in the turbopump time constant would cause a corresponding increase or decrease in τ_7. τ_5 is the time constant associated with the response of P_{44} to changes in P_{40} (Block G_4 is the reduced block diagram). τ_8 is derived from τ_5, but is not identical to it. These time constants were modified by the effect of block G_2, i.e., by the fact that variations in flow cause variations in turbopump discharge pressure.

The steady-state gain, K_3, is the open loop gain of the system. It is equal to about half the gain of G_1.

To determine how the turbopump would perform, a root locus of G_5 was constructed. This is shown in Figure 5.2-11. This graph indicates that, at the design point (with a gain of about 12), the system will have a damping ratio of about 0.224, a natural frequency of about 52 rad/sec (or about 9 Hz), and a settling time of 0.3 sec. To obtain a damping ratio of 0.7, the gain would have to be reduced to about 3. One of the characteristics of the system which was established in the analog tests was that turbopump gain is subject to wide variations in gain. These variations are on the order of a factor of 3. If the highest gain is to produce a damping ratio of 0.7, the Mach 8 gain, which is the lowest gain, would have to be reduced by about this factor. Thus, the uncompensated gain should be about 1. This is too low to provide an effective control system.

Two forms of compensation were tried, lead compensation and lag compensation. The lead compensation scheme demands that the turbine control valve be fast enough to compensate for the slowness of the turbopump. The effect of lead compensation is shown in Figure 5.2-12. As can be seen, the natural frequency has been increased to 55 rad/sec (about 9 Hz), and the settling



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$$G_5 = \frac{K_3}{(\tau_1 \; S + 1)\;(\tau_7 \; S + 1)\;(\tau_8 \; S + 1)}$$

ORIGINAL			FINAL	
Symbol	Size, sec	Source	Symbol	Size, sec
τ_1	0.0144	Turbine Control Valve	τ_1	0.0144
τ_3	0.274	Turbopump	τ_7	0.192
τ_5	0.0138	Fuel Plenum	τ_8	0.0145

$$K_3 = \frac{KK_1'}{K_2' + K_3' + K_1 K_1' K_3'} = \frac{K}{2.1}$$

Figure 5.2-10. Final Block Diagram

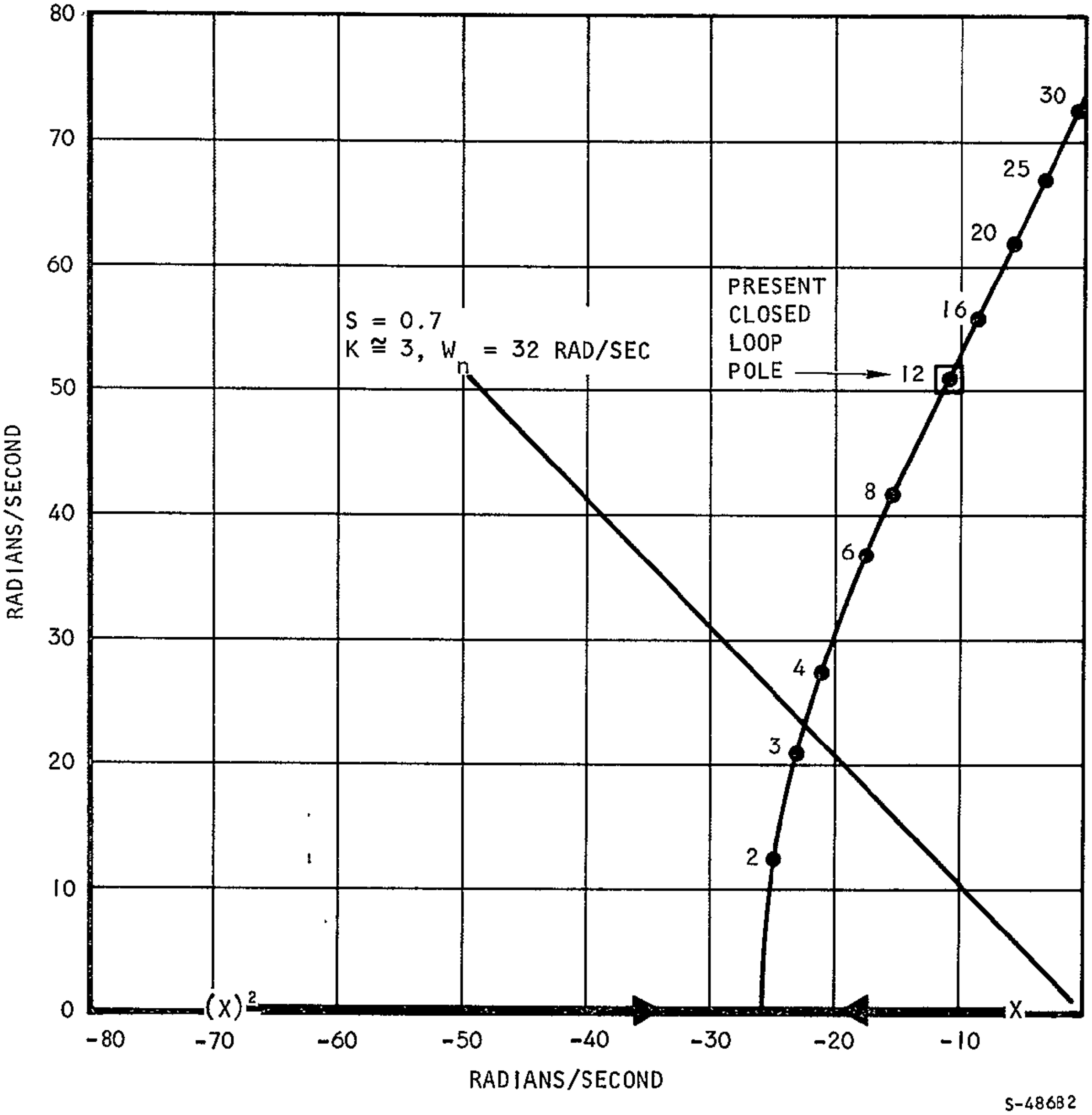

Figure 5.2-11. HRE Turbopump Uncompensated Root Locus Parameterized by Steady-State Gain

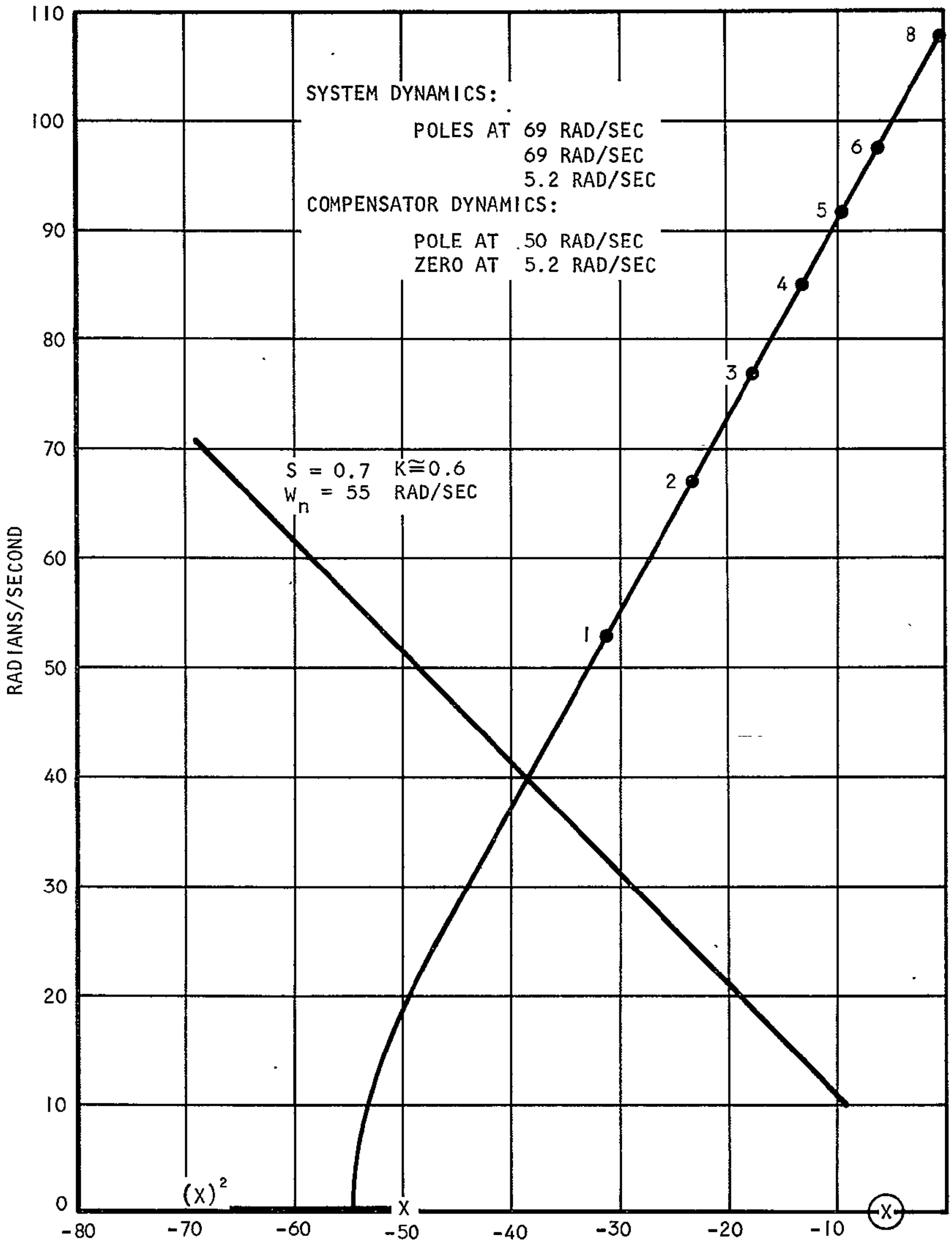

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Figure 5.2-12. HRE Turbopump Root Locus with Lead Compensation time decreased to about 1/10 sec. The gain, however, has been reduced by a factor of three, precluding the use of this type of compensation.

The lag compensator has the effect of approximating proportional plus integral control. The root locus for this control is shown in Figure 5.2-13. The gain required for a damping ratio of 0.7 has been increased from 3 to 15. The natural frequency and settling time have not been changed. The overall effect of this compensator (which is to increase the allowable gain) is in the correct direction, although the gain increase provided by this particular compensator is not as large as would be liked. From these initial calculations, an estimate of the expected characteristics of a compensated turbopump control system can be made. The estimate would include

Gain range: from 30 to 100

Settling time: 0.3 sec

Damping ratio: from 1.0 to 0.7

These characteristics imply reasonable performance. This analysis does not cover the operating regimes which fall in the (+) region of the $\Delta P/N^2$ curve. A closer study of the model is needed for this region.

5.3 TEMPERATURE CONTROL SYSTEM

The temperature control system study consisted of the following sequential steps: (1) derivation of linear math models for three flow paths, (2) analysis of the basic dynamics of the uncoupled flow paths, synthesis of compensators for the uncoupled flow paths, (3) analysis of the coupling effects for two types of couplings, (4) evaluation of the compensator of the fully coupled three flow path system. (Item 4 has been initiated but remains largely incomplete.)

5.3.1 Derivation of Linear Mathematical Models

The basic cooling system consists of numerous components which behave in a nonlinear manner. The complete system is therefore characterized by a set of nonlinear equations which do not readily lend themselves to analysis. It was therefore necessary to initiate the study with the derivation of a linear mathematical model. Two techniques were available to accomplish this: (1) an analytical linearization through a Taylor series expansion about the operating point, and (2) an experimental linearization through the use of frequency response test of the nonlinear model. Although both techniques should have yielded similar results, the experimental method was selected. The reasons for this choice were

(a) The existence and availability of the nonlinear analog mechanization

(b) The desire to achieve an analytical model consistent with the analog model

(c) The greatly reduced possibility of error as compared with the analytical linearization technique

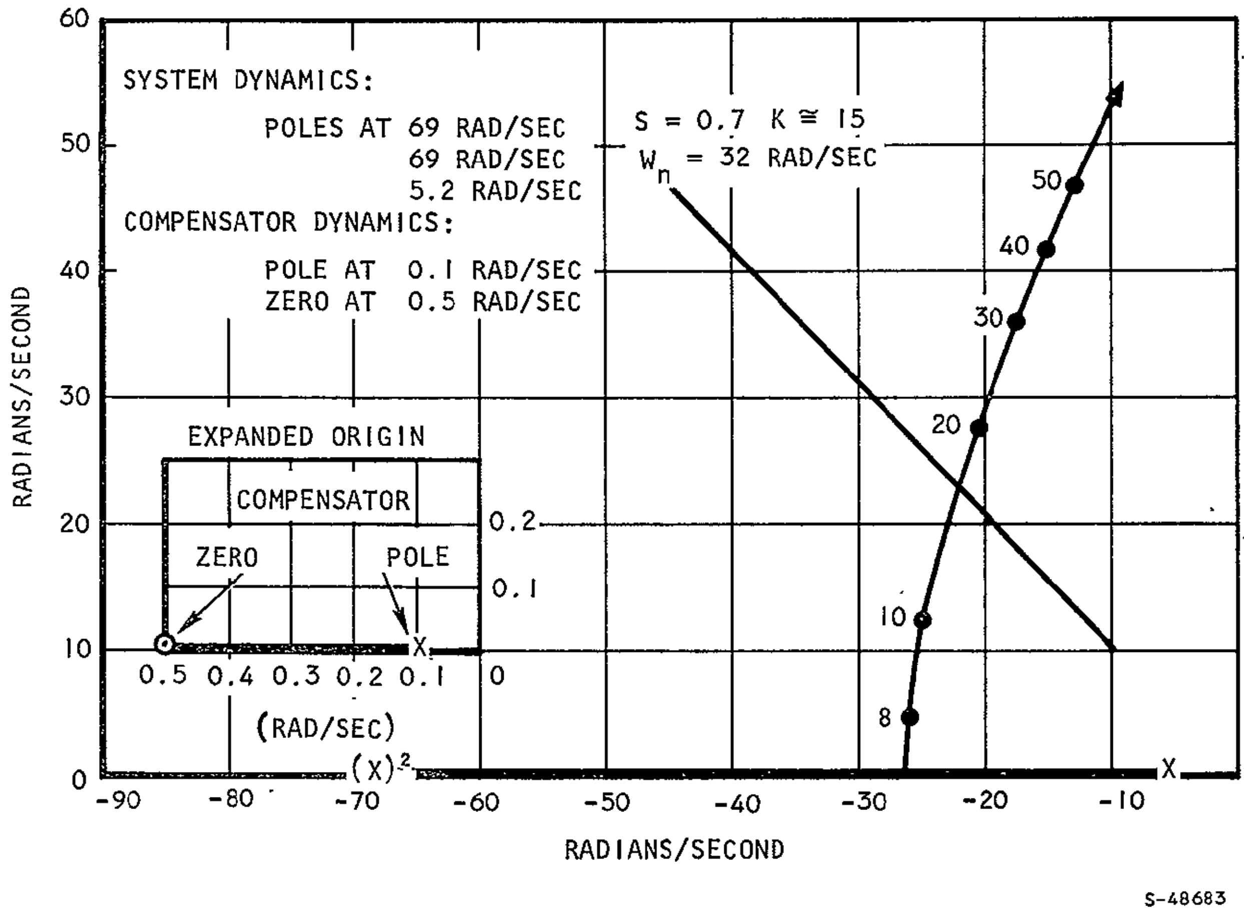

Figure 5.2-13. HRE Turbopump Root Locus with Lag Compensation

(d) The expedience with which the model could be obtained as compared with the analytical linearization technique

The cooling system may be considered to consist of four flow paths, four control valves, a dump valve, and a turbopump. The independent variables are the five valve areas, and the dependent variables are the four flows. A complete model of the system (relating all outputs to all inputs) thus would seem to require twenty equations or transfer functions. At the flight condition of Mach 8, one control valve (the spike) is ineffective and therefore the dump valve is used to control the flow in that path. This fact reduces the number of equations to 16. A careful examination of the four flow paths indicates that three of the paths (innerbody, forward outerbody, and aft outerbody) are very similar. This allows the number of equations to be reduced to 12 while still retaining all coupling phenomena. The three flow paths selected for linearization and analysis were

(a) Spike

(b) Innerbody

(c) Aft outerbody

The frequency response data obtained from test of the analog mechanization of cooling system are presented as Bode diagrams in Appendix B. Analytical expressions for the 12 W_i/A_j transfer functions were obtained by trial and error fitting of the Bode diagrams. The accuracy of the "fit" is indicated by the broken line on each Bode. In general, a realtively good fit was obtained up to 10 or 20 Hz. This can be considered an acceptable fit in view of the low pass characteristics of the heat exchanger.

A discussion of the frequency response test and the equipment used may be found in Appendices B and C.

5.3.2 Analysis of Uncoupled Basic Dynamics

The three uncoupled flow transfer functions are

Spike:

$$W_2/A_5 = \frac{4340}{(S^2 + 37.6S + 985)} \quad K_{ss} = 4.41$$

Innerbody:

$$W_{10}/A_2 = \frac{102.5}{(S + 11.9)} \quad K_{ss} = 8.6$$

Aft Outerbody:

$$W_7/A_4 = \frac{837}{(S + 125.6)} \quad K_{ss} = 6.68$$

As can be seen from these equations, the variation of the predominant time constant is more than an order of magnitude while the variation of steady-state gain is approximately a factor of two. These facts would lead one to assume that the compensation requirements would be vastly different in each of the three flow paths. As will be shown a little later, this is not the case.

The above transfer functions represent only the plumbing (line, manifold, etc.) and turbopump components of the system. The additional components in each path include the sample and hold, valve, heat exchanger, and sensor. The complete system for each of the three loops are shown in Figures 5.3-1, 5.3-2, and 5.3-3.

The dynamics of the uncompensated, uncoupled, closed loop system were analyzed by first performing an S to Z transformation of the continuous part of the system (with T = 0.025 sec) and then conducting a Z-plane root locus. (Both operations were accomplished by digital computer programs.) The result of the S to Z transformations are present below in transfer function form and in Figures 5.3-4, 5.3-5, and 5.3-6 in graphical form.

Spike:

$$T_{sensor}/T_{error} = \frac{0.483(Z+0.0074)(Z+0.1507)(Z+1.068)(Z+11.0)}{(Z-0.00043)(Z-0.732)(Z-0.98)(Z^2+0.391)} \quad K_{ss}=6.78\times10^3$$

Innerbody:

$$T_{sensor}/T_{error} = \frac{4.33(Z+0.017)(Z+0.394)(Z+4.79)}{(Z-0.0043)(Z-0.732)(Z-0.743)(Z-0.983)} \quad K_{ss} = 3.06\times10^4$$

Aft outerbody:

$$T_{sensor}/T_{error} = \frac{34.9\ (Z+0.00879)(Z+0.197)(Z+2.96)}{(Z-0.0043)(Z-0.043)(Z-0.732)(Z-0.937)} \quad K_{ss} = 1.05\times10^4$$

5.3.2.1 Uncoupled Spike Dynamics

The effect of increasing gain on the spike uncompensated, uncoupled, closed loop poles is illustrated in Figure 5.3-4. The definition of gain used here is the value of adjustable gain of the system (e.g., the valve driver gain) and not the overall gain. As the gain is increased, the two largest aperiodic poles (due to the heat exchanger and valve) move toward each other, meet, and break away to form a complex pair; the complex pair of roots (due to the plumbing and turbopump) move to the left toward the two intermediate valve negative value zeros; the pole and zero nearest the origin form a dipole

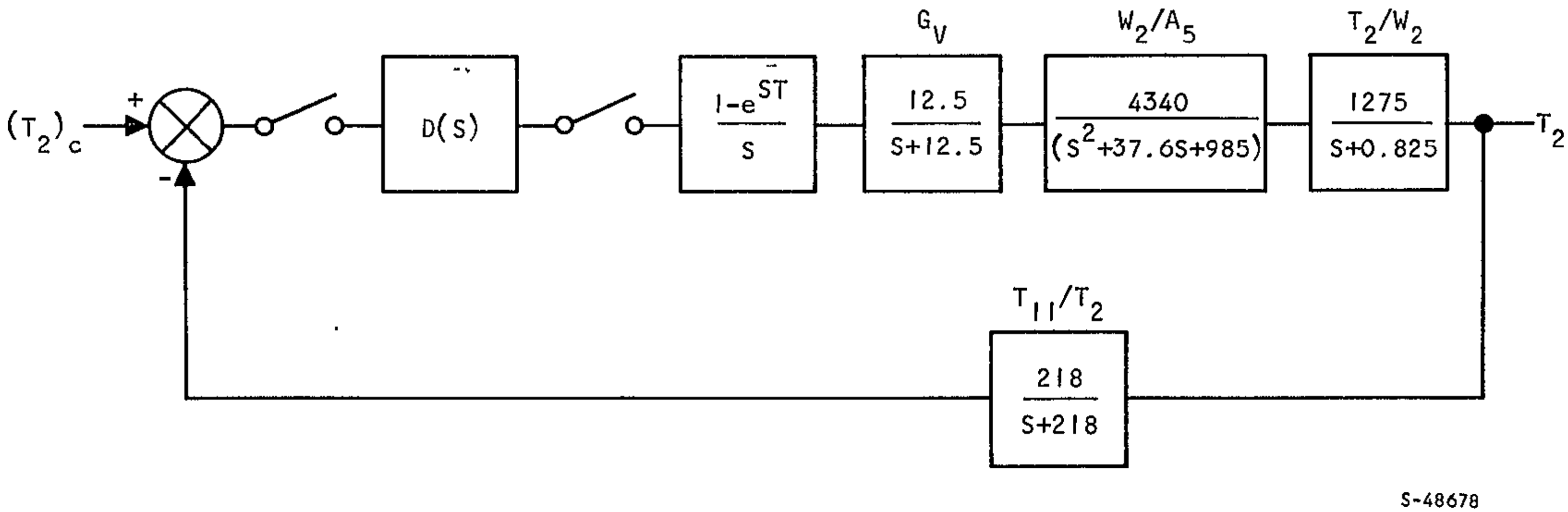

Figure 5.3-1. Block Diagram of Spike Primary Flow Path

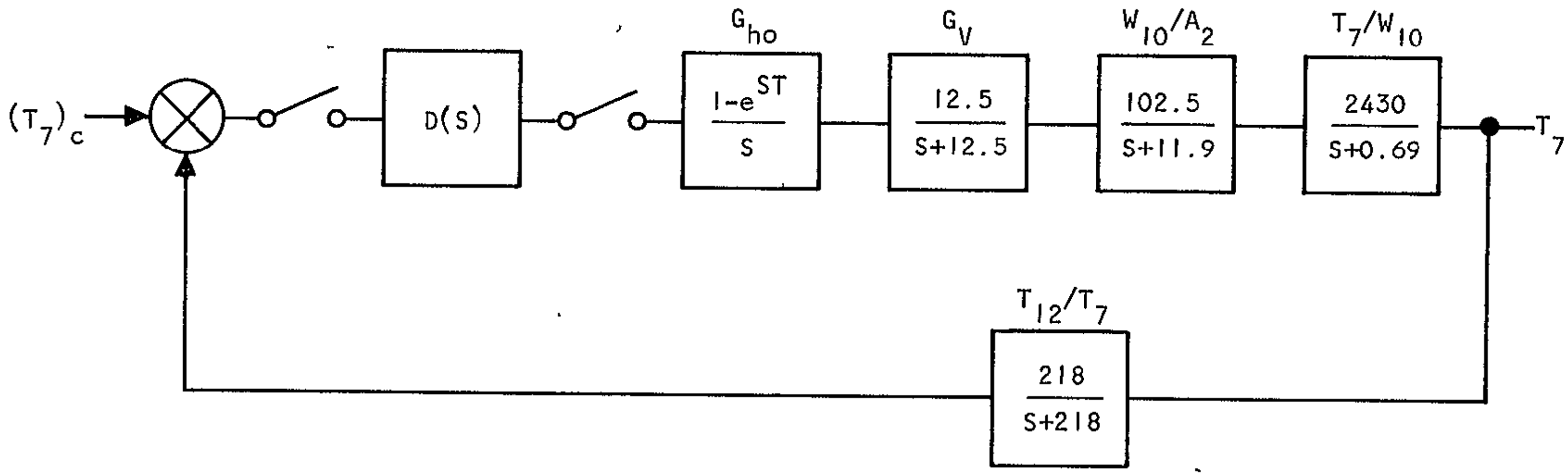

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Figure 5.3-2. Block Diagram of Primary Innerbody Flow Path

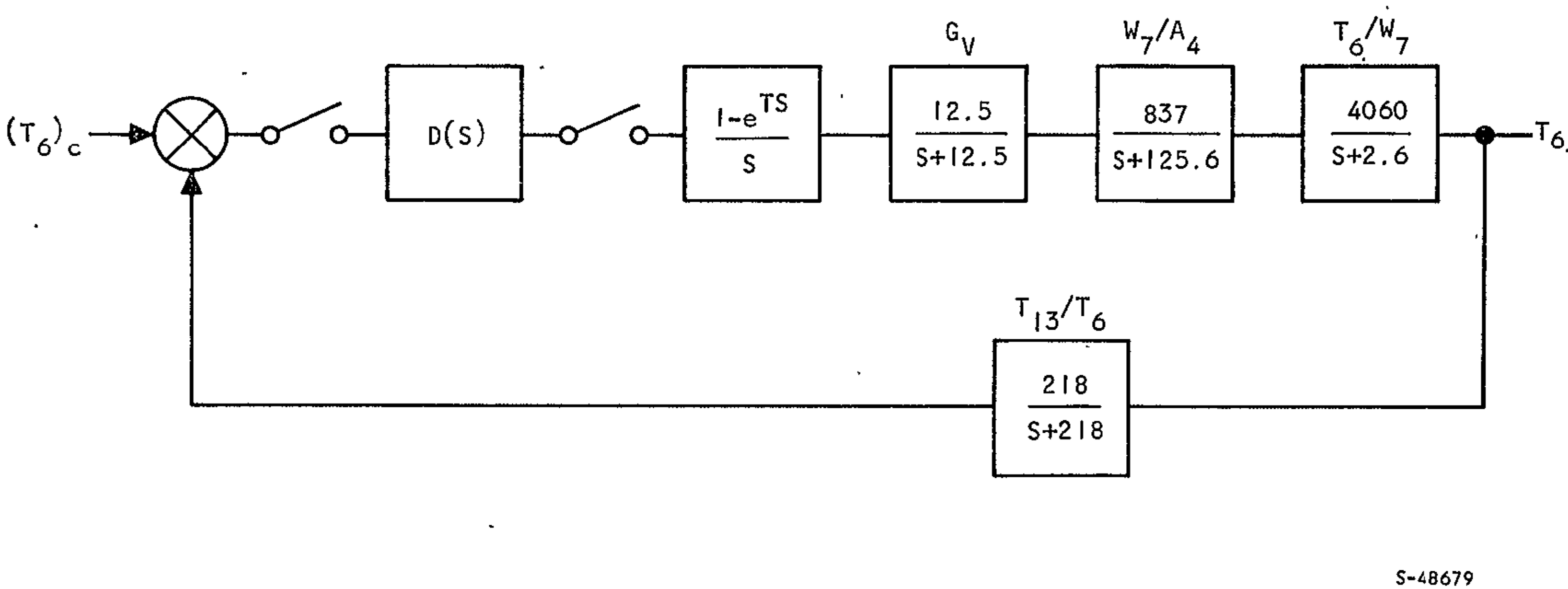

Figure 5.3-3. Block Diagram of Primary Aft Outerbody Flow Path

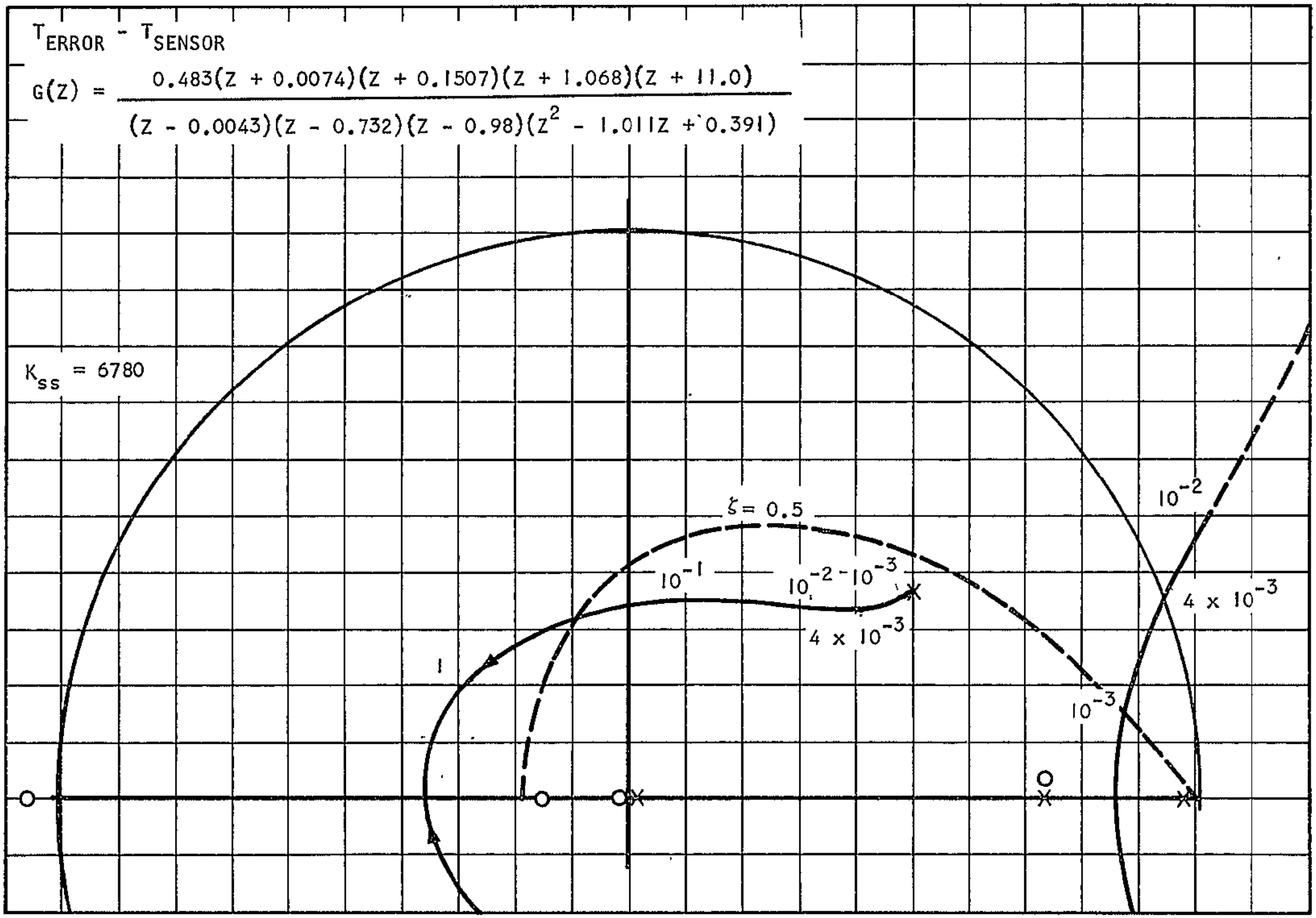

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Figure 5.3-4. HRE Spike Primary Control

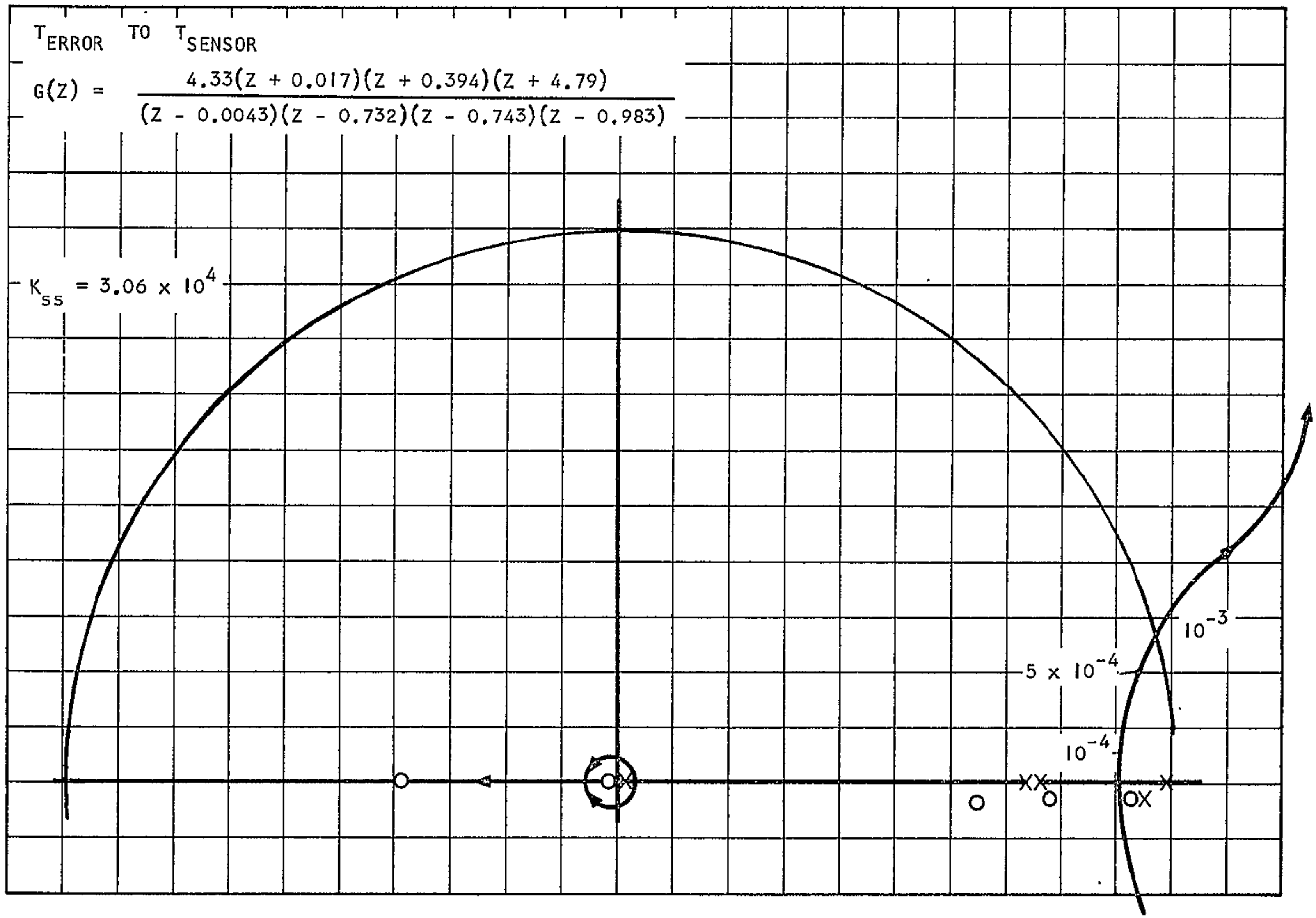

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Figure 5.3-5. HRE Innerbody Primary Control

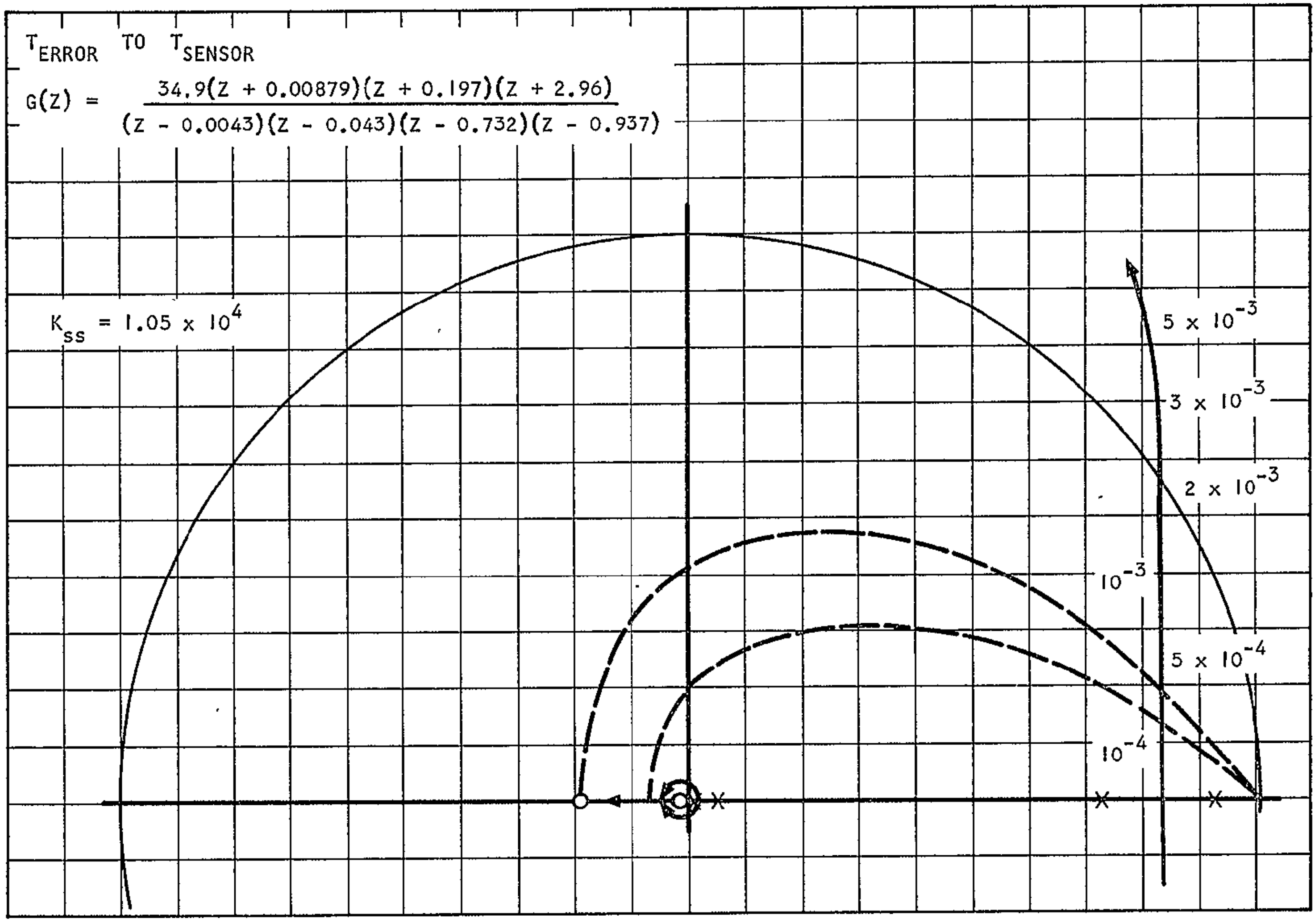

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Figure 5.3-6. HRE Aft Outerbody Primary Control and are of little consequence (or interest). As the gain is further increased to a value of approximately 4×10^{-3}, the complex pair due to the heat exchanger and control valve, cross the unit circle and the system becomes unstable. The marginal value of the overall system gain is given by the product of the fixed gain and the adjustable gain: $(6.78 \times 10^{3}) \times (4 \times 10^{-3}) = 27.1$. An examination of the root locus, shown in Figure 5.3-4 indicates that at all stable points on the locus either the frequency is too low, the gain is too low, or both conditions exist. Thus, simple gain adjustment will not yield satisfactory performance, and compensation is required.

5.3.2.2 Uncoupled Innerbody Dynamics

The effect of increasing gain on the innerbody uncompensated, uncoupled, closed loop roots is shown in Figure 5.3-5. As the gain is increased, the two largest aperiodic poles (due to the heat exchanger and control valve) move toward each other, meet, and break away to form a complex pair; the aperiodic pole (due to the plumbing and turbopump) moves toward the aperiodic pole near the origin (due to the sensor). As the gain is further increased to a value of approximately 10^{-3}, the complex pair (due to the control valve and heat exchanger) cross the unit circle and the system becomes unstable. The marginal value of the overall system gain is given by the product of the fixed and adjustable gains as $3.06 \times 10^{4} \times 10^{-3} = 30.6$. (Which was approximately the same value as the spike marginal gain.) As in the case of the spike, simple gain adjustment would not yeild satisfactory performance and therefore compensation is required.

5.3.2.3 Uncoupled Aft Outerbody Dynamics

The effect of increasing gain on the aft outerbody uncompensated, uncoupled closed-loop roots is shown in Figure 5.3-6. As can be seen from a comparison of Figures 5.3-5 and 5.3-6, the effect is very similar to what occurs in the case of the innerbody. The marginal value of the overall system gain is $(1.05 \times 10^{4}) \times (2 \times 10^{-3}) = 21$. (Which is approximately the same value obtained in the cases of the spike and the innerbody). And once again, simple gain adjustment would not yield satisfactory performance and therefore compensation is required.

5.3.3 Design of Compensation

As in the case of the injector systems, no criteria (such as natural frequency, damping ratio, setting time, ripple factor, etc.) have been established for the control system performance. The compensator thus cannot truly be synthesized but rather must be selected arbitrarily at this time. If both the gain and the natural frequency can be significantly improved while maintaining a damping ratio of 50 or 60 percent, the system response will be acceptable. The compensator selected to achieve these goals was a second order lag-lead cnnfiguration of the following form:

$$D(Z) = \frac{0.07\ (Z - 0.9)\ (Z - 0.85)}{(Z - 0.999)\ (Z + 0.05)} \quad K_{ss} = 1$$

The effect of increasing gain on spike compensated, uncoupled, closed loop poles is illustrated in Figure 5.3-7. As the gain is increased, the two largest aperiodic poles (the larger compensator pole and the heat exchanger pole) move toward each other, meet, and break away to form a double dipole (together with the two compensator zeros); the complex poles (due to the plumbing and turbopump) move down and to the right due to attraction of the compensator zeros; the two smallest positive poles (due to the sensor and control valve) move toward each other, meet, and break away to form a complex pair near the origin; and the negative compensator pole moves toward the zero near the origin to form a dipole. As the gain is further increased to approximately 2.5×10^{-1}, the complex pair due to the plumbing and turbopump cross the unit circle and the system becomes unstable. The marginal value of the overall system gain of the compensated system is 1700. A gain of 5×10^{-2} yields a system characterized by a steady-state gain of 340, a natural frequency of 20 rad/sec, and a damping ratio of 50 percent. With this compensation, the spike loop should have acceptable performance.

5.3.4 Analysis of Coupling Effects

The inclusion of the coupling effects in the analysis changes the entire nature of the problem from scalar to vector. The increased complexity can be readily appreciated when one considers the difficulty of simultaneously closing mixed continuous and discrete data loop. As in the case of continuous vector problems, the only systematic technique for synthesizing discrete-data multi-input control systems is by the application of modern control theory. When the number of independent variables exceeds three or four, a computer must be used to solve the equations. Unfortunately, no existing program could be found. It was therefore necessary to resort to a cut-and-try technique.

The coupling transfer functions for the three loops considered in this analysis are presented below.

Spike

$$W_2/A_2 = \frac{26.2}{S + 10.65} \quad K_{ss} = 2.45$$

$$W_2/A_3 = \frac{29.8\ (S + 62.8)}{(S + 31.4)(S + 31.4)} \quad K_{ss} = 1.9$$

$$W_2/A_4 = \frac{16500\ (S + 62.8)^2}{(S^2 + 27.6\ S + 630)(S + 205)^2} \quad K_{ss} = 2.45$$

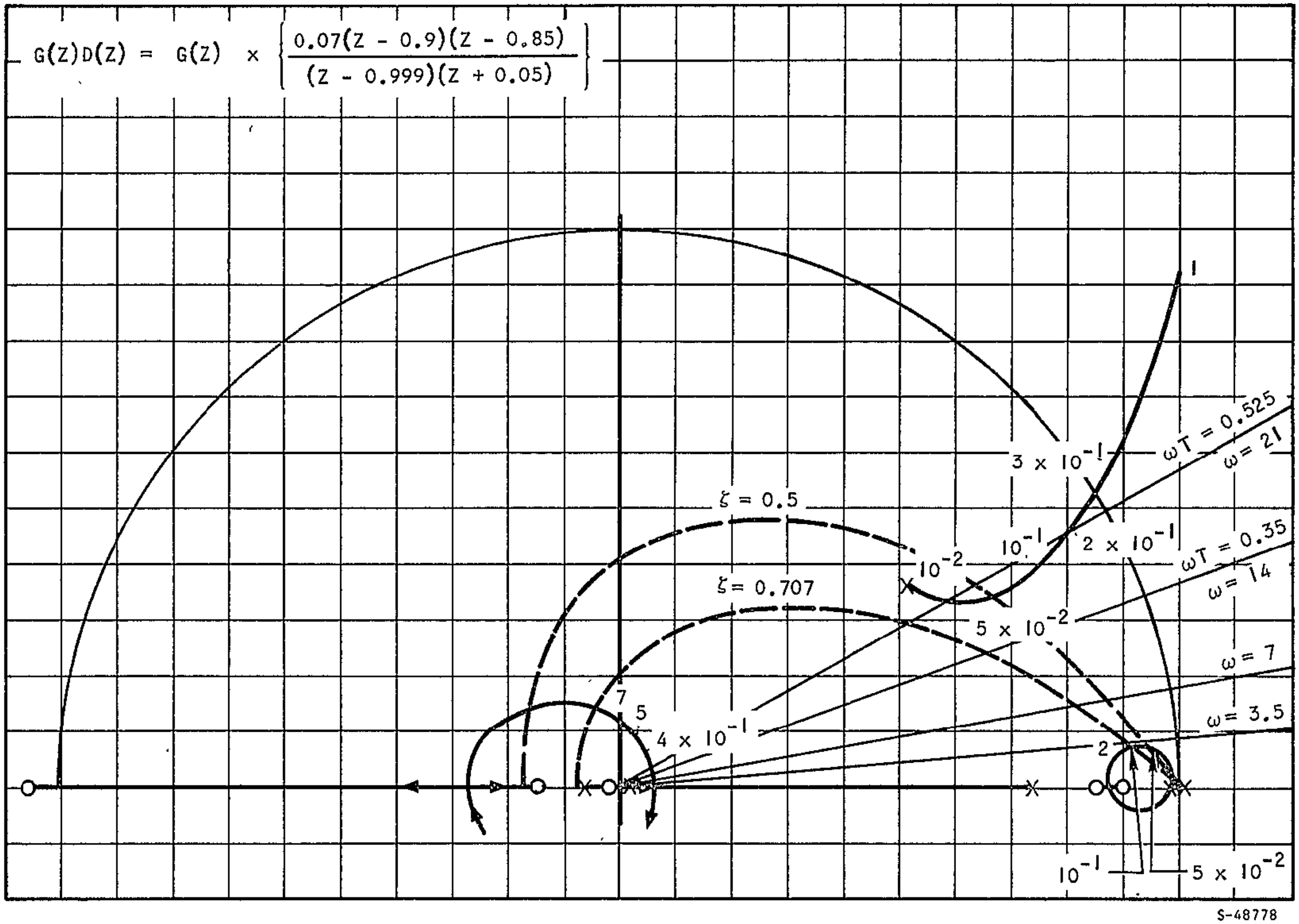

Figure 5.3-7. HRE Spike Primary Control

Innerbody

$$W_{10}/A_3 = \frac{763\ (S + 24.2)}{(S + 9.4)(S + 32.9)(S + 56.4)}\ K_{ss} = 1.06$$

$$W_{10}/A_4 = \frac{156.5(S + 18.8)(S + 18.8)}{(S + 5.14)(S + 86.6)(S + 86.6)}\ K_{ss} = 1.44$$

$$W_{10}/A_5 = \frac{137.5\ (S + 18.8)(S + 25)(S + 31.4)}{(S + 7.52)(S + 49)(S + 48.3)(S+47.7)}\quad K_{ss} = 2.4$$

Aft Outerbody

$$W_7/A_2 = \frac{32.0}{(S + 15.7)}\ K_{ss} = 2.04$$

$$W_7/A_3 = \frac{1670}{(S + 26.4)(S + 26.4)}\ K_{ss} = 2.39$$

$$W_7/A_5 = \frac{403000(S + 75.3)(S + 75.3)(S + 75\ 3)}{(S^2 + 29s + 840)(S + 370)(S + 374)(S + 378)}\ K_{ss} = 3.93$$

In the following sections, two cases of coupling are analyzed: spike innerbody and aft innerbody/outerbody. These two cases reflect the two types of couplings which are possible and should give valuable insight into the problems of three and four loop couplings.

5.3.4.1 Spike-Innerbody Coupling

Spike innerbody coupling represents a case of additive couplings. This descriptive name comes from the following characteristics: (a) an increase in the innerbody temperature commands an increase in the flow of the innerbody (control valve opens), (2) an increase in the innerbody flow causes a decrease in the spike flow, (3) a decrease in spike flow results in an increase in the spike temperature and commands the dump valve to open, and (4) when the dump valve opens, the flow in the innerbody increases (downsteam pressure decreases). The result is an effective gain increase due to additive coupling.

Figure 5.3-8 shows the compensated spike uncompensated innerbody in a coupled but unreduced block diagram. In order to continue the analysis, it was necessary to reduce Figure 5.3-8 to an equivalent single transfer function. It was at this point of difficulty (i.e., large numbers of multiple singularities) and complexity in the coupled system that the single precession root extraction routine, which was used successfully on the uncoupled loops, proved to be

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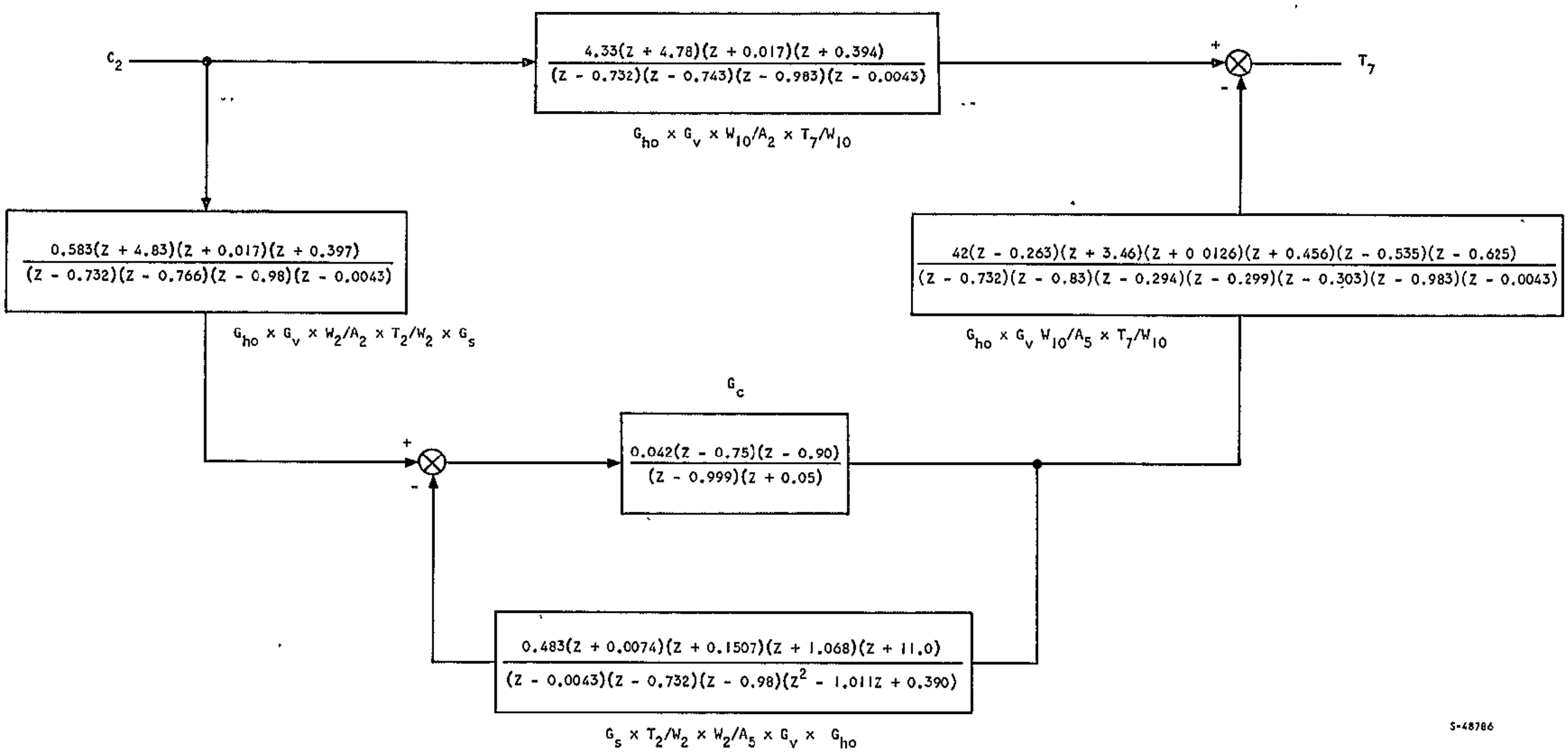

Figure 5.3-8. Spike Innerbody Block Diagram (Unreduced)

inadequate. The difficulty is clearly illustrated by Figure 5.3-9. The input data consists of 3 quadratic and 12 linear factors. The computer first expands them to form a check polynomial. As can be seen from Figure 5.3-9, the input and check polynomials agree to six significant figures and yet some of the roots have only one significant figure correct. Normally, this would not be of great concern, but in the Z-plane the difference between Z = 0.9 and Z = 1.0 is of great importance. It was therefore necessary to detour from the analysis and modify the computer program to work in greater precision.

After performing the indicated block diagram, with algebra, the system reduces to the form shown in Figure 5-3.10. The complexity of the system, which consists of 16 poles and 15 zeros, is quite apparent. By taking advantage of some of the near pole-zero cancellations, the system can be reduced to 12 poles and 11 zeros. The coupled system is characterized by two pairs of complex poles, both of which are due to the compensated spike loop. The dynamic behavior of the coupled system as loop gain is increased is shown in Figure 5.3-11.

As the gain is increased, the low frequency complex closed loop spike poles, due to the compensation pole and the heat exchanger pole, move at near constant frequency toward the unit circle. At a gain of approximately 4×10^{-5}, the poles cross the unit circle and the system becomes unstable. A comparison of Figures 5.3-12 and 5.2-8 reveals that coupling the compensated spike to the uncompensated innerbody reduces the marginal gain by a factor of 25, i.e., the effect of this coupling is very degrading.

The effect of applying compensation to the coupled system is shown in Figure 5.3-13. The shape of the critical locus remains basically the same. The application of compensation has increased the value of marginal gain to 6×10^{-3}, which is a factor of 15. A comparison of Figures 5.3-12 and 5.3-13 reveals that coupling the compensated spike to the compensated innerbody reduces the marginal gain by a factor of 20.

The conclusion that can be reached from the above discussion is that the compensation derived for the uncoupled loop is unsatisfactory in the case of two additively coupled loops.

5.3.4.2 Aft Outerbody - Innerbody Coupling

Aft outerbody-innerbody coupling represents a case of differential coupling. This descriptive name comes from the following characteristics: (1) an increase in innerbody temperautre commands an increase in innerbody flow (control valve opens), (2) an increase in the innerbody flow causes a decrease in the aft outerbody flow (due to the decrease in upstream pressure), (3) a decrease in aft outerbody flow results in an increase in the aft outerbody temperature which causes the aft outerbody control valve to open, and (4) when the aft outerbody control valve opens the upstream pressure decreases, which causes a decrease in the innerbody flow. The net result is an effective lower gain due to differential coupling.

Figure 5.3-14 shows the compensated aft outerbody and the uncompensated innerbody in a coupled but unreduced block diagram form. The reduced block

NUMERATOR INPUT DATA

QUADRATIC FACTORS

1.000000E 00	-1.840000E 00	8.330000E-01
~~1.000000E 00~~	~~-1.990000E-02~~	~~1.300000E-03~~
1.000000E 00	-1.117000E 00	4.220000E-01
1.000000E 00	-4.880000E-01	9.000000E-02

LINEAR FACTORS

1.000000E 00	7.700000E-02
1.000000E 00	1.415000E-01
1.000000E 00	-4.460000E-01
1.000000E 00	-6.670000E-01
1.000000E 00	-7.550000E-01
1.000000E 00	-8.800000E-01
~~1.000000E 00~~	~~-9.870000E-01~~
1.000000E 00	1.065000E 00
1.000000E 00	1.100000E 01

DENOMINATOR INPUT DATA

QUADRATIC FACTORS

1.000000E 00	-1.011000E 00	3.910000E-01
~~1.000000E 00~~	~~-1.195000E 00~~	~~4.350000E-01~~
1.000000E 00	-1.820000E 00	8.360000E-01

LINEAR FACTORS

~~1.000000E 00~~	~~-4.300000E-03~~
~~1.000000E 00~~	-6.600000E-03
1.000000E 00	4.630000E-02
1.000000E 00	-2.940000E-01
1.000000E 00	-2.990000E-01
1.000000E 00	-3.030000E-01
1.000000E 00	-6.960000E-01
1.000000E 00	-7.320000E-01
1.000000E 00	-7.660000E-01
1.000000E 00	-8.300000E-01
1.000000E 00	-9.800000E-01
~~1.000000E 00~~	~~-9.830000E-01~~

NUMERATOR DEGREE 17 GAIN 4.730000E 00

COEFFICIENTS

1.000000E 00	5.083600E 00	-5.072941E 01	1.410392E 02	-1.797523E 02
7.020776E 01	1.128271E 02	-2.030239E 02	1.591933E 02	-7.259713E 01
1.890346E 01	-1.963547E 00	-2.776960E-01	9.513617E-02	-5.060174E-03
-6.137707E-04	1.199945E-05	-1.024095E-06		

DENOMINATOR DEGREE 18 GAIN 1.000000E 00

COEFFICIENTS

1.000000E 00	-9.873600E 00	4.527849E 01	-1.279360E 02	2.490778E 02
-3.538631E 02	3.788189E 02	-3.109285E 02	1.970284E 02	-9.619213E 01
3.576396E 01	-9.884195E 00	1.941708E 00	-2.481502E-01	1.635764E-02
2.391355E-05	-5.629791E-05	6.015516E-07	-1.552864E-09	

Figure 5.3-9. S-Plane Frequency Response and Root Locus Program

ROOT LOCUS

```
 K =  0.                      DEGREE = 18

COEFFICIENTS
    1.000000E 00    -9.873600E 00     4.527849E 01    -1.279360E 02     2.490778E 02    -3.538631E 02
    3.788189E 02    -3.109285E 02     1.970284E 02    -9.619213E 01     3.576396E 01    -9.884195E 00
    1.941708E 00    -2.481502E-01     1.635764E-02     2.391355E-05    -5.629791E-05     6.015516E-07
   -1.552864E-09

ROOTS             0 ZERO        6 REAL        6 COMPLEX

REAL
    1.146388E 00     4.829034E-01     3.249548E-01    -4.630000E-02     6.599999E-03     4.300001E-03

COMPLEX PAIRS (ONLY)

    REAL             IMAGINARY         FREQUENCY         DAMPING RATIO

    1.101837E 00     1.855164E-01      1.117346E 00      9.861202E-01
    8.980713E-01     3.148613E-01      9.516668E-01      9.436825E-01
    6.474817E-01     3.299320E-01      7.266964E-01      8.909934E-01
    5.396441E-01     2.218638E-01      5.834718E-01      9.248847E-01
    5.024717E-01     3.697546E-01      6.238559E-01      8.054290E-01
    2.878672E-01     1.297342E-02      2.881594E-01      9.989860E-01

CHECK POLYNOMIAL DEGREE 18
    1.000000E 00    -9.873592E 00     4.527846E 01    -1.279359E 02     2.490776E 02    -3.538628E 02
    3.788186E 02    -3.109282E 02     1.970283E 02    -9.619205E 01     3.576393E 01    -9.884187E 00
    1.941706E 00    -2.481500E-01     1.635763E-02     2.391349E-05    -5.629786E-05     6.015511E-07
   -1.552863E-09

 K =  2.000000E-02            DEGREE = 18

COEFFICIENTS
    1.000000E 00    -9.779000E 00     4.575940E 01    -1.327350E 02     2.624201E 02    -3.708676E 02
    3.854605E 02    -3.002550E 02     1.778224E 02    -8.113244E 01     2.889627E 01    -8.095928E 00
    1.755956E 00    -2.744203E-01     2.535752E-02    -4.547788E-04    -1.143606E-04     1.736700E-06
   -9.843223E-08

ROOTS             0 ZERO        6 REAL        6 COMPLEX

REAL
    9.274940E-01     1.050478E 00     9.255966E-01     8.317778E-01     4.450061E-01    -5.608612E-02

COMPLEX PAIRS (ONLY)

    REAL             IMAGINARY         FREQUENCY         DAMPING RATIO

    1.347487E 00     1.493720E 00      2.011696E 00      6.698263E-01
    6.966691E-01     1.585505E-02      6.968495E-01      9.997411E-01
    5.583582E-01     3.315670E-01      6.493847E-01      8.598265E-01
    2.350027E-01     1.738250E-01      2.923036E-01      8.039678E-01
   -1.680019E-02     3.127185E-01      3.131695E-01     -5.364566E-02
    6.651800E-03     2.669936E-02      2.751549E-02      2.417474E-01

CHECK POLYNOMIAL DEGREE 18
    1.000000E 00    -9.779003E 00     4.575942E 01    -1.327351E 02     2.624203E 02    -3.708678E 02
    3.854607E 02    -3.002552E 02     1.778224E 02    -8.113248E 01     2.889628E 01    -8.095931E 00
    1.755957E 00    -2.744204E-01     2.535754E-02    -4.547800E-04    -1.143606E-04     1.736699E-06
   -9.843221E-08
```

Figure 5.3-9. S-Plane Frequency Response and Root Locus Program (Continued)

15

$$\frac{4.33(Z + 0.0189)(Z + 0.017)(Z - 0.757)(Z - 0.726)(Z - 0.895)(Z - 0.394)(Z + 4.80)(Z + 0.0184 \pm 0.1014j)(Z - 0.579 \pm 0.0761j)(Z - 0.871 \pm 0.42j)(Z - 0.458 \pm 0.290j)}{(Z - 0.983)(Z - 0.83)(Z - 0.766)(Z - 0.743)(Z - 0.696)(Z - 0.303)(Z - 0.299)(Z - 0.294)(Z + 0.0463)(Z - 0.0066)(Z - 0.0043)(Z - 0.732)(Z - 0.91 \pm 0.088j)(Z - 0.598 \pm 0.279j)}$$

16

102<

11

$$\frac{4.33(Z - 0.895)(Z - 0.394)(Z + 4.8)(Z + 0.0184 \pm 0.1014j)(Z - 0.579 \pm 0.0761j)(Z - 0.871 \pm 0.42j)(Z - 0.458 \pm 0.29j)}{(Z - 0.983)(Z - 0.83)(Z - 0.743)(Z - 0.696)(Z - 0.303)(Z - 0.299)(Z - 0.294)(Z - 0.0043)(Z - 0.91 \pm 0.088j)(Z - 0.598 \pm 0.279j)}$$

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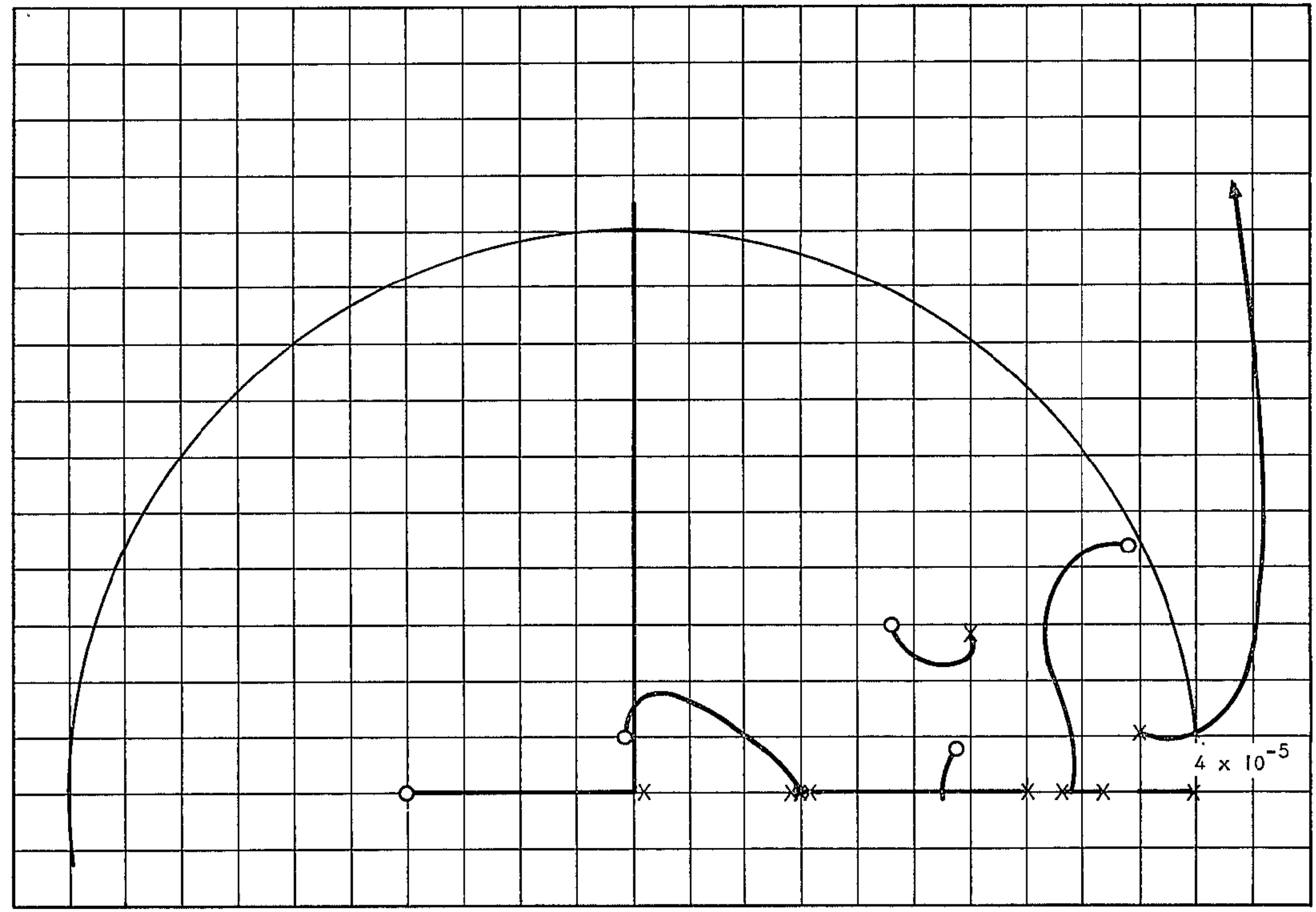
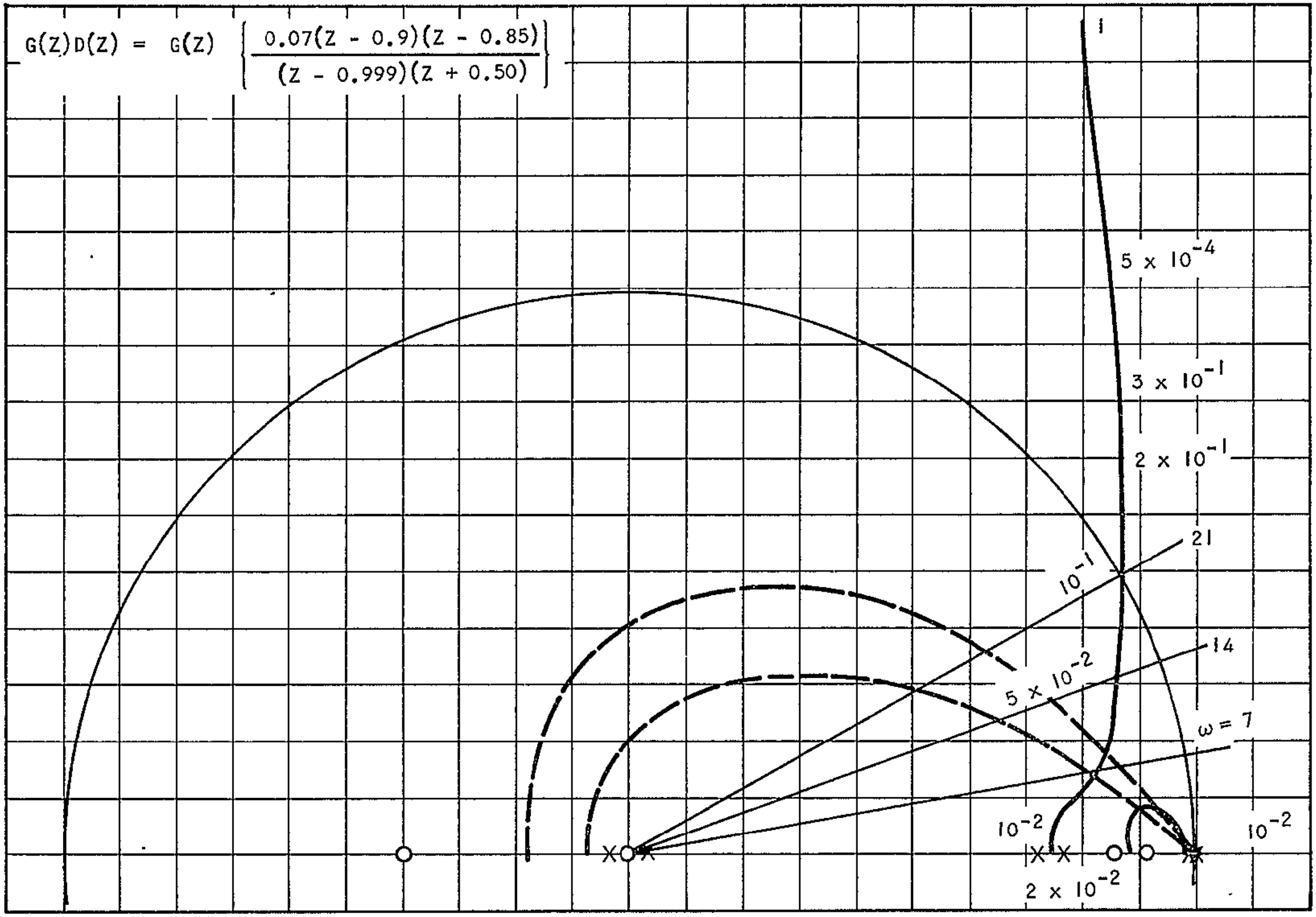
S-48788

Figure 5.3-10. Block Diagram of Coupled Innerbody-Spike Flow Paths (Reduced)



S-48779

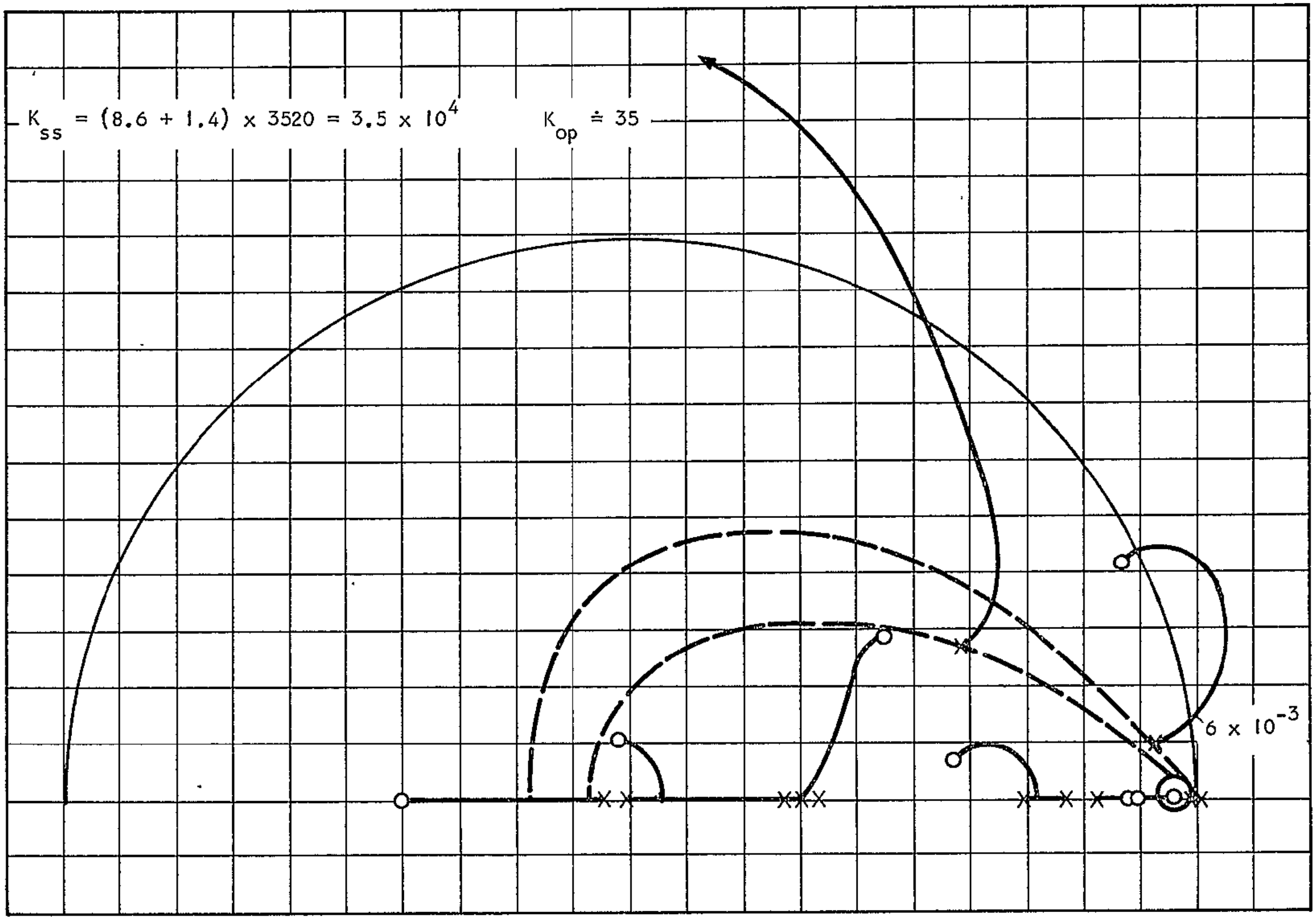
Figure 5.3-11. HRE Spike-Innerbody



S-48774

Figure 5.3-12. HRE Innerbody Primary Control

105<



S-48782

Figure 5.3-13. HRE Spike-Innerbody

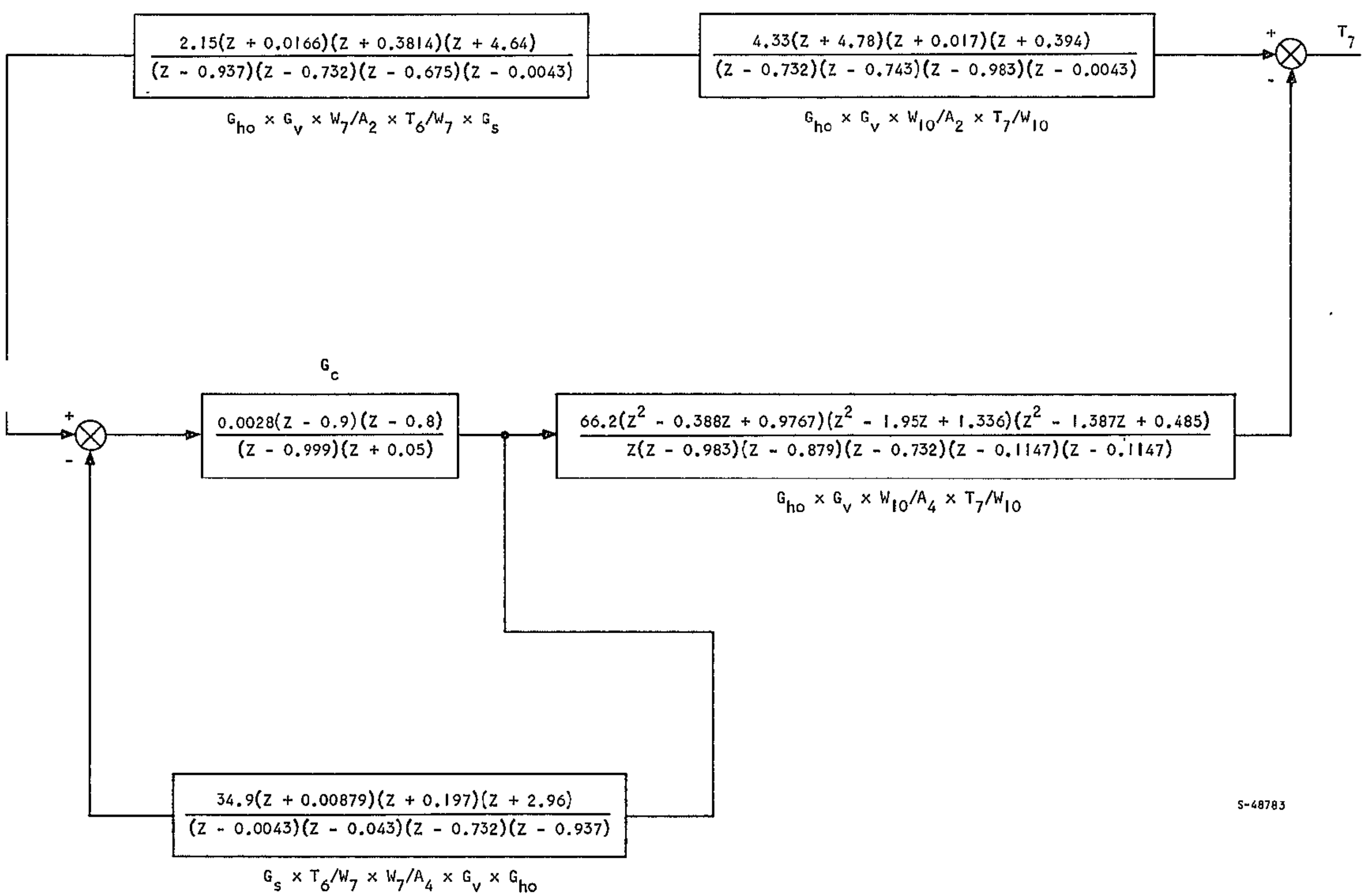


Figure 5.3-14. Aft Outerbody-Innerbody Block Diagram (Unreduced)

diagram is shown in Figure 5.3-15. The system is also quite complex consisting of 17 poles and 16 zeros. By taking advantage of the near pole-zero cancellation, the system can be reduced to 9 zeros and 10 poles. The simplifed configuration is shown in Figure 5.3-16. The effect of increasing gain on the system shown in Figure 5.3-16, is illustrated in Figure 5.3-17. As the gain is increased, the two largest aperiodic poles (due to the innerbody heat exchanger and plumbing) move toward each other, meet, and break away to form a complex pair of dominant poles (all other poles are either very near zeros or very close to the origin, and thus do not contribute to the locus). As the gain is increasec to a value of 10^{-3}, the dominant complex poles cross the unit circle and the system becomes unstable. A comparison of Figure 5.3-17 and 5.3-5 reveals that coupling the aft outerbody to the innerbody has done very little if anything to the shape of the critical locus or to the marginal gain. This is indeed surprising when one compares the coupled (Figure 5.3-14) and the uncoupled (Figure 5.3-2) open loop transfer functions.

From the above discussion, one would expect the uncoupled compensation would be just as effective in the case of the coupled systems as it was in the case of the uncoupled system. This is indeed the case; Figure 5.3-18 shows the effect of applying compensation to the coupled aft outerbody/innerbody loops. The shape of the loci has been altered considerably by the compensator poles and zeros. The critical locus now consists of the larger compensator pole and the aft outerbody heat exchanger pole. A comparison of Figure 5.3-17 and 5.3-18 reveals that the application of compensation has increased the value of the marginal gain from 10^{-3} to 10^{-1}. A comparison of Figure 5.3-12 and 5.3-18 indicates that although the shape of the critical locus has changed due to the coupling effects, the value of the marginal gain is the same for the compensated coupled system and the compensated uncoupled system.

The conclusion that can be reached from the above discussion is that for loops that are coupled in a differential manner, the effects of coupling are minor.

5.4 START-UP ANALYSYS

5.4.1 Problem

The problem was to obtain a time history of pressure, flow, and temperature at turbine inlet following a step in the pressure upstream of the pump from 0 to 60 psi. The equations governing the flows through the inoperative pump and turbine were given as well as the heat exchangers initial conditions at start-up time.

The analysis was to be performed with the existing HRE analog model in which the operating turbopump was replaced by an inoperative one.

5.4.2 Analysis

The time history of the temperature at the turbine is a useful function; not only is it part of the answer to the problem, but the instantaneous value

16

$$\frac{3.93(Z + 0.0166)(Z - 0.0043)(Z - 0.043)(Z - 0.732)(Z - 0.676)(Z - 0.983)(Z - 0.879)(Z + 4.93)(Z + 0.777)(Z + 0.379)(Z - 0.551 \pm 0.221j)(Z - 0.249 \pm 0.474j)(Z - 0.828 \pm 0.166j)}{Z(Z - 0.983)^2(Z - 0.88)(Z - 0.743)(Z - 0.675)(Z + 0.1246)(Z - 0.1147)(Z - 0.1147)(Z + 0.00816)(Z - 0.0043)(Z - 0.732)^2(Z - 0.823 \pm 0.160j)(Z - 0.493 \pm 0.309)}$$

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Figure 5.3-15. Block Diagram of Coupled Innerbody-Aft Outerbody Flow Paths (Reduced)

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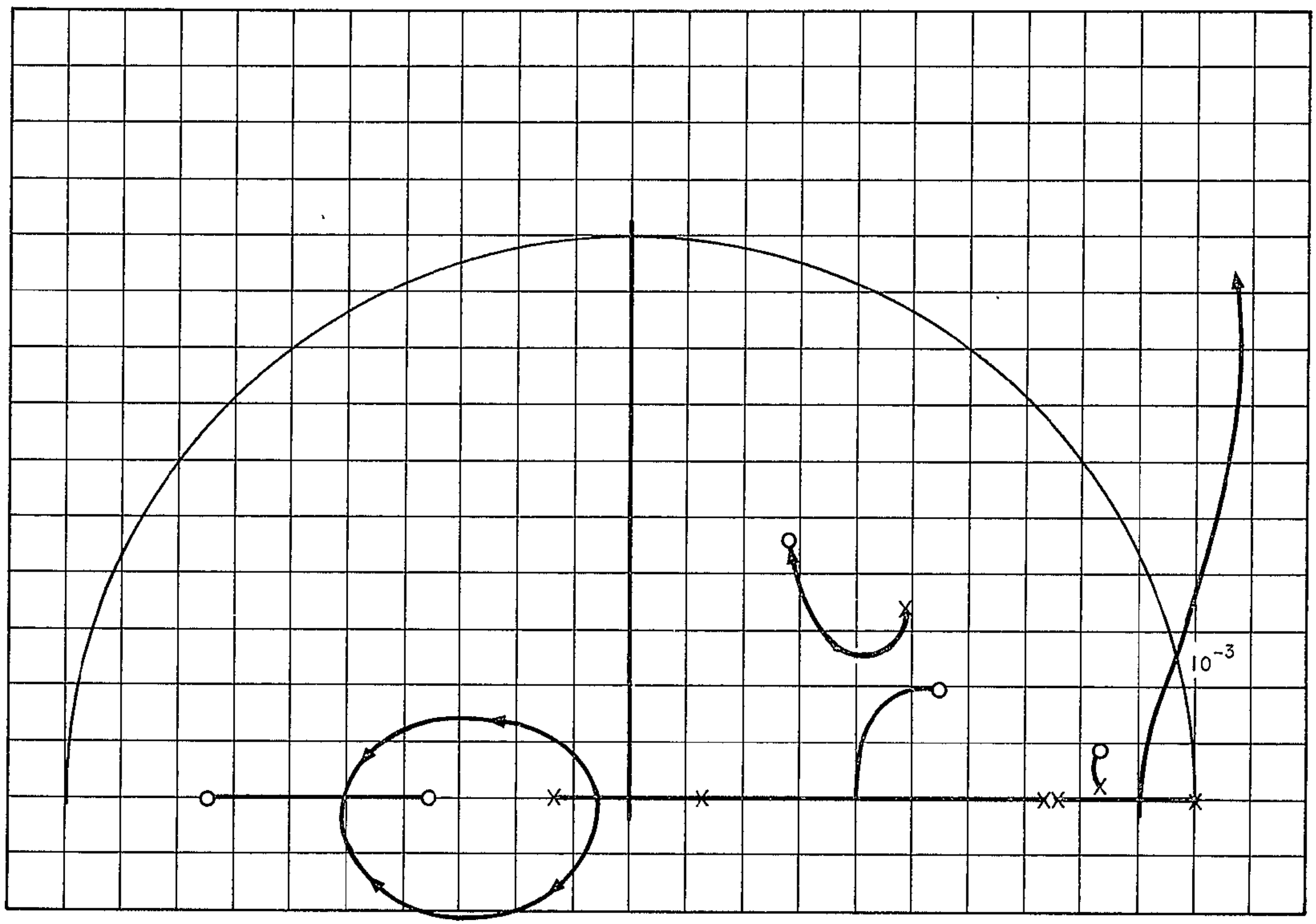
$$\frac{3.93(Z + 0.0166)(Z - 0.043)(Z + 4.93)(Z + 0.777)(Z + 0.379)(Z - 0.551 \pm 0.221j)(Z - 0.249 \pm 0.474j)}{Z(Z - 0.983)(Z - 0.743)(Z + 0.1246)(Z - 0.1147)(Z - 0.1147)(Z + 0.00816)(Z - 0.732)(Z - 0.493 \pm 0.309)}$$

10

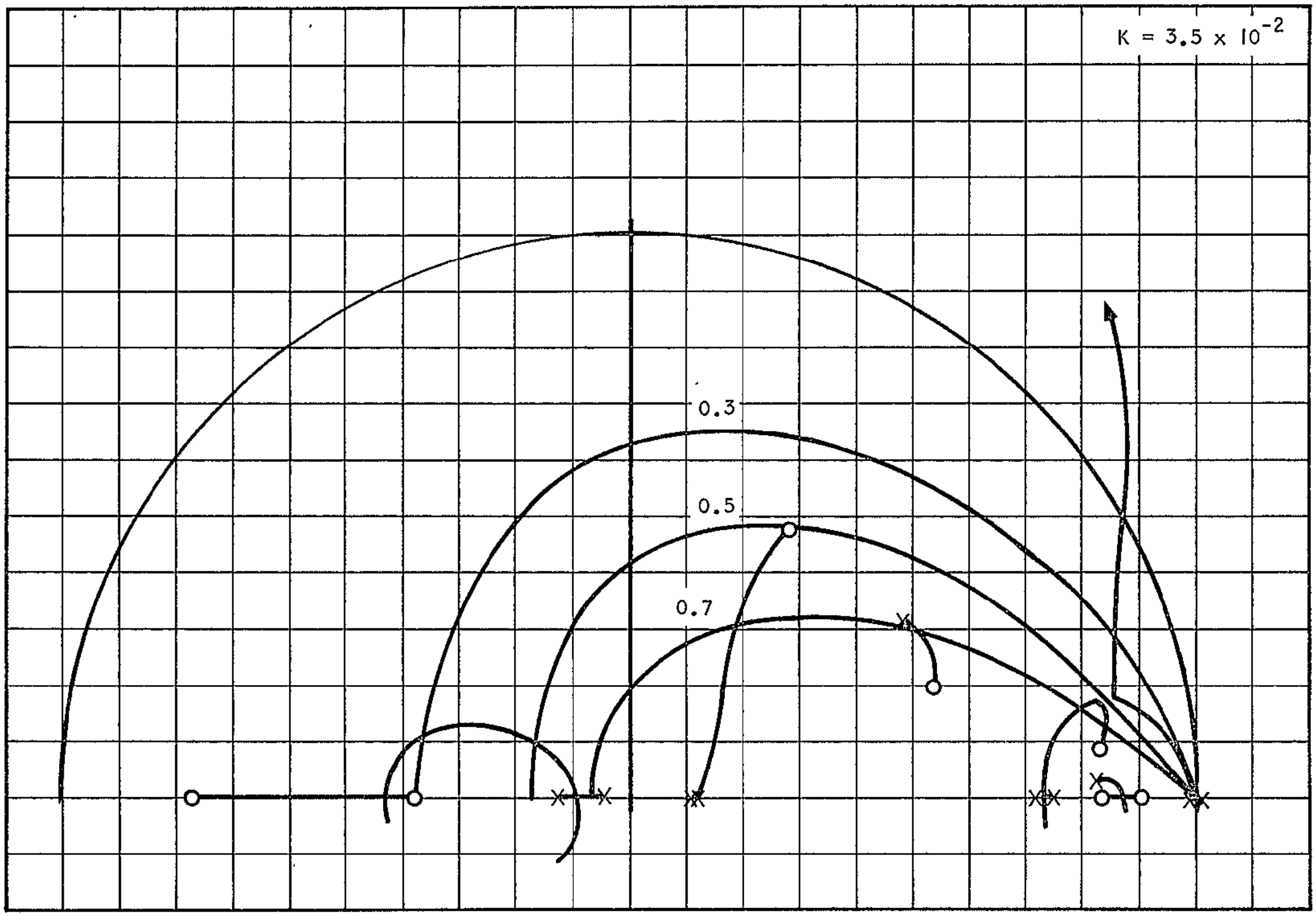
S-48785

Figure 5.3-16. Simplified System



S-48775

Figure 5.3-17. HRE Innerbody-Aft Outerbody



S-48777

Figure 5.3-18. HRE Innerbody-Aft Outerbody of this variable is a factor which at all times, during the transient and steady-state condition, affects the relationship between the pressure situation and the choked flow at the turbine ($W\sqrt{T}/P_{inlet} = 0.0207$). Although coolant temperatures throughout the system do affect the flows and pressures, it is through the turbine that the temperature effect has the most significant influence since most of the pressure is lost at this location. A typical steady-state pressure distribution is as follows:

Pressure out of the "purge and shut-off valve":	60 psi
Pressure at the turbine manifold:	54 psi
Ambient pressure:	3 psi

Unfortunately, none of the heat exchanger models in the analog simulation are suitable for study under the low flow conditions that exist during the start-up. The assumption that the average coolant temperature is the arithmetic mean of the in-flowing and the out-flowing coolant temperatures, which was used to generate the heat exchanger models, is not valid for very low coolant flows where the average coolant temperature gets very close to that of the out-flowing coolant. The implication of using such heat exchanger models is that computed out-flowing coolant temperatures are higher than the skin of the heat exchanger, which is physically impossible.

For these reasons, it was not possible to generate the flow, pressure, and temperature time histories. Instead, steady-state values were obtained and an evaluation of the time to reach steady-state was made.

The steady-state values were obtained from the computer by assuming a given constant turbine temperature and calculating by hand, using steady-state heat exchanger equations, the temperature at the turbine resulting from the mixture of the flows through the various heat exchangers. The difference between the assumed and calculated temperatures leads to a rapidly converging iteration process.

5.4.3 Results

The steady-state values of the pressure, flow, and temperature at the turbine following the opening of the shutoff valve, obtained as explained above, are as follows:

$p = 54$ psi

$W = 0.044$ lb/sec

$T = 590^{\circ}R$

The present knowledge of the dynamic behavior of the variables is summed up in Figure 5.4-1. The major unknowns are the initial temperature, and the time for the system to reach true steady-state. However, it can be said that if the steady-state power output is sufficient to start the turbine, it will start within the first 0.2 sec following the opening of the shutoff valve.

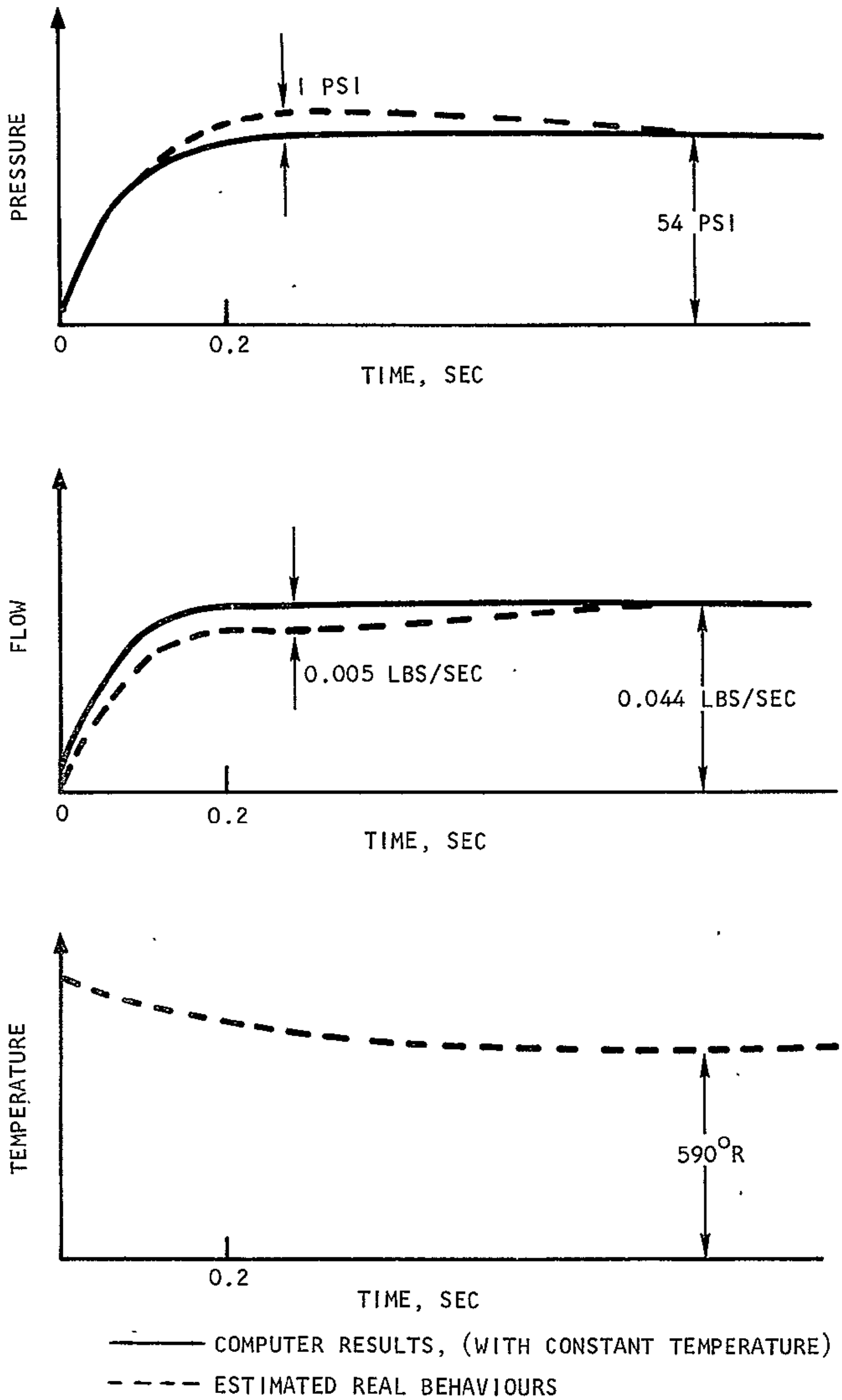


Figure 5.4-1. Dynamic Results

6. DESIGN EFFORT

6.1 DIGITAL COMPUTER

Changes have been made to the engine control programs to include the new method of fuel measurement and a modified combustor limit routine. These have affected the fuel distribution programs with respect to parameter input. Slight changes have also been made to the air mass flow computation.

A convenient means of controlling and monitoring the temperature controlle has been mechanized, and monitoring facilities for the remainder of the equipment is also detailed.

Test programs have been written to check out the computer interface unit and are listed in Appendix D.

An up-to-date storage estimate is given in Section 6.1.7, together with an analysis of available iteration rates, and suggested computer modifications.

A discussion of computer and console hardware performance during this reporting period is detailed in Section 6.1.2.

A list of the required signals to interface the control has been formed and is included in Appendix E.

Engineering software tools, developed for use on the MICRO D computer, and for determining function generator tables, are detailed in Appendix F.

6.1.1 Air Mass Flow Computation

The air mass flow computation is the same as reported in the fifth TDR, with the addition of a high and low range measurement for the spike tip pressure and the inclusion of a check on the reference voltage supplied together with the X-15 velocity components, x, y, and z, from the aircraft inertial platform. This reference voltage determines the validity of the component signals. Comprehensive limit checks for the component signals are retained in the program but these could possibly be reduced to a continuity check on the input. The new listing for this program is included in Appendix G.

6.1.2 Fuel Flow Computation

Fuel flow will be computed by a venturi type flow measurement in the fuel lines in place of the previously used method of flow measurement by means of combustor characteristics.

The fuel flow will be calculated from the equation

$$W = C \frac{P_I}{\sqrt{T_I}} \sqrt{\frac{P_I}{\Delta P}}$$

where P_I = fuel total pressure in the manifold

T_I = fuel total temperature in the manifold

ΔP = fuel differential pressure across the venturi

C = calibration constant

Due to space limitation within the engine, venturi tubes must be placed in both inboard and outboard injector lines on Manifold I. The fuel flow for Manifold I is the summation of the two measurements. This is reflected in the fuel flow distribution shown in Figure 6.I-I.

Additionally, one measurement of the fuel differential pressure across the venturi in manifold three is considered inadequate to cover the range. Two measurements are therefore made. This is reflected in the fuel flow subroutine flow chart shown in Figure 6.I-2.

The new listing for this program is shown in Appendix G.

6.I.3 Combustor Limit Pressure Computation

The combustor pressure ratio degree, below limit, is defined in the second TDR as

$$\Delta P = f\left(M_o, \frac{P_c}{P_{std}}\right) - \frac{P_c'}{P_c} \sqrt{\frac{T_{to}}{T_{std}}}$$

Previously, the error was computed for each of four peripheral measurements around the combustor, but this has now been determined to be unnecessary and in the above equation, P_c is the lowest peripheral pressure measurement on the combustor and P_c' is the corresponding peripheral measurement on the downstream combustor.

The modified combustor limit subroutine flow chart is shown in Figure 6.I-3 and the new listing is shown in Appendix G.

6.I.4 Fuel Flow Distribution

The use of independent parameters for fuel flow combustor pressure limit computations enables these parameters to be inputted during the required computation. This alleviates timing and checking difficulties detailed in the fifth TDR. The subroutines are written to accept a general set of

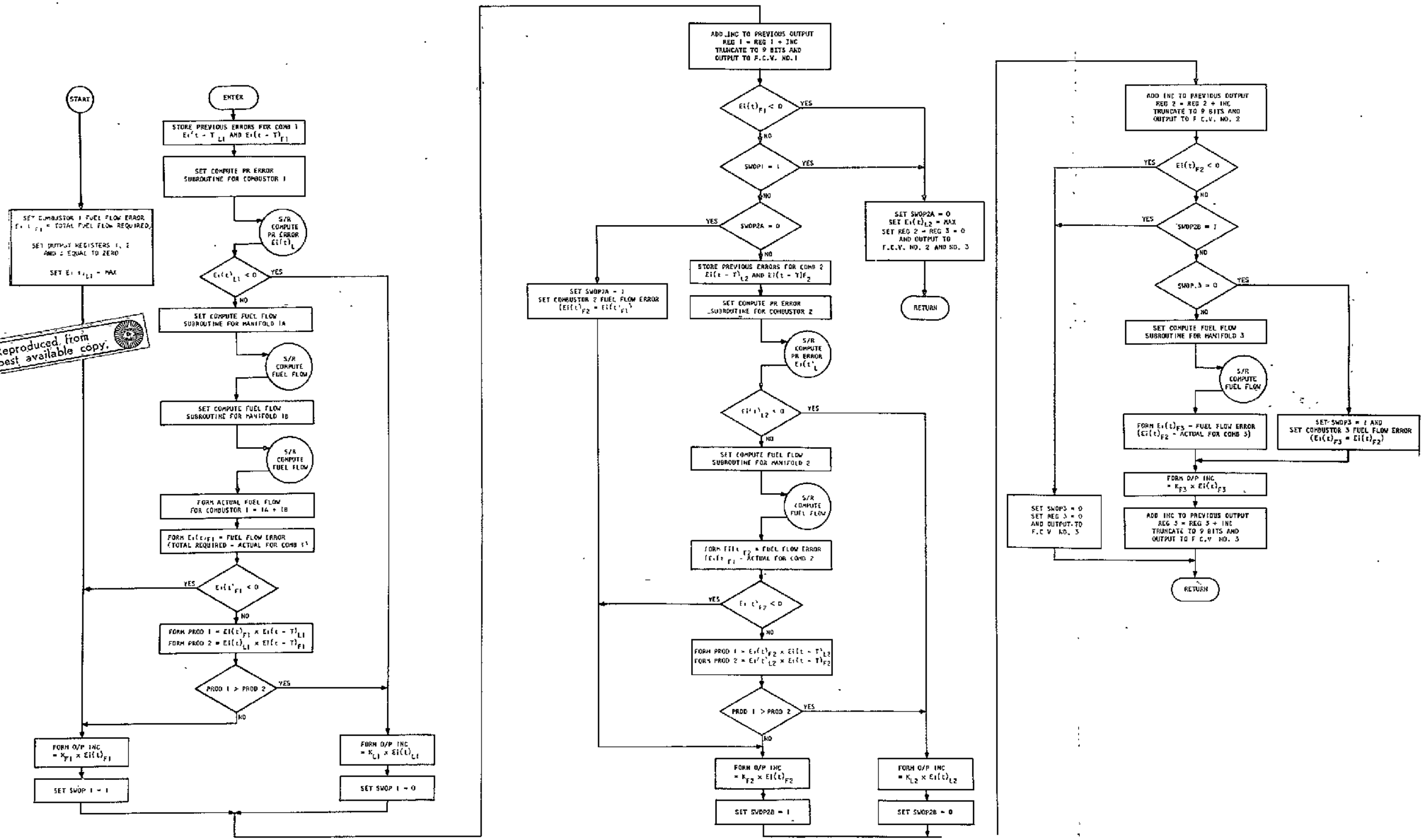


Figure 6.1-1. Fuel Flow Distribution

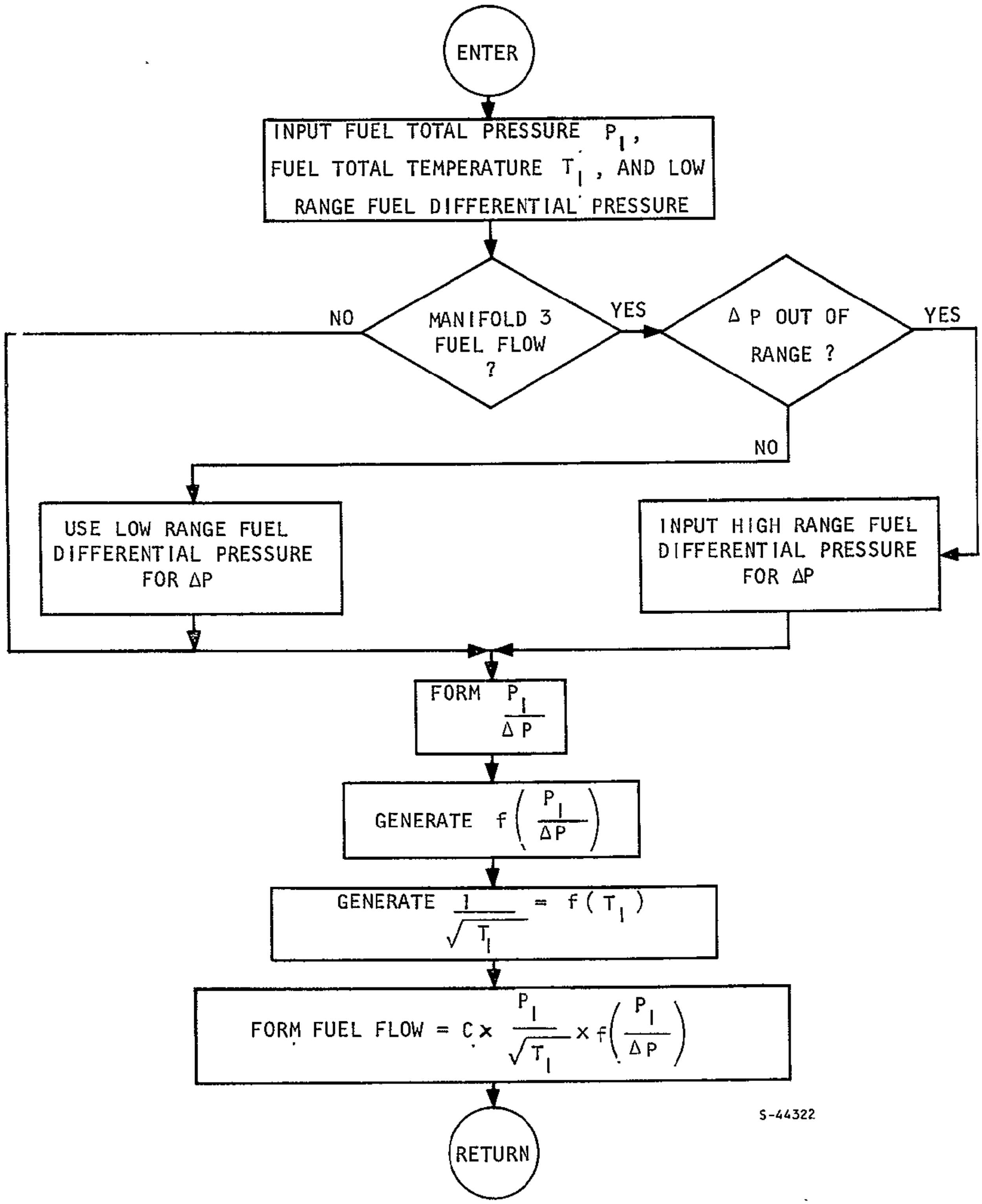


Figure 6.1-2. Manifold Fuel Flow Subroutine MK II

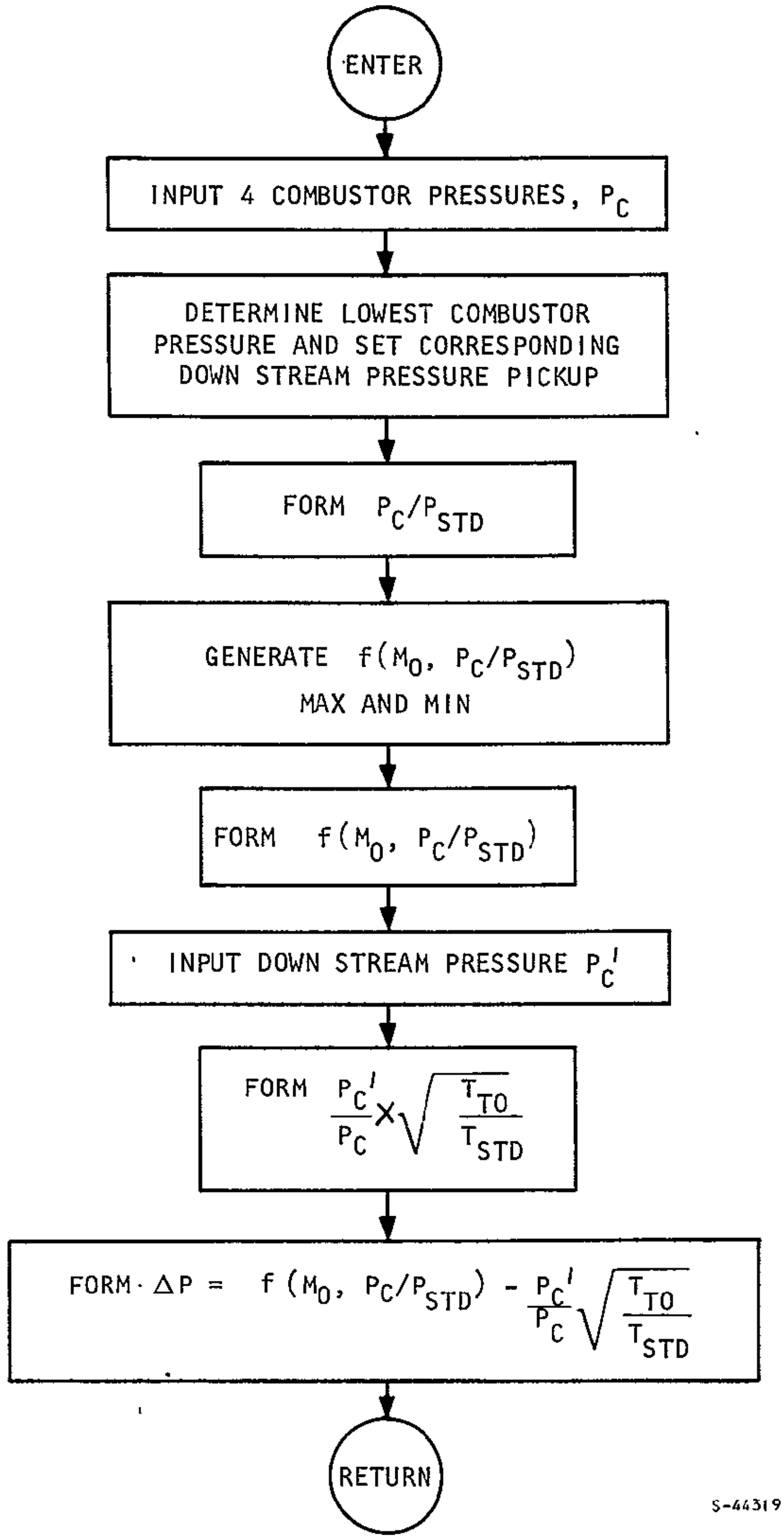


Figure 6.1-3. Combustor Limit Subroutine MK II

parameters. The individual manifold and combustor parameters are being selected, prior to entry of the subroutine, by an indexing procedure obtained by locating the required control values in identical positions in different sectors throughout the store and then selecting the appropriate sector.

The flow charts for subsonic and supersonic distribution are shown in Figure 6.1-4 and 6.1-1 and the new listing is shown in Appendix G.

6.1.5 Temperature Controller Offset Control

A study was made to determine if it is possible for the computer to perform all the functions of the temperature controller. The reasons for implementing the study originated from the desire to include all the necessary facilities for monitoring the operation of the temperature controller and to test its component parts in an automated fashion. The hardware required to perform this opeation appeared extensive. The possibility of reducing the hardware to practically zero therefore warranted some investigation. The flow chart to perform this operation is shown in Figure 6.1-5. Each input temperature required offset and scaling and some form of limit checking. This procedure is fairly lengthy and it was considered possible to provide the scaling of the temperature inputs using a table loop-up technique. The thermocouples can be divided into four groups and a conversion curve could be used to provide scaling and linearity correction. Inputting the thermocouple value in such a way as to be able to use it directly as an address to the table would greatly reduce the time required. Additionally, by masking off extreme values, the need for limit checking could be avoided during the control sequence. It would still be necessary to check the absolute values for monitoring purposes but this could be achieved at a much slower rate.

An estimate was made of the storage and instruction times required to perform this operation. The program required 1293 locations which includes four tables, one for each thermocouple group, containing 128 points. Of more concern was the cycle time of 1216 instruction times. Using the faster computer with a 12.333 μsec instruction time and operating the system at 40 cps this program would occupy approximately 0.6 of a sec every sec.

This amount of time could not be made available and the scheme was discarded. However, it became obvious that the thermocouple offsets would have to be varied for various flight conditons and the control of the offset settings would enable the computer to perform all the monitoring and testing facilities with very little increase in hardware. To control the offsets for the thermocouples, the computer could supply four analog voltages, one per channel, which would be connected to the signal conditioner in each channel. Since the thermocouples in each channel may have different reference levels, it becomes necessary to change the offset value for each individual thermocouple.

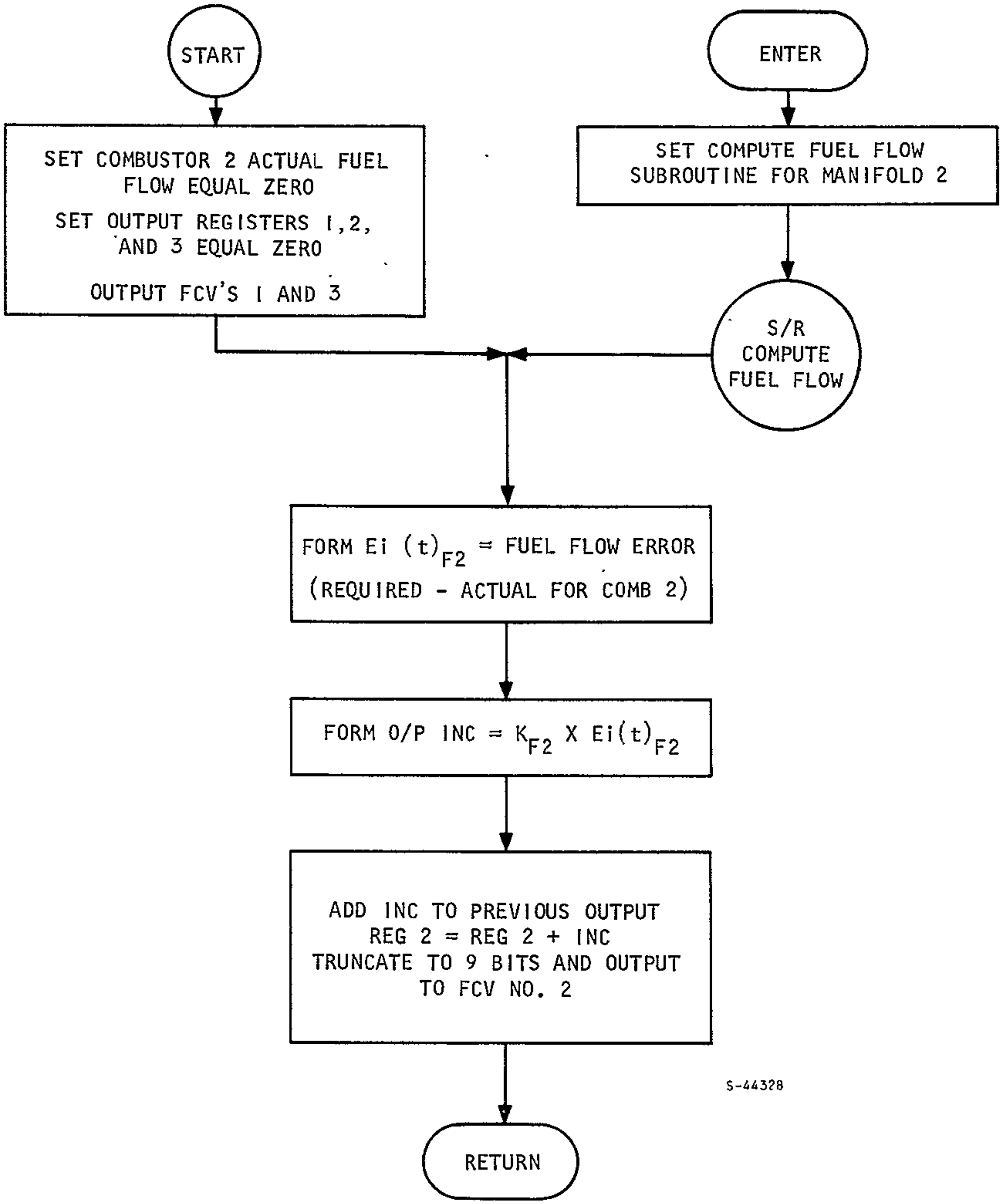


Figure 6.1-4. Fuel Flow Distribution Subsonic Combustion

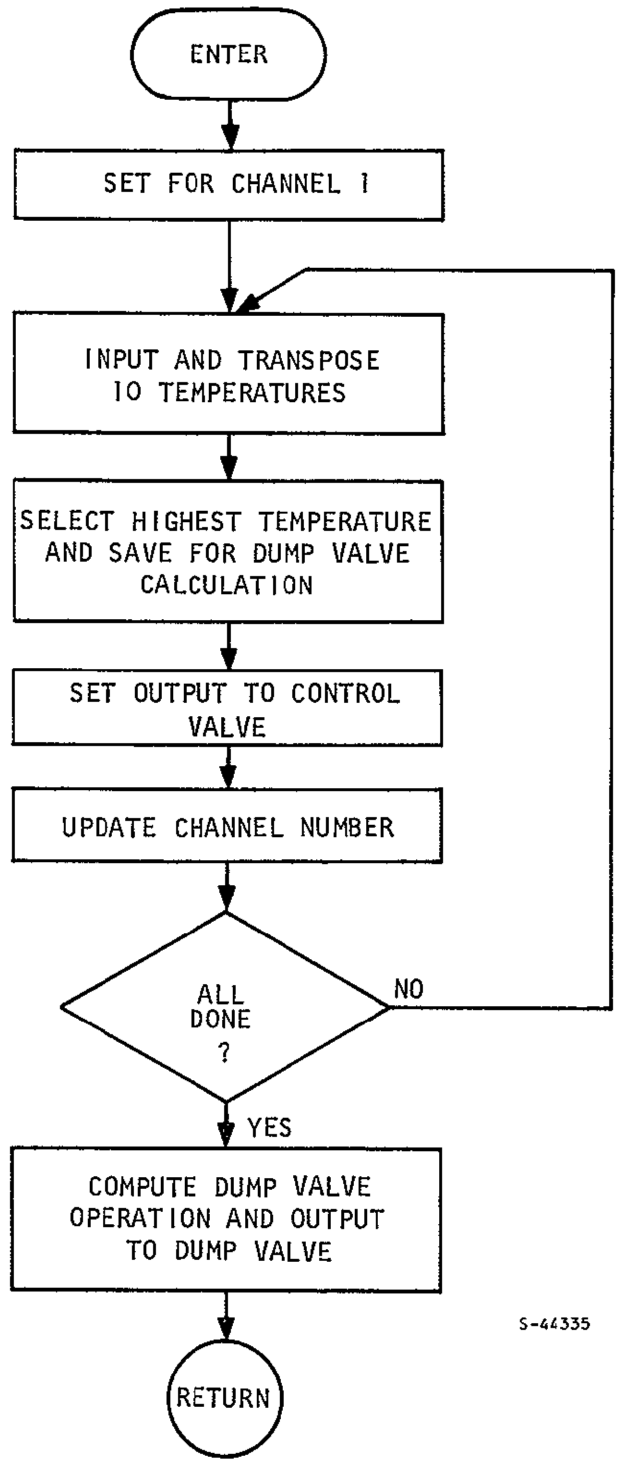


Figure 6.1-5. Temperature Control Subroutine

When the temperature controller multiplexer steps around it generates an interrup to the computer, and the computer then updates the four analog offsets as required. The flow chart for this operation is shown in Figure 6.1-6. The temperature multiplexer steps every 2 msec, and the computer is allowed 500 μsec from the interrup to the output all the temperature offsets. The scheme shown in Figure 6.1-6 takes approximately 16 instruction times from interrupt to last output. With the faster computer time of 12.3 μsec per instruction, this represents 196.8 μsec and is well within the available time. Assuming that there are 10 thermocouples per channel and that each requires a different offset, and that there are three sets of offsets for the various operating conditions, then storage required is 152 locations. The time to complete a cycle is 242 instruction times. With each instruction time occupying 12.3 μsec, a 40 cps iteration rate requires approximately 120 msec every sec.

6.1.6 Executive Function

The executive has the function of tying together all the system programs and controlling their sequence. The system programs can be divided into four major sections as follows:

Engine control programs

Temperature controller offset control program

Monitoring programs

Sequence control and subsidiary programs

6.1.6.1 Engine Control Programs

These programs have been detailed in previous reports and are further amended in this report (see Sections 6.1.1 through 6.1.4).

6.1.6.2 Temperature Controller Offset Control Program

This program is detailed in Section 6.1.5. The program controls the offsets provided to the temperature controller on an interrupt basis. Interrupts will occur into an executive area which will halt the present control sequence and pass control to the offset control program.

6.1.6.3 Monitoring Programs

The monitor program will include all programs required to monitor the control system both in flight and on the ground. These programs will vary in their intensity of monitoring dependent upon modes of operation, available time, and storage space. To date, only the inflight test monitoring programs have been formulated and are presented below. They can be divided into three sections.

- Fuel control monitoring

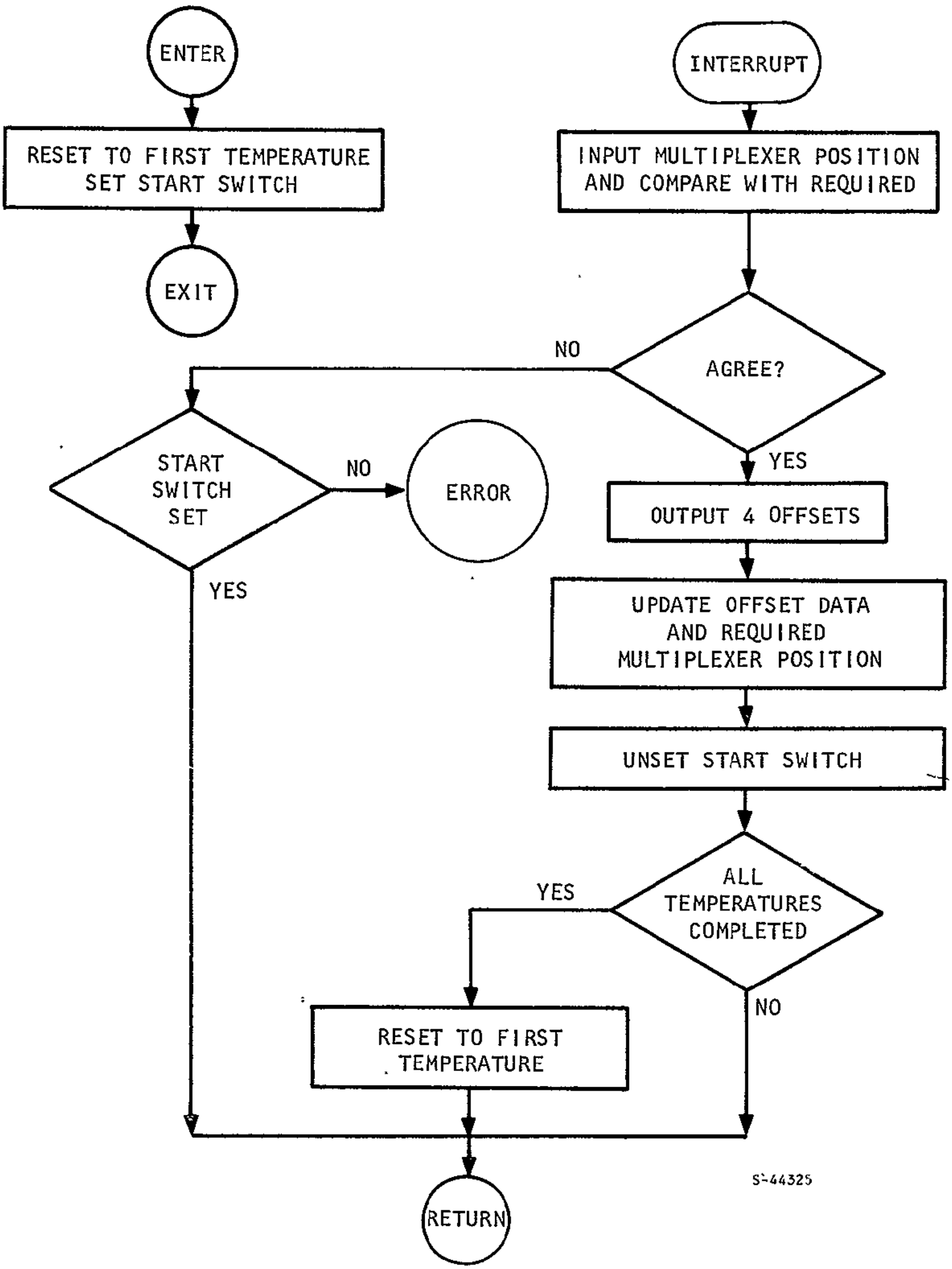


Figure 6.1-6. Temperature Offset Control

- Spike control monitoring

- Temperature control monitoring

6.1.6.3.1 Fuel Control Monitoring

The inputs to the fuel control programs are checked for limit exceedance within the control programs themselves, and only the performance of the fuel valves need be additionally monitored. The flow chart for a program to perform this task is shown in Figure 6.1-7. The fuel valve currents are compared with the required outputs to determine their performance.

6.1.6.3.2 Spike Control Monitoring

The computer is not included in the control loop of the spike and requires both actuator valve and spike position information to perform a monitoring task. For monitoring purposes three conditions can be observed to check the performance of the spike control system.

(a) The spike position, as seen by the control electronics, agrees with the commanded position within close limits. Under these conditions the spike actuator valve current should be within definable limits.

(b) The spike position, as seen by the control electronics, agrees with the commanded position only with large limits. Under these conditions the spike actuator valve current should also be within definable, but much larger, limits. In addition, the polarity of the positional error should correspond with the polarity of the valve current signal.

(c) The spike position, as seen by the control electronics, does not agree with the commanded position within definable limits. Under these conditions the polarity of the position error should correspond to the polarity of the valve current signal and the position error should be decreasing at a definable rate.

The flow chart for the program to perform this task is shown in Figure 6.1-8.

6.1.6.3.3 Temperature Control Monitoring

The computer provides only the offsets to the temperature control unit and will have to simulate the controller operation in order to monitor the controller performance. This entails inputting all the temperatures for each channel and performing credibility checks on the input, determining the highest temperature, and computing the required channel valve currents and dump valve current, and then comparing these computed values with the actual values. The flow chart for a program to perform this task is shown in Figure 6.1-9. As stated in Section 6.1.5, the computer could perform all the functions of the temperature controller on temperature controller operation but the iteration rate required for control would occupy too

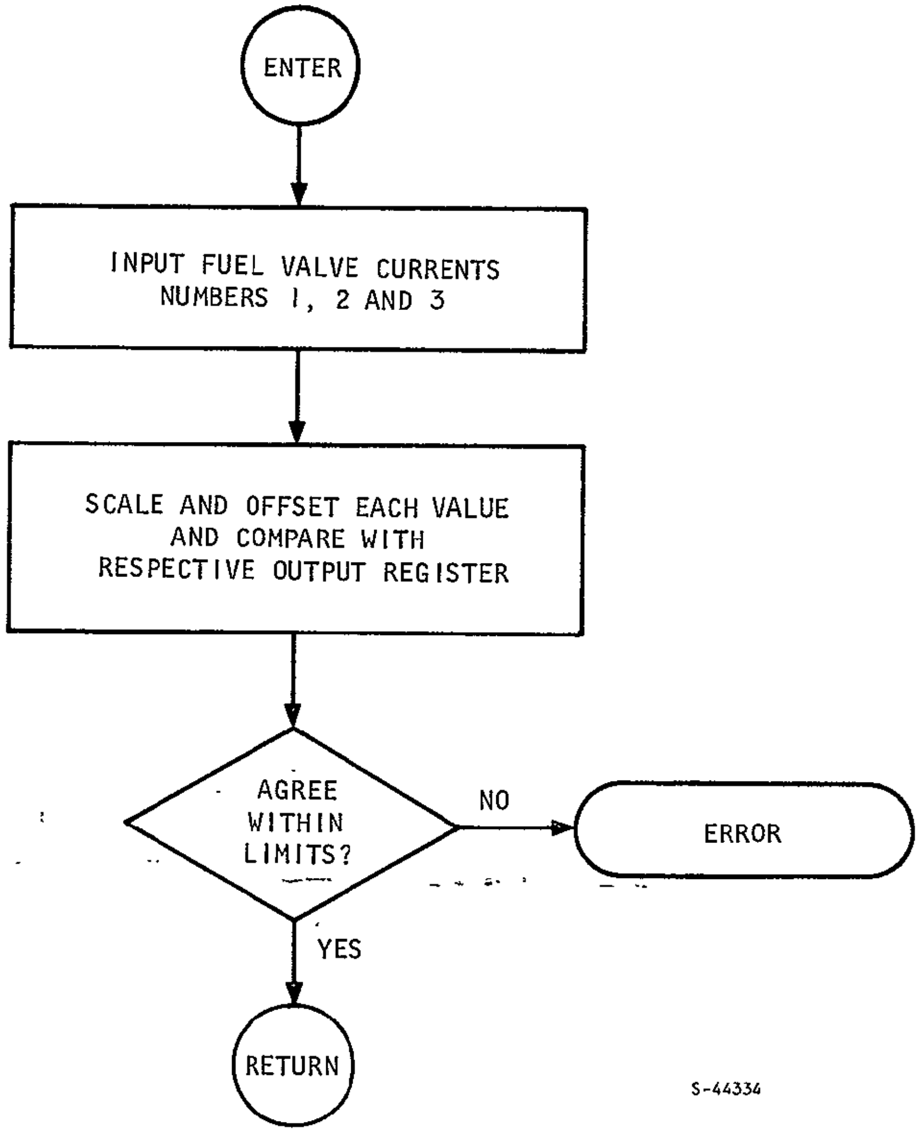


Figure 6.1-7. Fuel Control Valve Monitoring

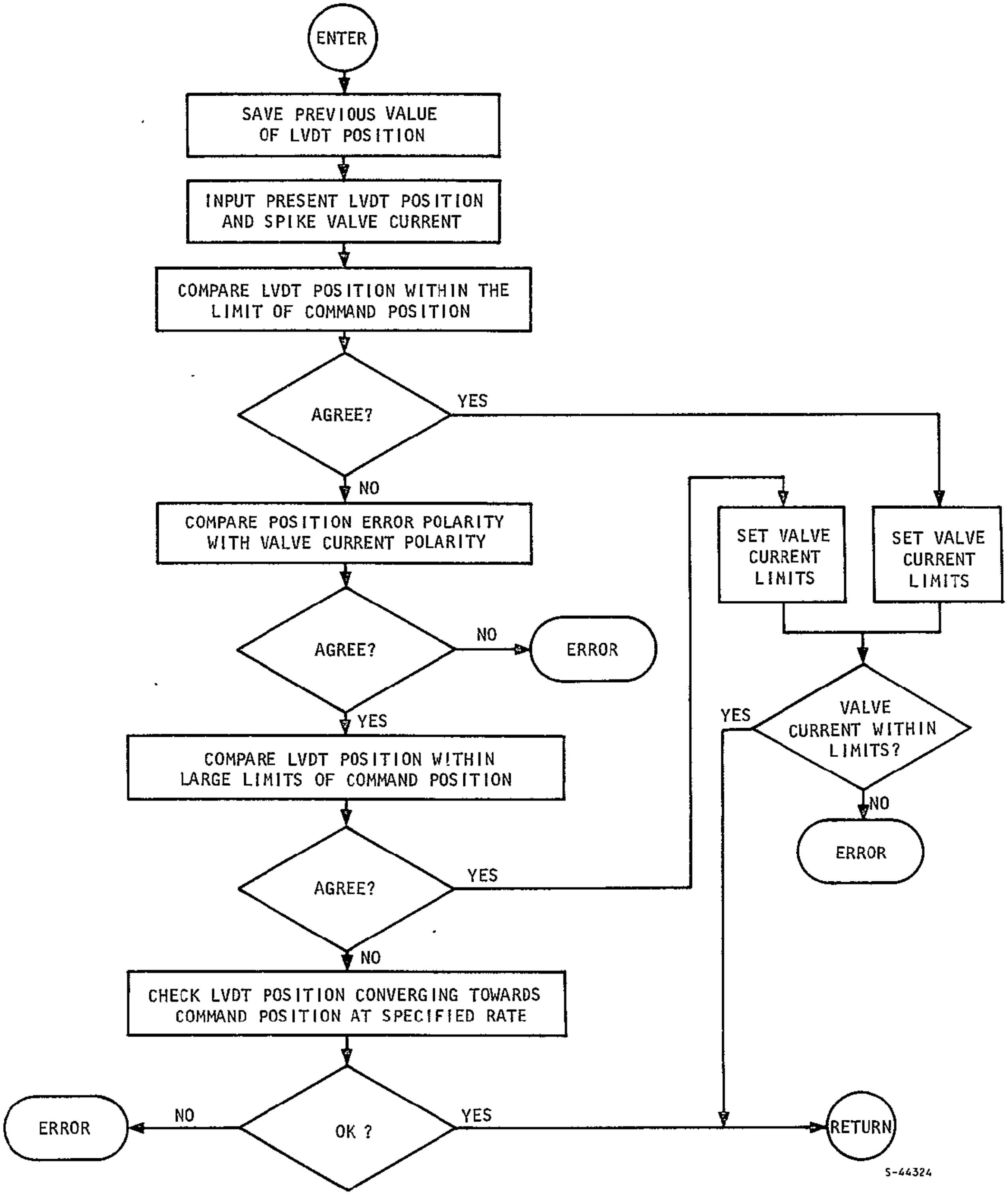


Figure 6.1-8. In-Flight Spike Monitoring

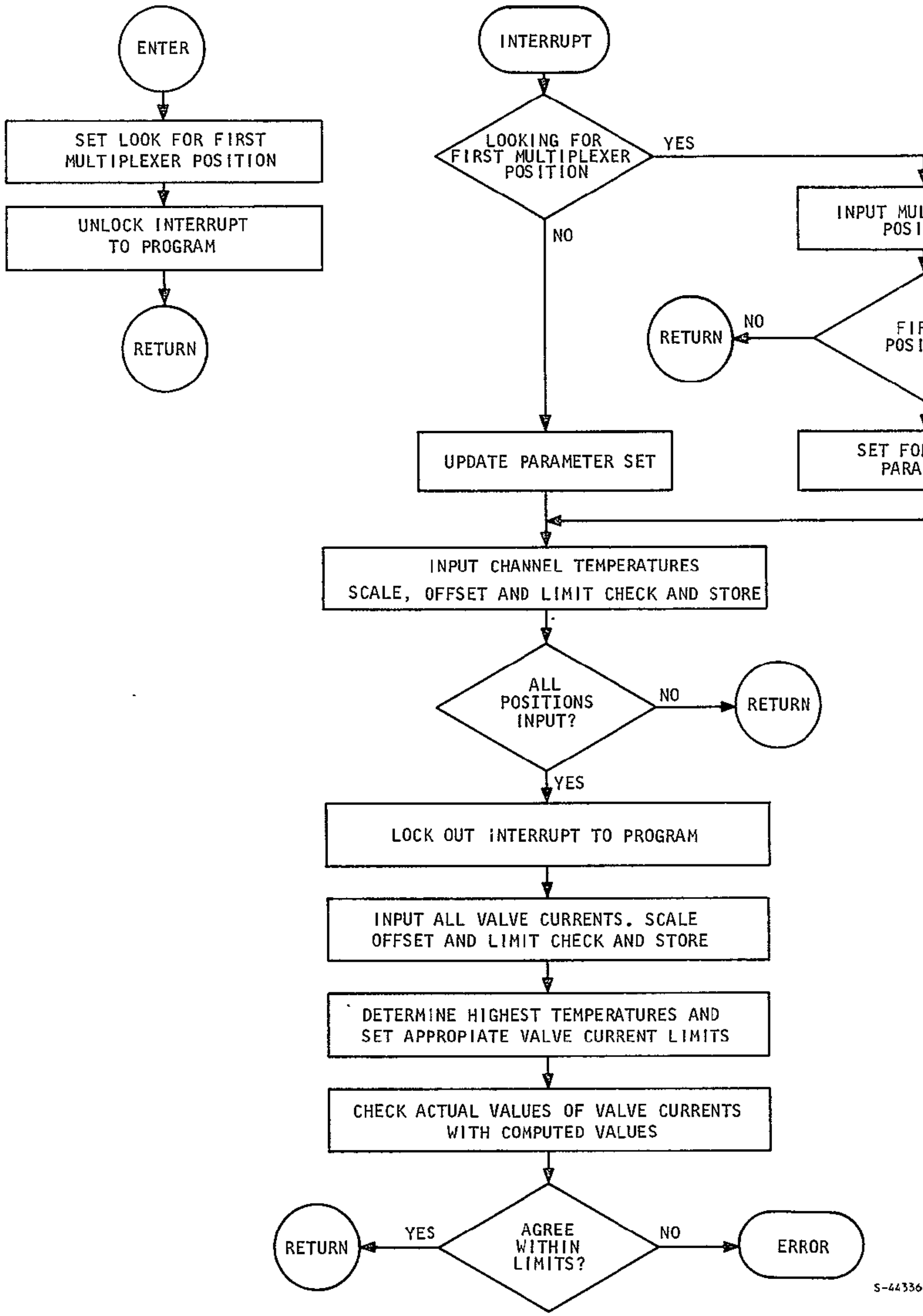


Figure 6.1-9. Temperature Control Monitoring

much computer time; whereas, the task can be performed on a single cycle basis at frequent intervals to provide an excellent monitoring feature.

6.1.6.4 Sequence Control and Subsidiary Programs

The object of the sequence control program is to tie all the major program sections together and to determine the correct mode of operation. The subsidiary programs are additional large-scale programs required during the run sequence. These are the engine start-up and shutdown program and the purge program.

6.1.6.4.1 Sequence Control

The flow chart for the sequence control program is shown in Figure 6.1-10. The airborne test sequence proceeds as follows:

Testing Complete System--This involves checking as much equipment as possible without operating any section of the control system. These tests have not been formulated to date but would include such items as computer diagnostics, comparison tests on input sensors, and current checks on actuator valves that can verify the electrical performance. Prior to the engine run the valve cannot be operated due to absence of pneumatic power. For example, the fuel control valve monitoring, specified in Section 6.1.6.3.1, could be used to check the electronics throughout its full range by outputting a string of commands through the computer output registers. Similarly, it may be possible to exercise the temperature controller by providing suitable offsets to the unit.

In the test sequence a watch will be made for operation of the pilot's switch or for the commencement of cooling. In either event a purge cycle will be initiated prior to entry to the next sequence.

Testing Fuel System, Monitoring Cooling--The same tests as performed in the previous sequence will be used except for those involving valve actuations, which will now be pneumatically energized, and exist for the temperature controller, which will be monitored as per Section 6.1.6.3.3, and its offsets controlled as per Section 6.1.5. A watch will be kept for the pilot's switch in which event the engine start-up will be initiated.

Engine Run--During the engine run, monitoring will be limited to those tests detailed in Section 6.1.6 together with some computer diagnostics. The iteration rates of these checks will depend upon the available operating time. During the engine run, a watch will be maintained for the pilot's switch, low gas supplies, or a test time exceedance, in which event an engine shutdown sequence will be initiated.

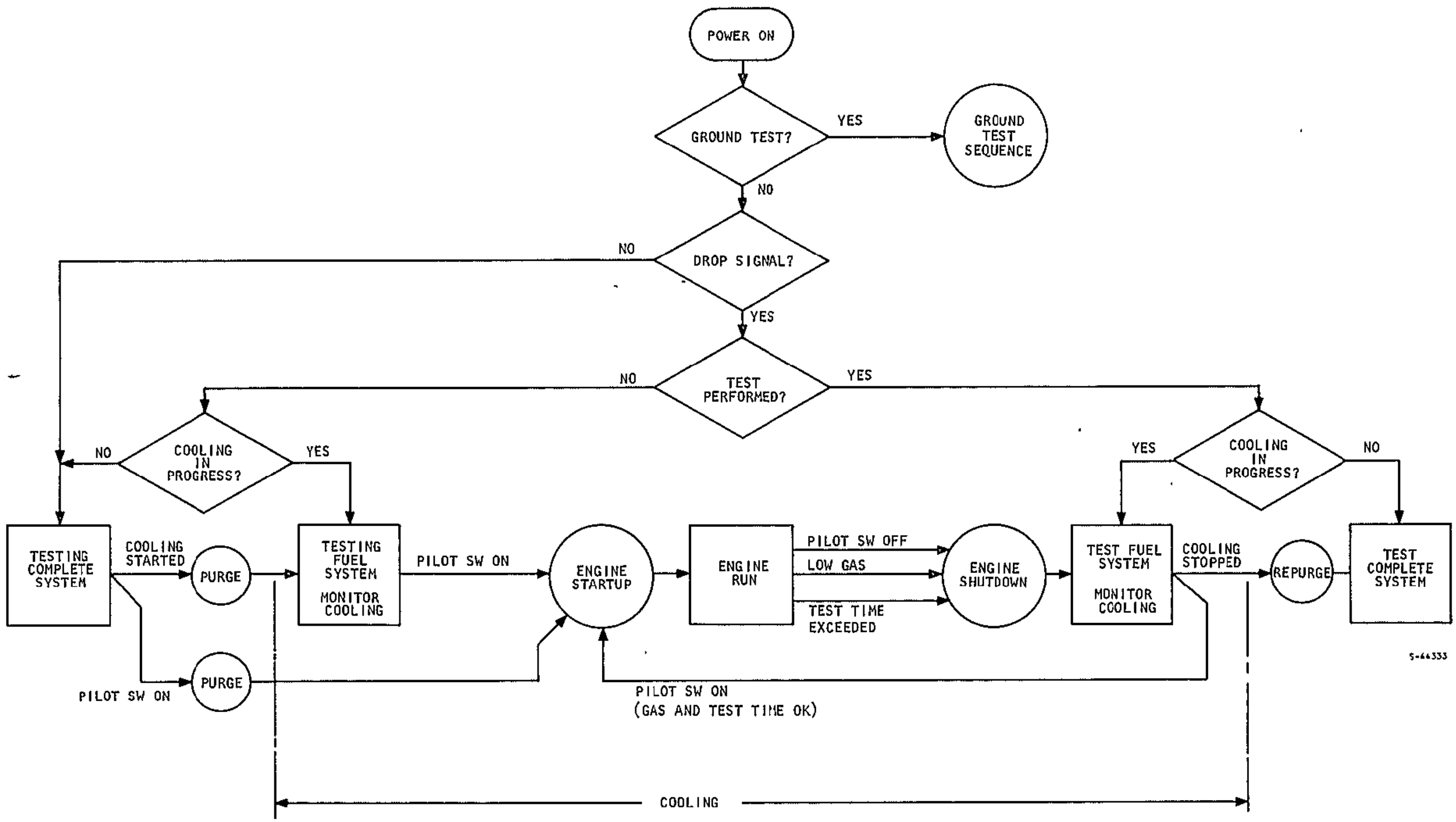


Figure 6.1-10. Sequence Control

Testing Fuel System, Monitoring Cooling--

Testing Fuel System, Monitoring Cooling--Revert to same testing as prior to engine run. A watch will be kept for the pilot's switch and if activated again, a restart will be permitted unless gas pressures are too low or the test duration has been exceeded. When cooling is stopped a repurge cycle is required. So far it has not been determined as to which mechanism should operate the repurge cycle. It can be performed under computer control, except that failure of the computer or the CIU could mean that no repurge could take place. It is more likely that the repurge would be controlled by an external mechanism with perhaps some computer monitoring.

Testing Complete System--After cooling has been terminated testing will revert to the first stage.

Figure 6.1-10 also shows the method of mode determination. When power is turned on, either after a previous interrupt or upon initial switch-on, the program can determine which phase it should be operating under. It should be noted that there is no direct entry into the engine run sequence; this is because no power interrupts will occur during an engine run.

To ensure that the control is operated in its correct sequence, control steps will be written throughout the program. At each control step the executive will check that this step is the next one in the sequence. These steps will be placed in strategic positions such as prior to any control change or any output. An additional safety feature can be obtained by writing a transfer to an error location in the return address of every subroutine used in the control sequence. If the subroutine is entered in any manner other than through its start it will cause an error to be generated which will stop the control program. If the subroutine is entered in the normal way a control stop at the commencement of the routine will ensure correct operating sequence.

6.1.6.4.2 Engine Start-Up and Shut-Down

The flow chart for engine start-up or shutdown is shown in Figure 6.1-11. The routine includes a purge routine required when the run is initiated before cooling is in progress as stated in the sequence control program. The start-up procedure is to enter the air mass flow, to compute data required for the other routines, position the spike, check for unstart conditions and switch on the ignition. The shut-down procedure closes the fuel valves and retracts the spike. If the shut down was initiated due to an aerodynamic function, a restart may be attempted according to the number of times a restart is allowed. Although the ignition is turned on in the start-up procedure, no account is taken of turning the ignition off. To date the ignition requirements are not complete. It seems likely that the subsonic ignition will be on for the complete test and will therefore be turned off in the shut-down program, whereas the supersonic igntion will be intermittent and will require separate treatment.

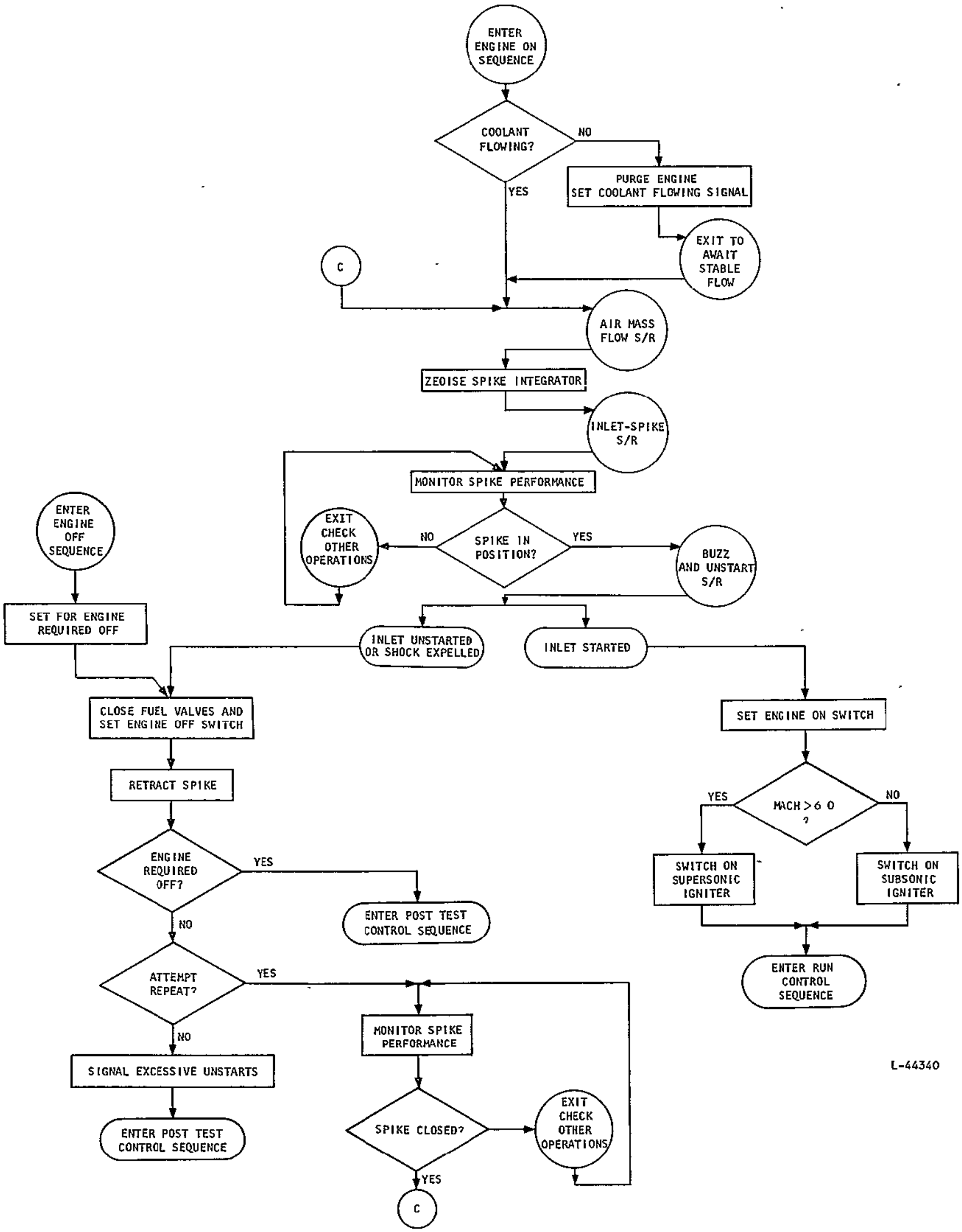


Figure 6.1-11. Engine Start-Up/Shut Down

6.1.6.4.3 Purge Operation

The flow chart for the purge subroutine is shown in Figure 6.1-12. The purge operation can be satisfactorily and safely controlled by the computer, because a failure in the computer system either does not complete the purge operation (open the hydrogen valve), or does not start the operation. Further, a double check is made on the purging time. The helium valve is opened and a count started both internally in the computer and externally in the CIU. When the external timer stops, the internal timer should have reached a definable limit. The rest of the control proceeds step by step.

A repurge cycle cannot be safely controlled by the computer in a similar way. If the computer is allowed to turn off the hydrogen valve it may do so accidentally while cooling is still required, resulting in an overheating condition.

6.1.7 Program Storage and Iteration

The storage requirements for the control software are shown in Table 6.1-1. Of the 5364 locations required, the engine control programs occupy some 3203 locations, the remainder being occupied by executive and monitoring facilities. The storage requirement for the engine control programs agrees very closely with the estimate made in the second TDR although the control system has undergone many changes. This earlier estimate did not include an allowance for the extensive monitoring facilities required by the control system, the inclusion of which has taken the total over the 4096 storage locations available. A stretched version of the ARMA computer is available with 8192 words of storage. It had an identical configuration and instruction set with a slight increase in size. It has been determined that this larger computer can be accommodated within the available space and does not require any changes to the CIU or power supplied. The larger machine has one major advantage over its smaller counterpart, and that is the availability of direct addressing. In the 4K machine, storage beyond the first 256 words must be addressed within 256 word blocks using an index register. This index register, called the sector register in the ARMA computer, contains the base address for each sector or 256 word block, and must be set before addressing any operand within a particular block. This limits the positions in which the operands may be placed without considerable manipulation of the sector register. In the 8K machine, this indexing feature is retained and in addition it is possible to directly address the whole 8192 words of storage. This enables the programmer to place the operands anywhere in storage and eliminates the housekeeping used to keep track of the appropriate contents of the sector register. The program listed for the engine control in this and pervious TDRs are written assuming the availability of this feature within the computer.

The inclusion of the extensive monitoring features have also affected the iteration rates available with the present machine. Table 6.1-2 shows the instructions required per cycle for the programs that could be in use during an engine test run. Each routine is taken for its worst case condition the supersonic fuel distribution dealing with three manifolds taking approximately

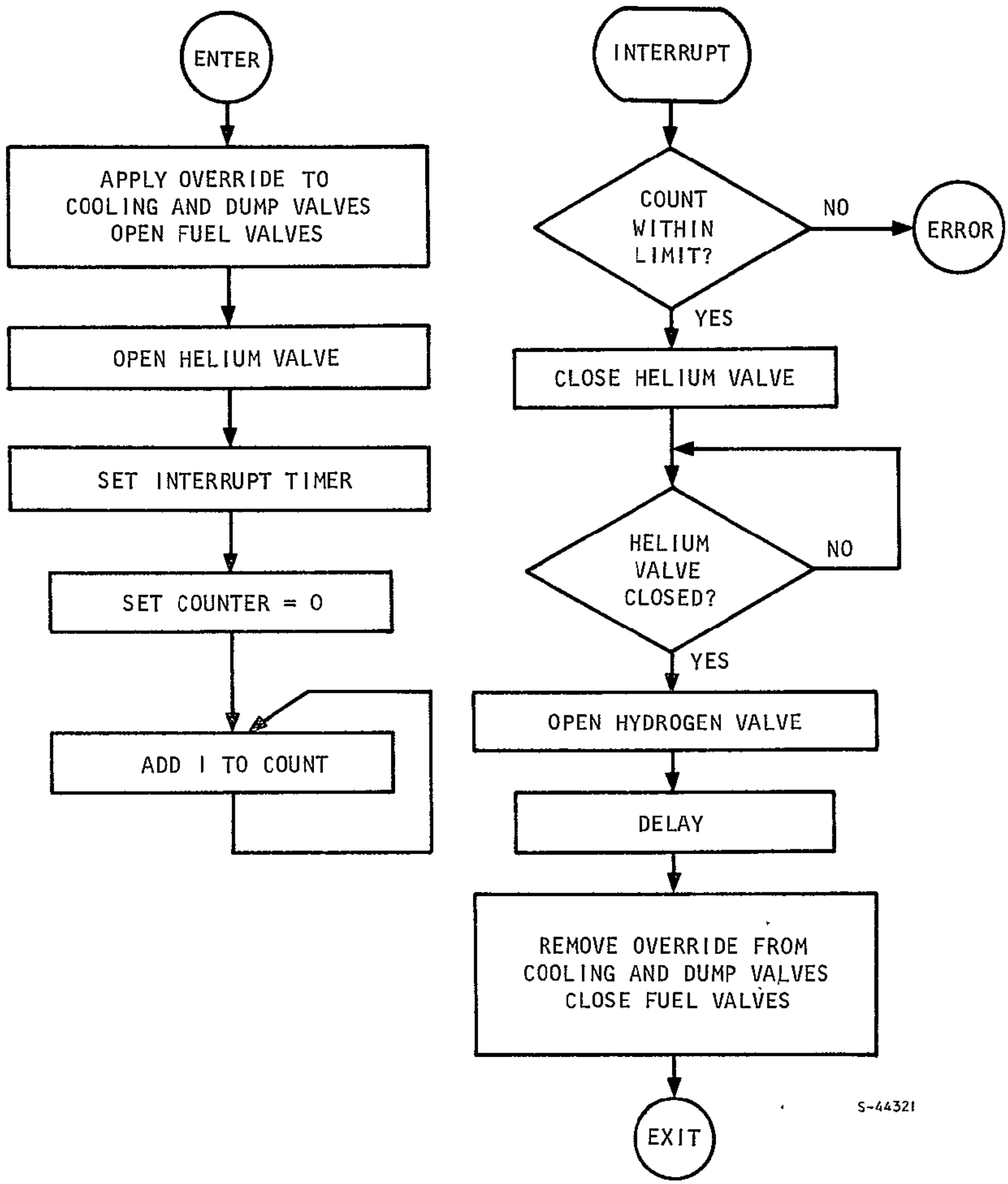


Figure 6.1-12. Purge Subroutine

TABLE 6.1-1

PROGRAM STORAGE REQUIREMENTS

Item	Storage
Engine Control Programs	
Air mass flow computation	1107
Inlet spike control	294
Buzz and unstart control	150
Fuel mass flow computation	195
Subsonic and supersonic fuel distribution	238
Manifold fuel-flow computation	544
Combustor limit computation	636
Interpolation routines	39
Executive Control Programs	
Temperature controller offset control	152
Engine start-up and shut-down control	393
Computer self -check	182
Teletypewriter control	350
Executive Monitoring Programs	
Fuel system	335
Inlet spike system	206
Temperature control system	375
Power supply system	168
Total	5364

TABLE 6.1-2

PROGRAM ITERATION RATES

Item	Instructions/ cycle	Cycles/ sec	Instructions/ sec
Air mass flow computation	1529	2	3058
Fuel mass flow (supersonic combustion)	49	2	98
Fuel distribution (supersonic combustion)	2530	12	30,360
Inlet spike control	71	5	355
Buzz and unstart control	173	5	865
Fuel valve monitoring	132	5	660
Inlet spike monitoring	118	5	590
Temperature controller monitoring	2264	2	4528
Power supply monitoring	160	2	320
Computer self test	134	2	268
Test run termination checks	18	5	90
Executive program linkages	---	---	47
Temperature controller offset servicing	242	40	9680

Total instructions/sec = 50,919

six times as many instructions per cycle as the subsonic distribution. The instructions per cycle for the engine control programs are taken from the listings given in this TDR andthe previous TDR, and the remainder have been taken from rough drafts of the programs. Table 6.1-2 also shows a probable mix of the programs for the control sequence. For this mix the total number of instructions per second is 50,919. The present computer has an instruction rate of 55,555 per second, which adequately covers the required rate. However, it appears highly probable that these iterations will not be fast enough, especially the fuel distribution rate. A modification is available which converts the operating speed of the ARMA computer from 18 μsec per instruction to 12.33 μsec per instruction, which raises the instruction rate to 81,081 per sec. The two computers are identical in every respect except for the basic clock rate. This faster machine would enable a distribution rate of 22 iterations per sec to be performed which, together with the same rates for the remaining tasks, would raise the number of instructions performed per sec to 76,219.

It is recommended, therefore, that the faster, larger version of the ARMA computer be obtained to perform the control function. The machine, termed MICRO D Type 8KD-1804-00, with fast clock option is identical to the MICRO D Type 4K-1802 except where detailed in Table 6.1-3.

TABLE 6.1-3

4K AND 8K COMPUTER CHARACTERISTIC DIFFERENCES

Computer Characteristics	4K Machine	8K Machine With Fast Clock
Memory capacity:	4096 words	8192 words
Instruction time:	18 μsec	12.33 μsec
Power supply:		
+25v	0.475 amps	0.720 amps
+15v	0.175 amps	0.250 amps
+5v	4.5 amps	5.5 amps
-15v	0.1 amp	0.1 amp
Size:		
Width	7-3/8 in.	7-3/8 in.
Height	4-1/2 in.	5 in.
Depth	4-7/16 in.	7-3/8 in.
Weight:	5.75 lb	11 lb

6.1.8 Digital Computer Hardware

6.1.8.1 MICRO D Computer

To date, the computer and console hardware have been running for 256.5 hr. The computer continues to behave normally and no defects have occurred.

6.1.8.2 MICRO D Console

During this reporting period the consòle was fitted with an improved line filter, recommended by the manufacturer, to eliminate interference generated on the 60 cps, 110 v.supply, causing program halts as described in AiResearch Trouble Report 18163 (Data Item No. 26.13). This field modification, designated FM 1043 by the computer manufacturer, was installed at the Torrance plant and was accepted by AiResearch quality control. The modification to the test console proved effective against outside interference but problems still existed when using the teletypewriter.. When the paper tape reader on the teletypewriter was in use, the interference continued and a preliminary analysis by our engineering staff suggested the possibility of grounding problems within the teletypewriter and computer console. This type of problem had been avoided in the engine control hardware by careful design. Unfortunately, before the investigation could be continued the teletypewriter developed a fault and the control system activity was terminated before the teletype could be repaired.

Also during this reporting period, a dry-joint was discovered on the test console that caused a "2" digit to be displayed on the six-digit nixie display register. This joint was resoldered and the fault was corrected.

6.1.8.3 Console Teletypewriter

During this reporting period the teletypewriter developed a self-induced "form feed" which was diagnosed by the teletype repair service as a worn out clutch. The clutch was replaced and the teletypewriter returned to AiResearch in October 1968.

6.2 POWER SUPPLY

This section provides a summary of the power supply circuit development. The block diagram shown in Figure 6.2-1 shows the main elements of the power supply. A summary of the supply characteristics is shown in Table 6.2-1.

During this reporting period, the power supply design was completed, and functional testing was conducted on all the major elements. The only design change in the power supply has been the addition of another isolated, 5-vdc power supply. Appendix H contains a summary of the power supply status.

6.2.1 System Description

A detailed block diagram of the overall power supply, monitoring, and on/off sequencer system with proper interface circuits is shown in Figure 6.2-2.

The method selected for the 5-vdc ±5 percent, 7 to 8 amp supply uses a three-phase, full-wave rectified system which gives a dc output with less than 5-percent ripple without any filter. The ripple frequency is 6 x 400 Hz and a filter of moderate size will reduce the ripple magnitude appreciably.

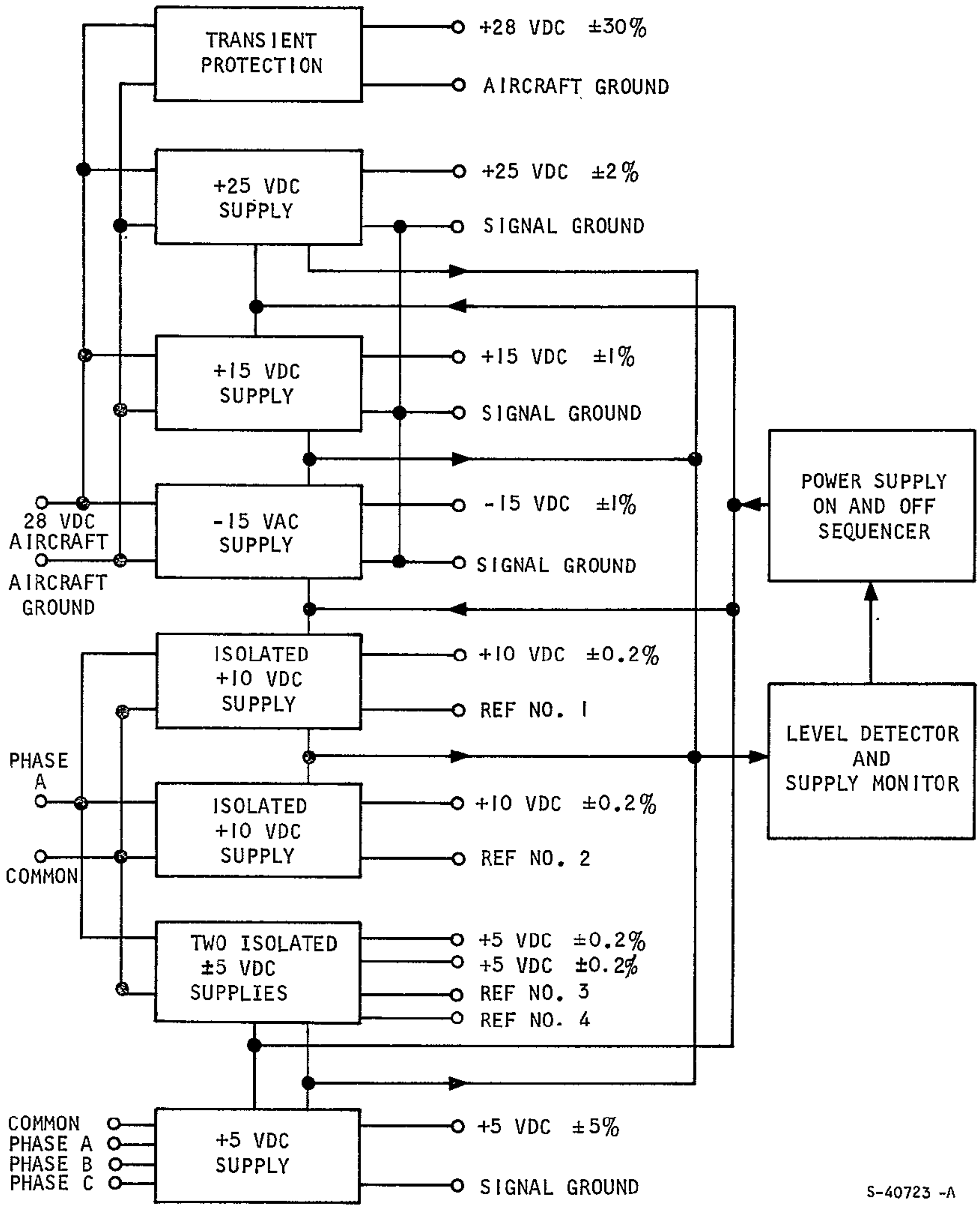


Figure 6.2-1. Initial Power Distribution and Monitoring Block Diagram

TABLE 6.2-1

SYSTEM POWER REQUIREMENTS

Supply Output Number	Output Voltages, vdc	Accuracy Require-ment, percent	Maximum Load Current, amps	Minimum Load Impedance, ohms	Expected Load Requirement Changes, percent	Power Delivered to Control Systems	Input Power Used	Grounds or Refer-ences	Isolation Requirements
1	+28	±30	1.000	28.	±50	28 w	28 vdc	Aircraft ground	---
2	+25	±2	0.475	52	±20	12 w	28 vdc	Signal ground	---
3	+15	±1	0.115	13.5	±20	17 w	28 vdc	Signal ground	---
4	-15	±1	0.859	17.5	±20	13 w	28 vdc	Signal ground	---
5	+10	±0.2	0.120	83	±20	1.2 w	115 vac 1 phase	Ref. No. 1	Complete isolation
6	+10	±0.2	0.120	83	±20	1.2 w	115 vac 1 phase	Ref. No. 2	Complete isolation
7	+5	±0.2	0.005	6.25	±20	25 mw	115 vac 1 phase	Ref. No. 3	Complete isolation
8	+5	±0.2	0.005	6.25	±20	25 mw	115 vac 1 phase	Ref. No. 4	Complete isolation
9	+5	±5	7.800	0.64	±20	40 w	115 vac 3 phase	Signal ground	---

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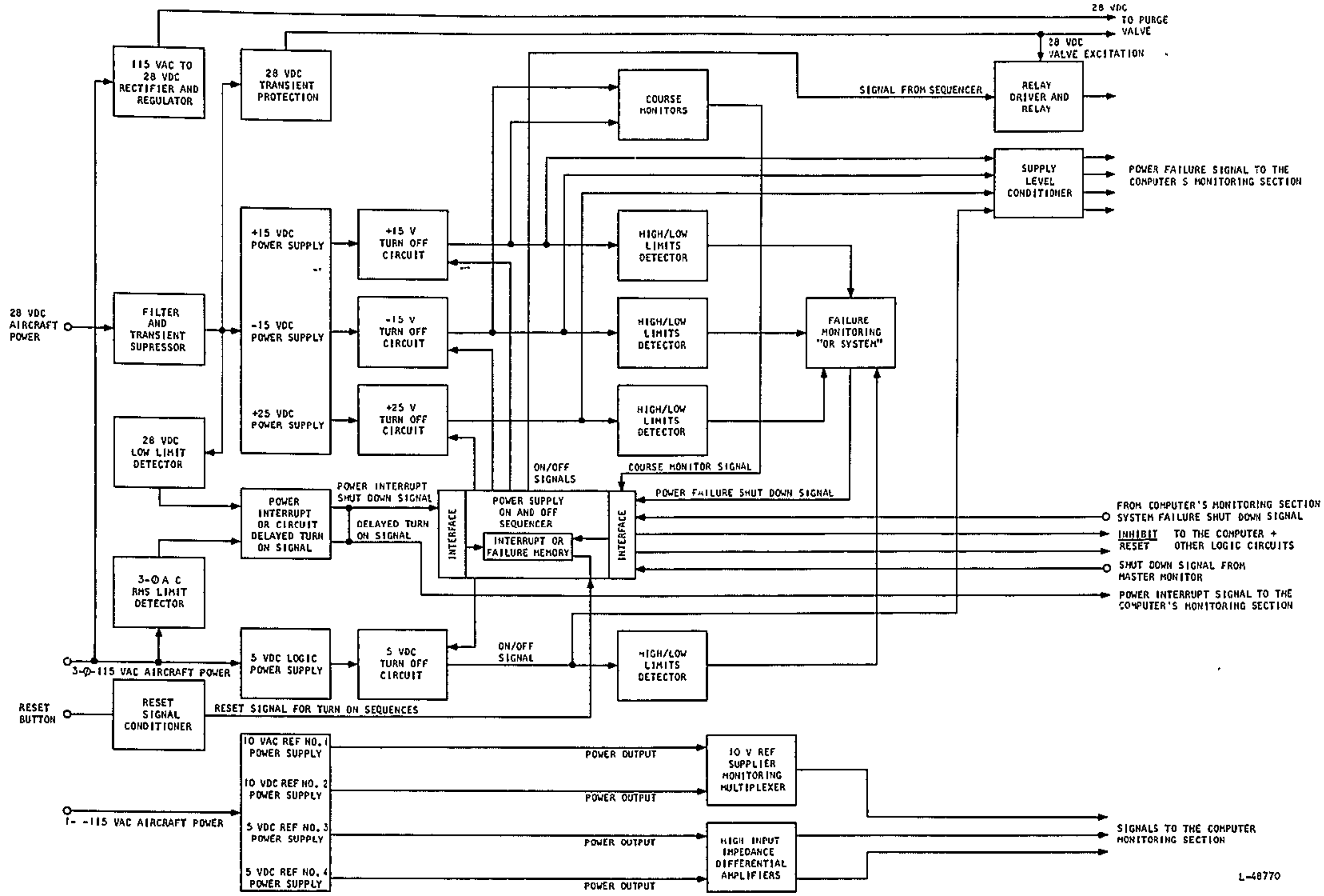

Figure 6.2-2. Block Diagram of HRE Power Supply, Monitoring, and ON/OFF Sequencing System

The +25-vdc, +15-vdc and -15-vdc supplies all need much better regulation than 5 percent. Since all of these carry heavy currents, the preferred method in these cases is to use high frequency dc-to-dc pulse width chopper supplies. The pulse width method was selected because of the large input voltage range specified for the 28-vdc aircraft power. The chopping frequency to be used will be between 10 and 50 kHz. This will decrease the filter size to about 1/25 of that needed for 400 Hz 115-vac, single-phase aircraft power input.

The power consumption of the low-current, highly regulated supplies will be much lower than any of the other supplies. The output voltages can be several volts lower than the source values and the power losses due to regulation will still be negligible. Total isolation is a requirement for these highly regulated supplies. The most suitable solution is to use 115-vac, 400-Hz single-phase power since the total power requirement is quite small.

6.2.2 Supplies Using 115-vac, Single-Phase Aircraft Power (Reference Supply)

The specification calls for four different isolated reference supplies: two identical +10-v ±0.2-percent supplies; and two identical ±5-v ±0.2-percent supplies. The input source chosen is the 115-vac, single-phase, 400-Hz aircraft power.

A precision voltage supply is obtained when the output impedance for any frequency is much lower than the load impedance. This is achieved with a high-gain comparator. A second requirement is that a good stable reference for the comparator must be established.

The μA709, a high-gain operational amplifier, is used to compare the output voltage with the reference and to provide the control drive for the supply output. This device features low offset, high-input impedance, low-output impedance, large input common mode range, and high output swing underload.

The reference voltage is established with a temperature compensated zener diode. However, this voltage reference diode will only regulate without upsetting the temperature stability when the bias current is limited to a change of less than 10-percent. By using a preregulated voltage reference, the bias current range of 10-percent maximum can be achieved. For the 10-v reference supplies, the final 10-v output will be used as a preregulated voltage reference. However, for the 5-v reference supplies, a preregulated voltage reference has to be created with a second zener diode. The reasons for this is that temperature compensated zener diodes are only available in rather odd voltage ranges with no range below 5 v.

The μA709 operation requires a positive and a negative voltage source with limits from ±12 v to ±18 v. This is delivered from the 115-v source through a "ac-to-ac" transformer, then full-wave rectified and filtered.

The schematic of the four reference suuplies is shown in Figure 6.2-3.

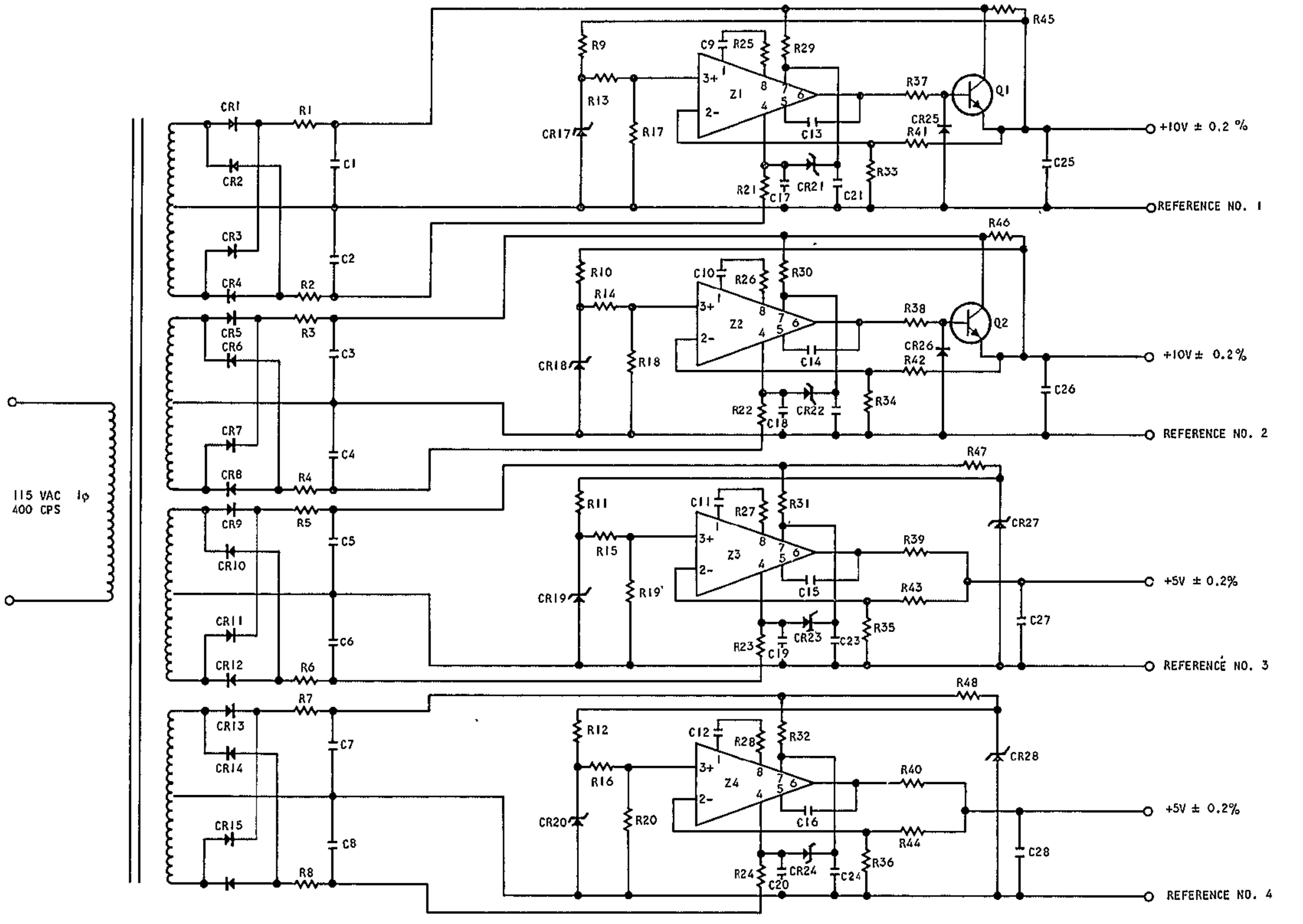

Figure 6.2-3. HRE Power Supply, Reference Supplies

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PARTS LIST FOR FIGURE 6.2-3

R1 = 5 Ω ±5 percent, 3 w
R2 = 62 Ω ±5 percent, 1/2 w
R3 = 5 Ω ±5 percent, 3 w
R4 = 62 Ω ±5 percent, 1/2 w
R5 = 5 Ω ±5 percent, 3 w
R6 = 62 Ω ±5 percent, 1/2 w
R7 = 5 Ω ±5 percent, 3 w
R8 = 62 Ω ±5 percent, 1/2 w
R9 = 2.7 KΩ ±0.5 percent, 1/4 w
R10 = 2.7 KΩ ±0.5 percent, 1/4 w
R11 = 2 KΩ ±0.5 percent, 1/4 w
R12 = 2 KΩ ±0.5 percent, 1/4 w
R13 = 10 KΩ ±0.01 percent, 1/4 w
R14 = 10 KΩ ±0.01 percent, 1/4 w
R15 = 10 KΩ ±0.01 percent, 1/4 w
R16 = 10 KΩ ±0.01 percent, 1/4 w
R17 = 10 KΩ ±0.01 percent, 1/4 w
R18 = 10 KΩ ±0.01 percent, 1/4 w
R19 = 10 KΩ ±0.01 percent, 1/4 w
R20 = 10 KΩ ±0.01 percent, 1/4 w
R21 = 100 KΩ ±5 percent, 1/4 w
R22 = 100 KΩ ±5 percent, 1/4 w
R23 = 100 Ω ±5 percent, 1/4 w
R24 = 100 Ω ±5 percent, 1/4 w
R25 = 1.5 KΩ ±5 percent, 1/4 w
R26 = 1.5 KΩ ±5 percent, 1/4 w
R27 = 1.5 KΩ ±5 percent, 1/4 w
R28 = 1.5 KΩ ±5 percent, 1/4 w
R29 = 100 Ω ±5 percent, 1/4 w
R30 = 100 Ω ±5 percent, 1/4 w

R31 = 100 Ω ±5 percent, 1/4 w
R32 = 100 Ω ±5 percent, 1/4 w
R33 = 5 KΩ ±0.01 percent, 1/4 w
R34 = 5 KΩ ±0.01 percent, 1/4 w
R35 = 5 KΩ ±0.01 percent, 1/4 w
R36 = 5 KΩ ±0.01 percent, 1/4 w
R37 = 200 Ω ±5 percent, 1/4 w
R38 = 200 Ω ±5 percent, 1/4 w
R39 = 200 Ω ±5 percent, 1/4 w
R40 = 200 Ω ±5 percent, 1/4 w
R41 = 10.6 KΩ ±0.01 percent, 1/4 w
R42 = 10.6 KΩ ±0.01 percent, 1/4 w
R43 = 2.81 KΩ ±0.01 percent, 1/4 w
R44 = 2.81 KΩ ±0.01 percent, 1/4 w
R45 = 51 KΩ ±5 percent, 1/4 w
R46 = 51 KΩ ±5 percent, 1/4 w
R47 = 1 KΩ ±2 percent, 1/4 w
R48 = 1 KΩ ±2 percent, 1/4 w

C1 = 33 μfd. ±10 percent 50 vdc
C2 = 15 μfd. ±10 percent 35 vdc
C3 = 33 μfd. ±10 percent 50 vdc
C4 = 15 μfd. ±10 percent 35 vdc
C5 =
C6 =
C7 = 33 μfd. ±10 percent 50 vdc
C8 = 10 μfd. ±10 percent 35 vdc
C9 = 330 pfd. ±10 percent 100 vdc
C10 = 330 pfd. ±10 percent 100 vdc
C11 = 330 pfd. ±10 percent 100 vdc
C12 = 330 pfd. ±10 percent 100 vdc

C13 = 47 pfd. ±10 percent 100 vdc
C14 = 47 pfd. ±10 percent 100 vdc
C15 = 47 pfd. ±10 percent 100 vdc
C16 = 47 pfd. ±10 percent 100 vdc

CR1 = μT4010
CR2 = μT4010
CR3 = μT4010
CR4 = μT4010
CR5 = μT4010
CR6 = μT4010
CR7 = μT4010
CR8 = μT4010
CR9 = μT4010
CR10 = μT4010
CR11 = μT4010
CR12 = μT4010
CR13 = μT4010
CR14 = μT4010
CR15 = μT4010
CR16 = μT4010
CR17 = 1N457A
CR18 = 1N457A
CR19 = 1N457A
CR20 = 1N457A
CR21 = μZ833
CR22 = μZ833

CR23 = μZ833
CR24 = μZ833
CR25 = 1N457
CR26 = 1N457
CR27 = 1N4775A
CR28 = 1N4775A

Z1 = μA709
Z2 = μA709
Z3 = μA709

Q1 = 2N3997
Q2 = 2N3997

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6.2.3 Supply Using 115-vac, Three-Phase Aircraft Power (+5-v Logic Supply)

A three-phase transformer with a full-wave-output rectifier unit provides proper dc output. The ripple content is less than 5 percent so filtering is unnecessary. However, the 115-vac source changes from 102 v to 180 v, so an output regulator becomes a necessity.

Most voltage regulators contain five functional elements; output indicator, comparator, reference, amplifier, and control, as shown in Figure 6.2-4. A voltage regulator uses an error or difference signal to correct any error in the output. The voltage difference between the reference and the output indicator is detected and amplified by the comparator and the amplifer elements. The control element senses the magnitude and phase ofthe amplified difference and regulates the output voltage inthe proper direction to correct any change.

The output indicator consists of two resistors working as a voltage divider. The comparator, reference, and signal amplifier are all built into one unit, the LM105.

The LM105 is an integrated voltage regulator. The gain is not sufficient so an extra amplifer stage is added. The control element is constructed with one power transistor (drive transistor). To achieve highest possible efficiency, as low as possible voltage drop (V_d) across thedrive transistor is needed, which is the heavy load current carrier. By providing an extra voltage source to drive the transistor base (the amplifer output) at a higher voltage (but much lower current) than the main input voltage source, the driver transistor can be operated with a voltage drop almost as low as its saturation voltage (see Figure 6.2-4).

The circuit diagram of the +5-v logic supply is shown in Figure 6.2-5.

6.2.4 Supply Monitoring, Level Detection, and ON/OFF Sequencing

This section will be divided into four subsections. The block diagram shown in Figure 6.2-2 gives an overall description of all the following circuits:

- Power interrupt level detection, which includes the following parts:
  - (a) 28-v aircraft power low-limit detector
  - (b) 3-phase ac aircraft power low-limit detector
  - (c) Power interrupt "OR" circuit
  - (d) Delay circuit for turn on signal

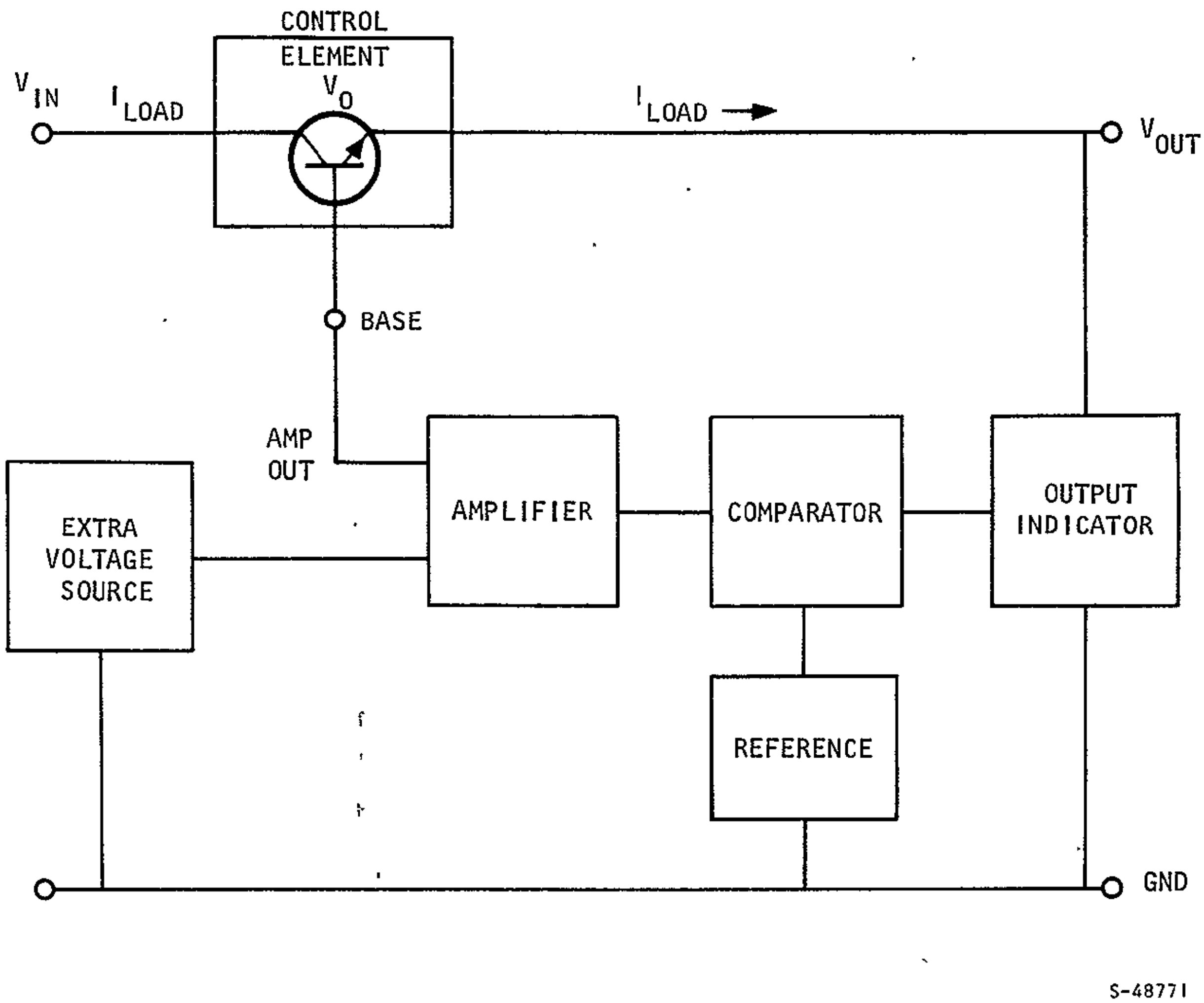

Figure 6.2-4. Series Voltage Regulator Block Diagram

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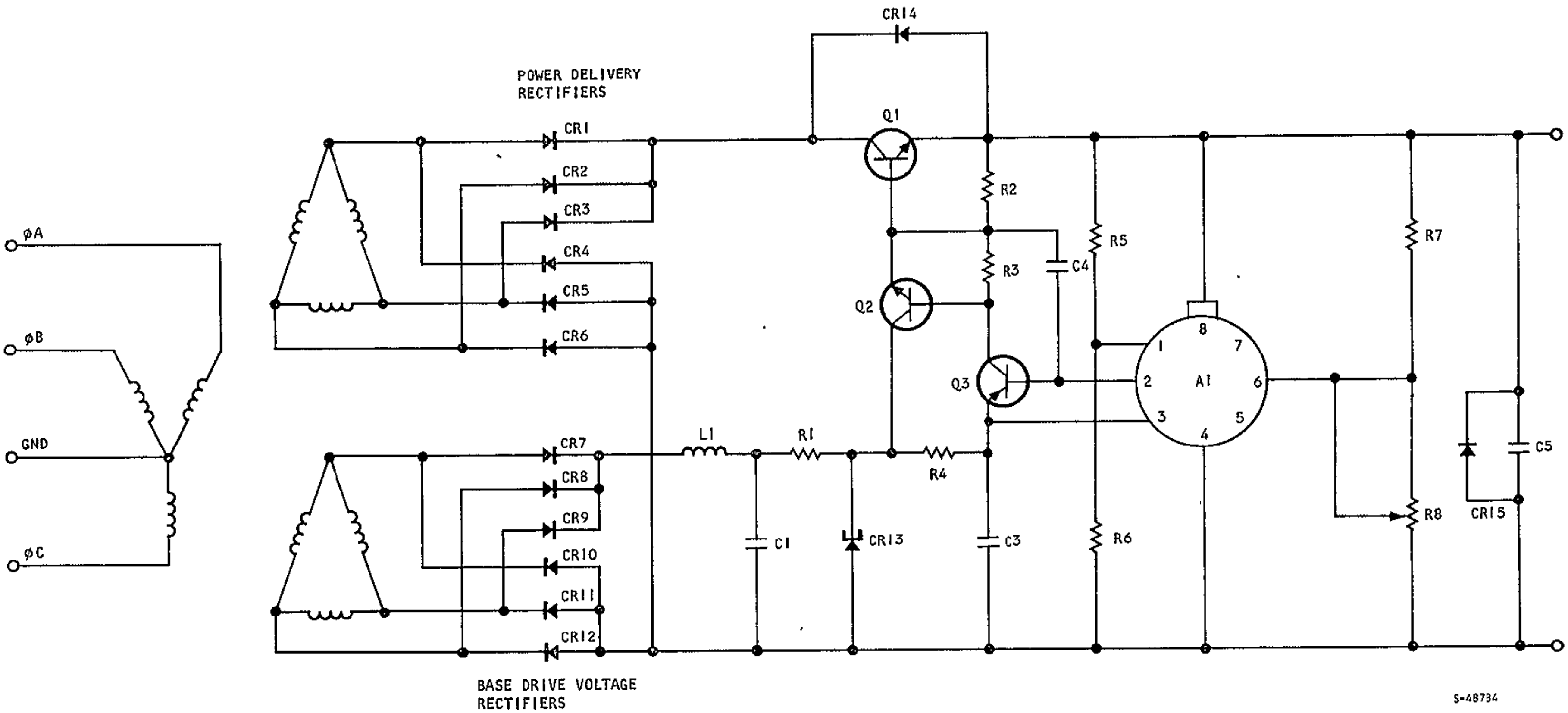

Figure 6.2-5. HRE Power Supply, Three-Phase-to-DC Supply

PARTS LIST FOR FIGURE 6.2-5

R1	=	1 Ω ±5 percent, 1/2 w
R2	=	6.8 Ω ±5 percent, 1/2 w
R3	=	6.8 Ω ±5 percent, 1/2 w
R4	=	10 Ω ±5 percent, 1/2 w
R5	=	33 Ω ±5 percent, 1/2 w
R6	=	270 Ω ±5 percent, 1/2 w
R7	=	6.5 KΩ ±1 percent, 1/4 w, 75 ppm/^{o}C
R8	=	5 KΩ pot.
C1	=	150 μf, ±10 percent, 20 v
C3	=	150 μf, ±10 percent, 20 v
C4	=	1 μf, ±10 percent, 20 v
C5	=	4000 μf, ±10 percent, 10 v
CR1	=	μT6105
CR2	=	μT6105
CR3	=	μT6105
CR4	=	μT6105
CR5	=	μT6105
CR6	=	μT6105
CR7	=	μT4010
CR8	=	μT4010
CR9	=	μT4010
CR10	=	μT4010
CR11	=	μT4010
CR12	=	μT4010
CR13	=	μZ7812
CR14	=	1N4001
CR15	=	1N4001
Q1	=	SDT8607
Q2	=	2N3054
Q3	=	2N2907
A1	=	LM105
T	=	ADC Electronics 1900

- Output failure monitoring, which includes the following circuits:

  a. high- and low-limit detectors (for +5-v, +15-v, +25-v, and -15-v supplies)

  b. failure monitoring "OR" circuit

  c. course monitors for the +15-v and -15-v supplies

- Supply ON/OFF sequencer, which includes the following:

  a. sequencer interface, power interrupt/failure signal memory

  b. sequencer timing board

  c. power supply turn-off switches

- Computer monitoring interface, which includes:

  a. interface between the reference supplies and the computer

  b. interface between the +15-v, -15-v, +25-v, and +5-v supplies outputs and the computer

  c. interface between the computer and the ON/OFF sequencer

The power interrupt level detector has the function of deciding when the source voltages (dc aircraft power and ac aircraft power) are too low for correct supply operation, and then command the supply shut-down to start. The second function is to sense when the sources are both back in normal operation range, and then initiate a turn-on sequence. This turn-on initiation has a time delay long enough to give the sequencer a chance to set in the complete supply-off condition before any turn-on starts. The circuit schematic of the interrupt detectors is shown in Figure 6.2-6.

The output failure monitoring commands the sequencer to start a supply shut down when any of the supply outputs is either too low or too high. Figure 6.2-7 describes the monitoring circuits. The sequencer timing board is represented on the schematic identified as AiResearch Drawing No. SK43876 (refer to page 6-20 of the Fifth Control System TDR). Its function is to provide the supply turn-off switches with properly delayed operating signals.

The memory circuit has the ability to distinguish an interrupt signal from a failure signal, and it memorizes which one appeared first with the shut-down signal. With this information the memory circuit will then decide if a power supply turn-on is acceptable. This circuit interfaces with the sequencer timing board, and will be physically located with it.

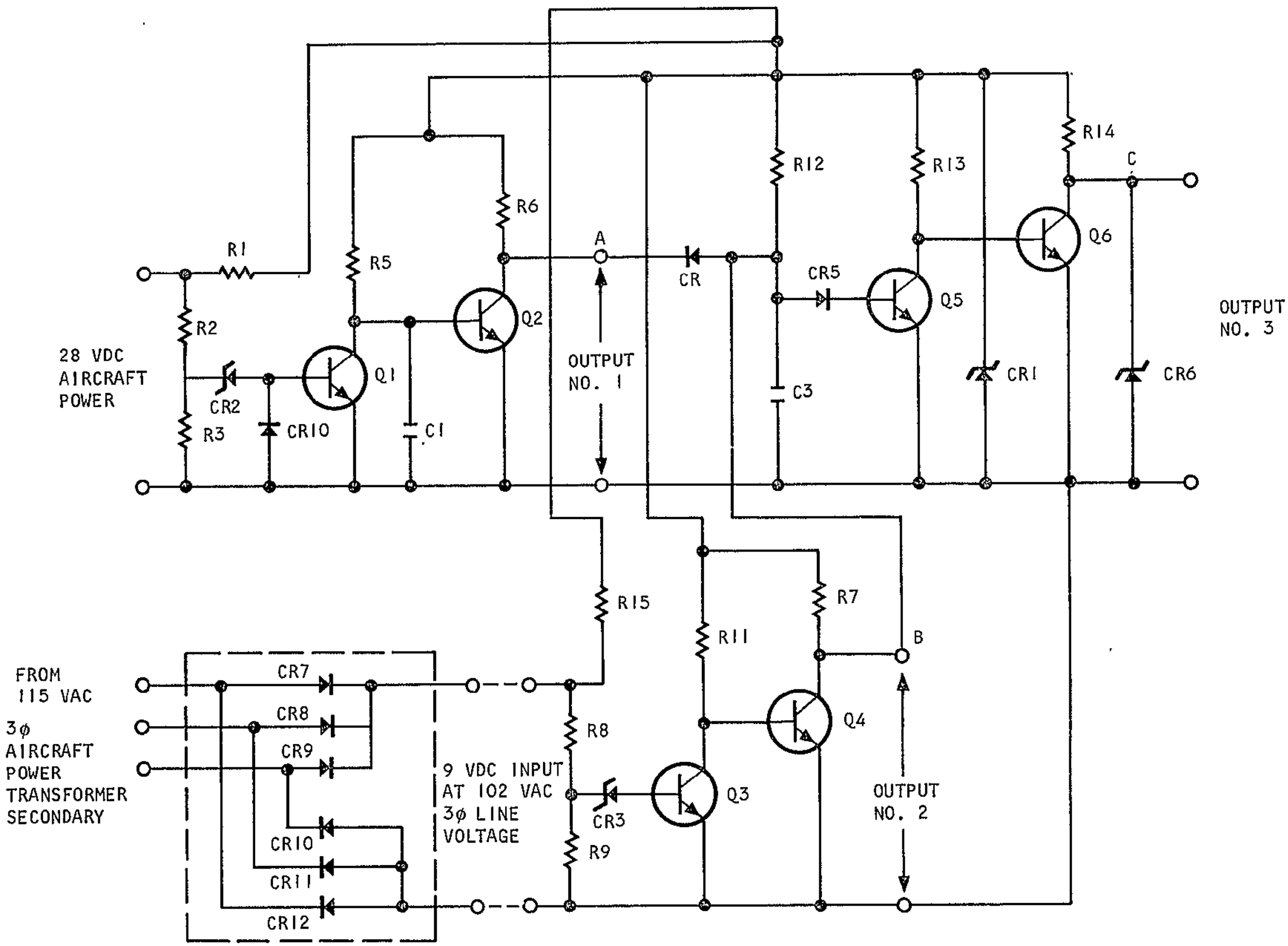

Figure 6.2-6. HRE Power Supply Monitoring, Power Interrupt Level Detection Schematic

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PARTS LIST FOR FIGURE 6.2-6

R1 = 2.4 KΩ ±1 percent, 1/4 w
R2 = 6.8 KΩ ±0.1 percent, 1/3 w
R3 = 4.36 KΩ ±0.1 percent, 1/8 w

R5 = 10 KΩ ±5 percent, 1/4 w
R6 = 4.3 KΩ ±1 percent, 1/8 w
R7 = 4.3 KΩ ±1 percent, 1/8 w
R8 = 6.8 KΩ ±0.1 percent, 1/8 w
R9 = 31.4 KΩ±0.1 percent, 1/8 w

R11 = 10 KΩ ±5 percent, 1/4 w
R12 = 150 KΩ ±5 percent, 1/4 w
R13 = 15 KΩ ±5 percent, 1/4 w
R14 = 10 KΩ ±5 percent, 1/4 w
R15 = 1 KΩ ±5 percent, 1/4 w

C1 = 0.022 μf ±10 percent, 10 v
C2 = 0.022 μf ±10 percent, 10 v
C3 = 0.68 μf ±10 percent, 10 v

CR1 = 1N754A
CR2 = 1N754A
CR3 = 1N754A
CR4 = 1N914 (1N457)
CR5 = 1N914 (1N457)
CR6 = 1N751A
CR7 = 1N914 (1N457)
CR8 = 1N914 (1N457)
CR9 = 1N914 (1N457)
CR10 = 1N914 (1N457)

Q1 = 2N2222A
Q2 = 2N2222A
Q3 = 2N2222A
Q4 = 2N2222A
Q5 = 2N2222A
Q6 = 2N2222A

150<

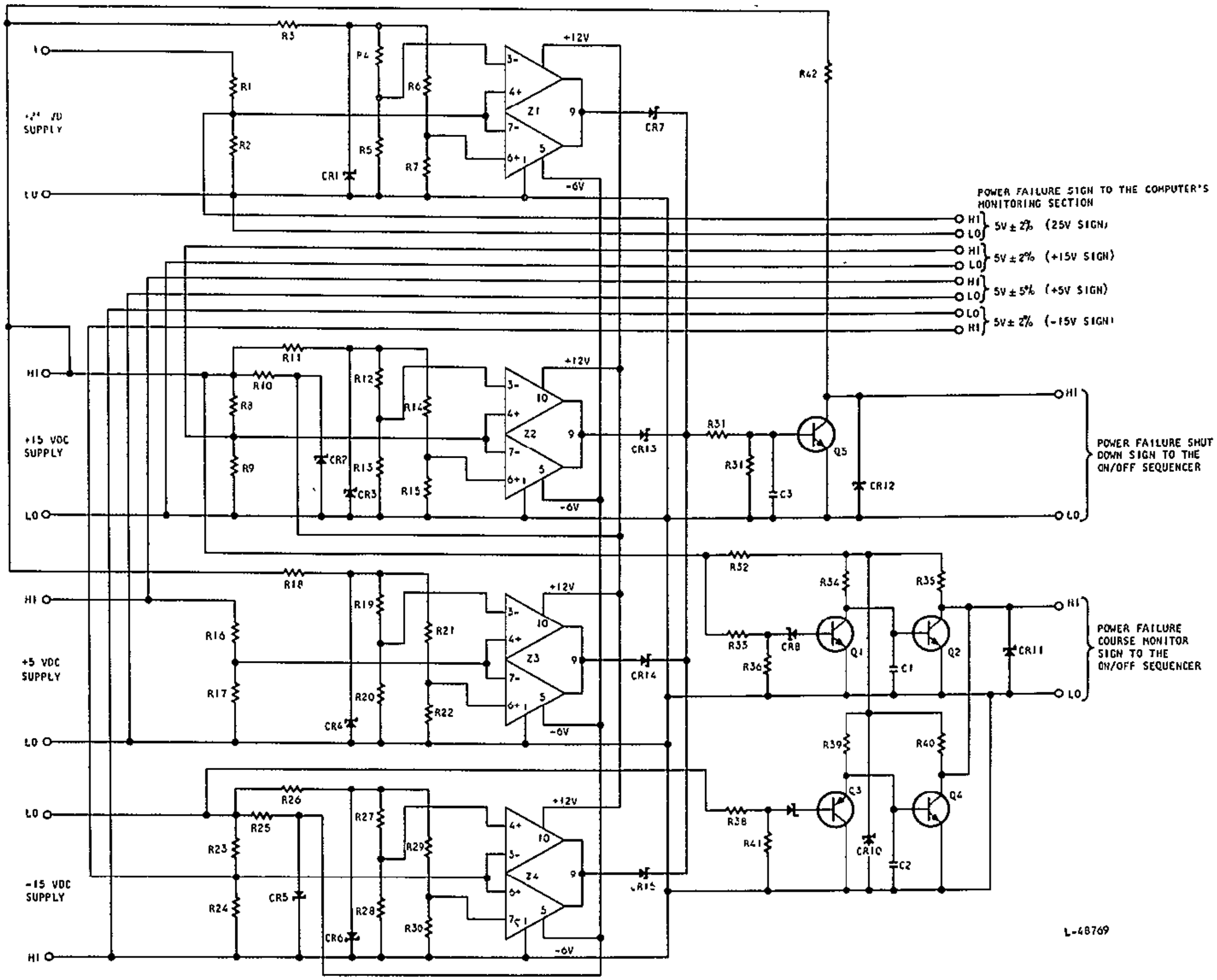

Figure 6.2-7. HRE Power Supply Monitoring, Output Failure Monitoring

PARTS LIST FOR FIGURE 6.2-7

R1 = 1062.6 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R2 = 264.4 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R3 = 270.0 Ω ±1 percent, 1/4 w, 25 ppm/°C

R4 = 369.66 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R5 = 500 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R6 = 452.26 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R7 = 401 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R8 = 637.59 Ω 0.1 percent, 1/4 w, 25 ppm/°C

R9 = 318.8 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R10 = 75 Ω ±1 percent, 1/4 w, 25 ppm/°C

R11 = 270.0 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R12 = 369.66 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R13 = 500 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R14 = 452.26 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R15 = 401 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R16 = 708.4 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R17 = 708.4 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R18 = 506.8 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R19 = 1214.6 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R20 = 500 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R21 = 1378.3 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R22 = 476.74 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R23 = 637.59 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R24 = 318.8 Ω ±0.1 percent, 1/4 w, 25ppm/°C

R25 = 300 Ω ±1 percent, 1/4 w, 25 ppm/°C

R26 = 270.0 Ω ±1 percent, 1/4 w, 25 ppm/°C

R27 = 369.66 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R28 = 500 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R29 = 452.26 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R30 = 401 Ω ±0.1 percent, 1/4 w, 25 ppm/°C

R31 = 8 K ±5 percent

R32 = 2 K ±5 percent

R33 = 6.8 K ±0.5 percent

R34 = 10 K ±5 percent

R35 = 6.8 K ±5 percent

R36 = 6.8 K ±5 percent

R37 = 2 K ±5 percent

R38 = 5.47 K ±0.5 percent

R39 = 10 K ±5 percent

R40 = 6.8 K ±5 percent

R41 = 5.42 K ±0.5 percent

R42 = 15 K ±5 percent

PARTS LIST FOR FIGURE 6.2-7 (Continued)

C1	=	0.013 μf ±5 percent, 10 vdc
C2	=	0.013 μf ±5 percent, 10 vdc
C3	=	0.006 μf ±5 percent, 10 vdc
Q1	=	2N2222A
Q2	=	2N2222A
Q3	=	2N2907A
Q4	=	2N2222A
CR1	=	IN4742
CR2	=	IN759A
CR3	=	IN4742
CR4	=	IN4742
CR5	=	IN753A
CR6	=	IN4742
CR7	=	IN751A
CR8	=	IN754A
CR9	=	IN754A
CR10	=	IN754A
CF11	=	IN751A
CR12	=	IN914
CR13	=	IN914
CR14	=	IN914
CR15	=	IN914
Z1	=	μA711 Fairchild-Dval comparator
Z2	=	μA711 " " "
Z3	=	μA711 " " "
Z4	=	μA711 " " "

6.3 COMPUTER INTERFACE UNIT (CIU)

6.3.1 Digital Portion of CIU

The hardware changes outlined in the Fifth Control System TDR have been implemented and checked out. These changes included an increased number of discrete outputs and the addition of individual digital registers for all analog outputs. Further, some changes have been incorporated to reduce software 'overhead' for 'busy' and 'interrupt' interrogation. A short discussion of the X-15 recorder interface is included.

6.3.1.1 Busy and Interrupt Facility

The status of the busy and interrupt lines can be determined by either (1) enabling the required busy or interrupt signal by setting and resetting discrete output, and then inputting the signal via the serial or interrupt input respectively, as appropriate, or (2) inputting the status of all busy and interrupt signals simultaneously via parallel discrete inputs.

Although the latter facility is still available, it is not now used because of the large number of processes involved in inputting the parallel character, shifting and masking, etc.

The remaining alternative has been modified so that the required busy or interrupt signal is addressed by the operand address register of the computer and inputted via the computer serial input. The discrete output signals associated with the interrupts are retained so that the interrupt-lockout facility is available.

More flexibility is obtained from this arrangement, since the interrupt and busy signals may be scanned during the processing of an analog input without breaking down the stored WOT instruction.

This approach requires some additional logic and seven additional inputs from the computer. These are "DINOT," the signal which is true when the computer is calling for a serial input, and P1 through P6. The six least significant bits of the computer operand register, P1 through P6 can be decoded to enable up to 64 serial inputs into the single serial input to the computer. However, since we require only eight enable signals, we can decode combinations of only two lines at a time.

This system, shown in Figure 6.3-1, replaces the enable gating for the busy lines, but the interrupt lines still require the enable-lockout gating before being OR-ed to produce the Master Interrupt. The interrupt signals used here are the 'origin' interrupts prior to the enable-lockout gating. This modification is part of the "Busy-Interrupt Logic" shown in Section 6.3.2, Figure 6.3-2.

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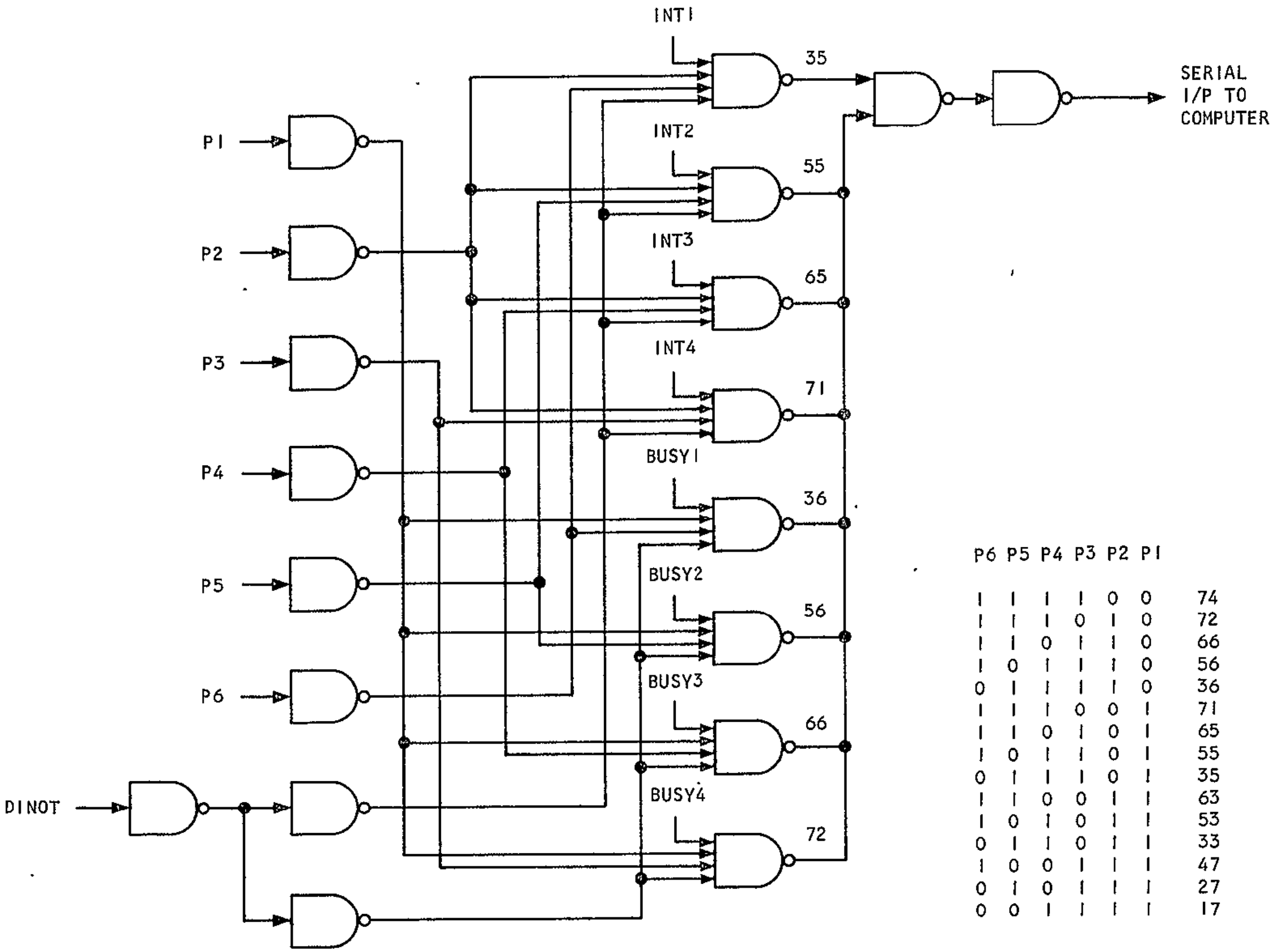

P6	P5	P4	P3	P2	P1	
1	1	1	1	0	0	74
1	1	1	0	1	0	72
1	1	0	1	1	0	66
1	0	1	1	1	0	56
0	1	1	1	1	0	36
1	1	1	0	0	1	71
1	1	0	1	0	1	65
1	0	1	1	0	1	55
0	1	1	1	0	1	35
1	1	0	0	1	1	63
1	0	1	0	1	1	53
0	1	1	0	1	1	33
1	0	0	1	1	1	47
0	1	0	1	1	1	27
0	0	1	1	1	1	17

INTERRUPT SIGNALS (74, 72, 66, 56, 36, 71, 65, 55, 35)

S-48826

Figure 6.3-1. A Section of "Interrupt/Busy Logic Block"

Testing was initiated with the computer connected to the CIU, but difficulties were encountered with a ground noise problem in the computer-CIU teletype hookup. It was apparent that a problem arose when transmitting from the teletype to the computer. A similar difficulty arose with the computer GSE teletype hookup.

It is considered that there are two separate problems: (1) the ARMA-GSE computer is susceptible to 'noise' when operating with the teletype (a trouble report has been initiated); and (2) with the present teletype hookup, a ground loop(s) arises when connection is made to the computer, but not when connection is made to the computer-simulator. However, this hookup is temporary, and when the final grounding scheme is implemented, a realistic base will exist for system evaluation.

The digital hardware has been completed and checked out as an entity, and is ready for operation with the analog section of the CIU. This will be done as the analog circuit boards become available.

6.3.1.2 The External Device Interface

The interface is configured for operation with:

(a) A recorder

(b) A data logger

(c) A tape reader

Its facilities include an input and an output interface described as follows:

Outputs:
(a) An 8-bit output highway, expandable to 12 bits (parallel)
(b) A STIM line to indicate presence of output data
(c) A control line to switch (externally) the data logger or the reader onto the input interface
(d) Outputs indicating the INT and busy status of the interface

Inputs:
(a) A 12-bit input highway
(b) A ready line to indicate the presence of input data

During off line maintenance of the HRE, the interface would work with the data logger and reader.

In 'airborne' operation the interface would work with the recorder.

6.3.1.2.1 Airborne Operation

The 8-bit output from the CIU is available in parallel or serial form. (This can be extended to 12 bits by extending the 'length' of the output register.)

Information is provided at the output interface on demand by a command from the recorder. This command is put into to the system via a ready line. The computer must anticipate the demand by having data ready; that is, after each transfer is made the computer must load the interface with another sample before the next ready occurs. If the output data is purely segmented in nature and does not change sequence with changing demands on computer time, then it is not necessary to identify output data by associating them with addresses.

If the computer cannot provide samples within the time period allowed by the recorder (or in the fixed sequence), then each sample must be tagged with an address. This effectively halves the sample rate.

The maximum input rate to a prime channel of the recorder is 200 samples/sec (9 bits per sample). Assuming that only the 8-bit output (as currently provided) is needed, and that it is necessary to provide addresses, then the maximum sample rate is 200/2 = 100 samples/sec. The minimum rate is zero, since the computer could refuse to supply data. This would not matter within the recorder, since the lack of a sample is recognizable (addressed samples).

If a subcommutator input is used, then the maximum sample rate is reduced and is given by: $\frac{\text{Subcommutator sample rate}}{2}$ (assuming sample plus address).

6.3.1.2.2 Serial Versus Parallel Transfers

The data output to the recorder can be supplied in either serial or parallel format. If serial transfers are made, the recorder must provide the shift clock to the external device register. The minimum shift rate is determined as follows.

Assume maximum sample rate of 200 samples/sec

Each sample is 9 bits

$$\text{Window time} = \frac{1}{80 \text{ inputs} \times 200 \text{ samples/sec}} = \frac{1}{16{,}000} \text{ sec}$$

$$= 62.5\ \mu\text{sec}$$

Therefore, shift rate

= 9 shifts in 62.5 μsec
i.e., 6.95 μsec interval
or a rate of 144 kHz

In practice, the shift rate may be higher than this, because not all of the window may be available for shifting data (unless the PCM system has a buffer register, in which case 1/200 = 5 msec would be available for shifting data).

In any event, the CIU is capable of shifting at 10 MHz plus, which allows a considerable speed margin.

In parallel operation there is no speed consideration.

In either scheme it is necessary to define the actual interfaces in terms of line drivers/receivers. This remains to be done and depends on actual flight hardware for both the CIU and the PCM system.

6.3.1.2.3 Computer Time

Assuming that the computer was providing data at the rate 200 samples per second, the transfer time is WOT plus WOT, i.e., 18 + 18 = 36 μsec.

The time required to slot samples in computer memory is typically another 18 + 18 or 36 μsec. Total time per sample is 72 μsec at 200 samples per second, this requires 200/10 x 72 = 1.44 msec in each 1/10 second interval.

At an iteration (system) rate of 10/sec, there is 100 msec for processing the control program, and 1.44 msec represents 1.75 percent of this time. Therefore, in practice, an output rate of 200 samples/sec is feasible (9-bit sample).

6.3.1.3 System Status

The digital portion of the system is complete and checked out, ready for integration with the remainder of the system. The stimuli-display lights have been modified to accommodate the present system configuration, and have been checked out.

The implementation of the proposed power and ground scheme remains to be completed, and it is anticipated that this will correct the existing malfunction in the teletype circuit.

Schematics are complete for the digital circuits and for the stimuli-display facilities.

6.3.2 Computer Interface Unit-Analog Output Section

The analog output section has been redesigned to accommodate the specific requirements of the temperature control offset signals. The present design of the analog output section is shown in Figure 6.3-2. The four temperature control offset signals now have individual DACs, and do not end in analog sample and hold devices. This approach provides the high accuracy required for these signals, and alleviates the need for ultrafast analog sample and hold devices.

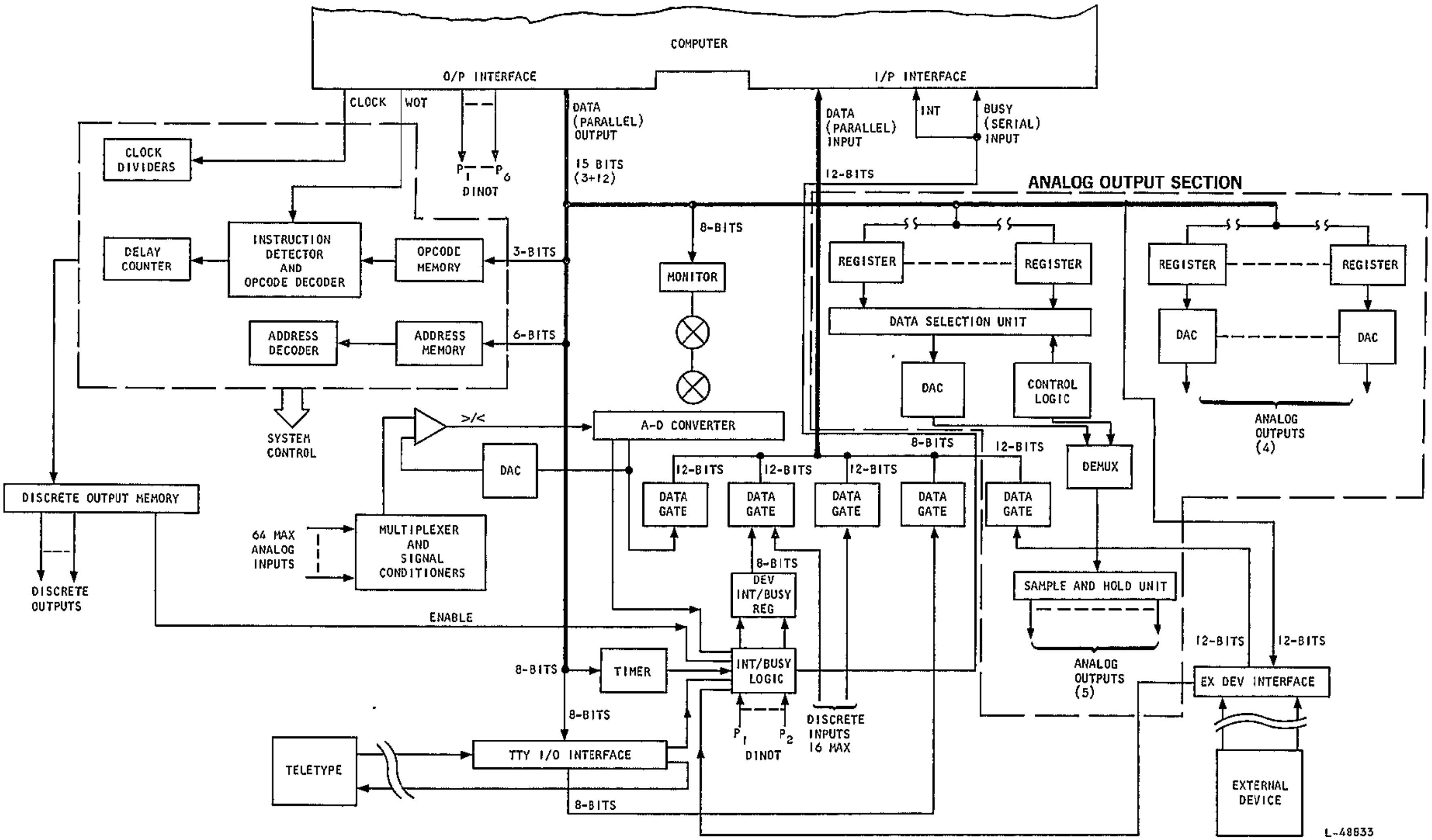

Figure 6.3-2. Present Design CIU-Data Flow Diagram

The previous design is shown in Figure 6.3-3. In this design all of the signals have their own digital registers. The signals from the registers are multiplexed into one DAC, and this signal is then demultiplexed to the individual sample and hold amplifiers. This design minimizes the number of DACs, which would have to be used in the analog output section, but ultimately has problems related to speed and accuracy in this application.

If a temperature control channel had ten thermocouple inputs, and the sampling rate of the control is 40 samples per sensor per second, then each sensor will be sampled for 1/400th of a second, or 2.5 msec. Of these 2.5 msec, 1 msec may be used to allow the sensor signal and thermocouple amplifier to settle out. It is the responsibility of the offset signals to be able to provide individual offsets for each thermocouple signal; i.e., 400 different offsets per second. A difficulty occurs due to the fact that the CIU multiplexer and the temperature control multiplexers operate asynchronously. The CIU system must, therefore, operate much faster than the temperature controls, with settling times of 100 μsec or less. This requirement makes the use of analog sample and hold amplifiers a marginally acceptable design.

The overriding concern in establishing the present design was the increase in signal accuracy, which is gained by eliminating the multiplexer, demultiplexer, and sample and hold amplifier from each signal path. This accuracy requirement (0.2 percent) applies only to temperature control offset signals. For this reason, only these signals have separate DACs, and all other analog output signals are transmitted with hardware, which is identical (except for the number of signals) to the previous design. The hardware status is described in detail in Appendix I for each of the final breadboards.

6.3.2.1 Data Handling Scope

This system has the capability of handling the following signal list.

Inputs

(a) 26 pressure transducers

(b) Eight thermocouples

(c) Spike actuator position transducer (LVDT)

(d) Six remote inputs (from aircraft)

(e) 17 signal monitor inputs (including two for pressure transducer excitation supplies, and the four main DC voltages from the power supply)

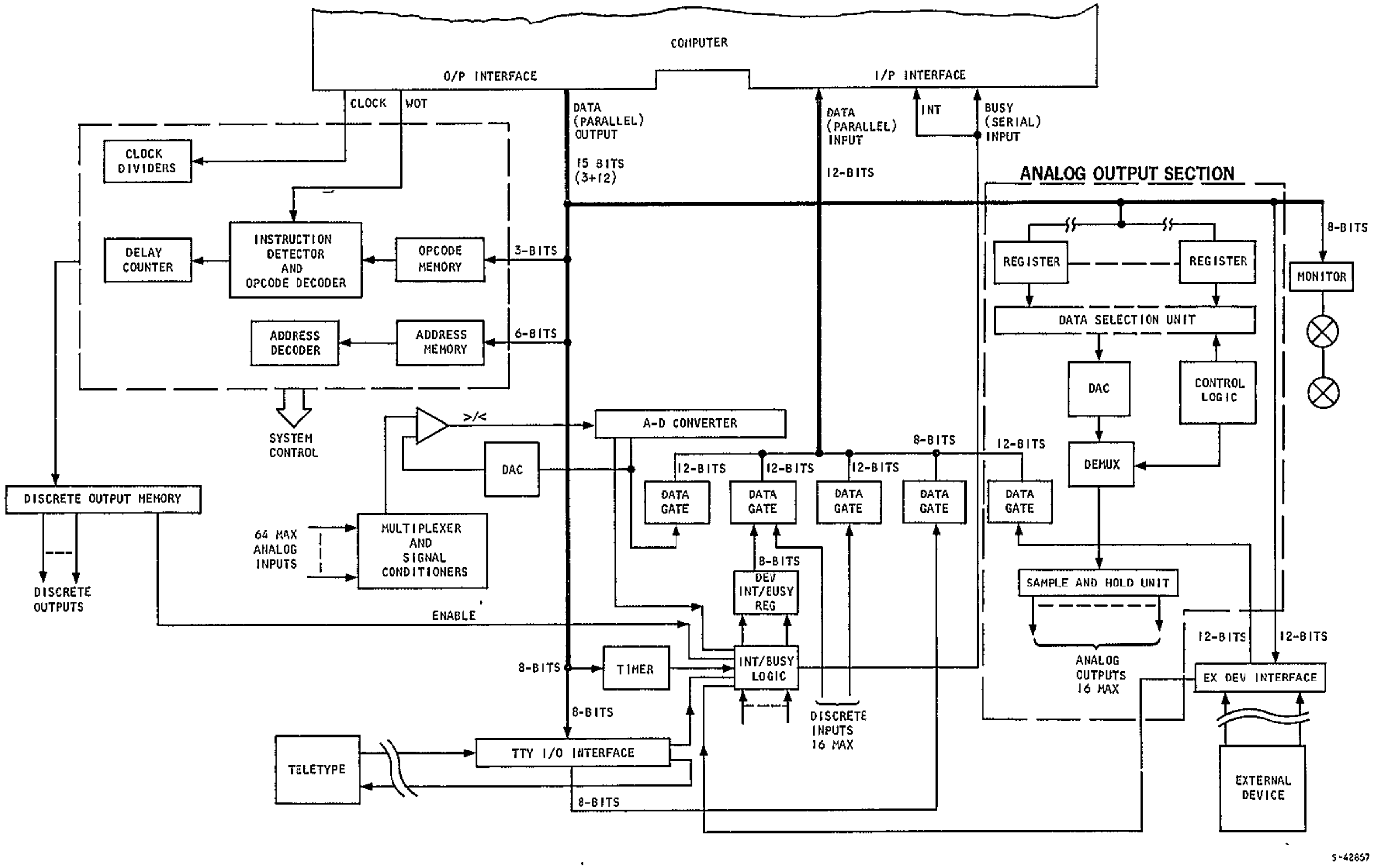

Figure 6.3-3. Previous Design CIU - Data Flow Diagram

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Outputs

(a) With a multiplexed DAC it provides three fuel control valves (manifold) signals, one spike position command, and has provision for two unassigned channels

(b) Four outputs derived from separate DACs for the temperature control loop

At this time, DACs two through five (the two unassigned multiplexed outputs, the isolated 10-v input switches and amplifier, and the submultiplexer for the power supply dc voltages) have not been assembled on the system breadboard. Design of this circuitry is essentially complete. Redesign of the +5-v reference to accommodate the additional loading of the added DACs has been completed.

The design of the thermocouple signal conditioning amplifier is complete, except for a final choice of bias points, which relate to utilization of the computer in a single or double straight line fit to the thermocouple characteristic. The details of this design are contained in Appendix J. Analysis of the oscillator for the spike loop electronics was also completed. Error budgets for most of the signal paths through the various electronics have been completed.

Although some of the paths require additional computation (e.g. errors for alternator, multiplexed and remote input buffer to be added for remote inputs), it is anticipated at this time that satisfactory accuracy will be achieved.

A delineation of the error budget for the main signal paths is presented in Appendix K.

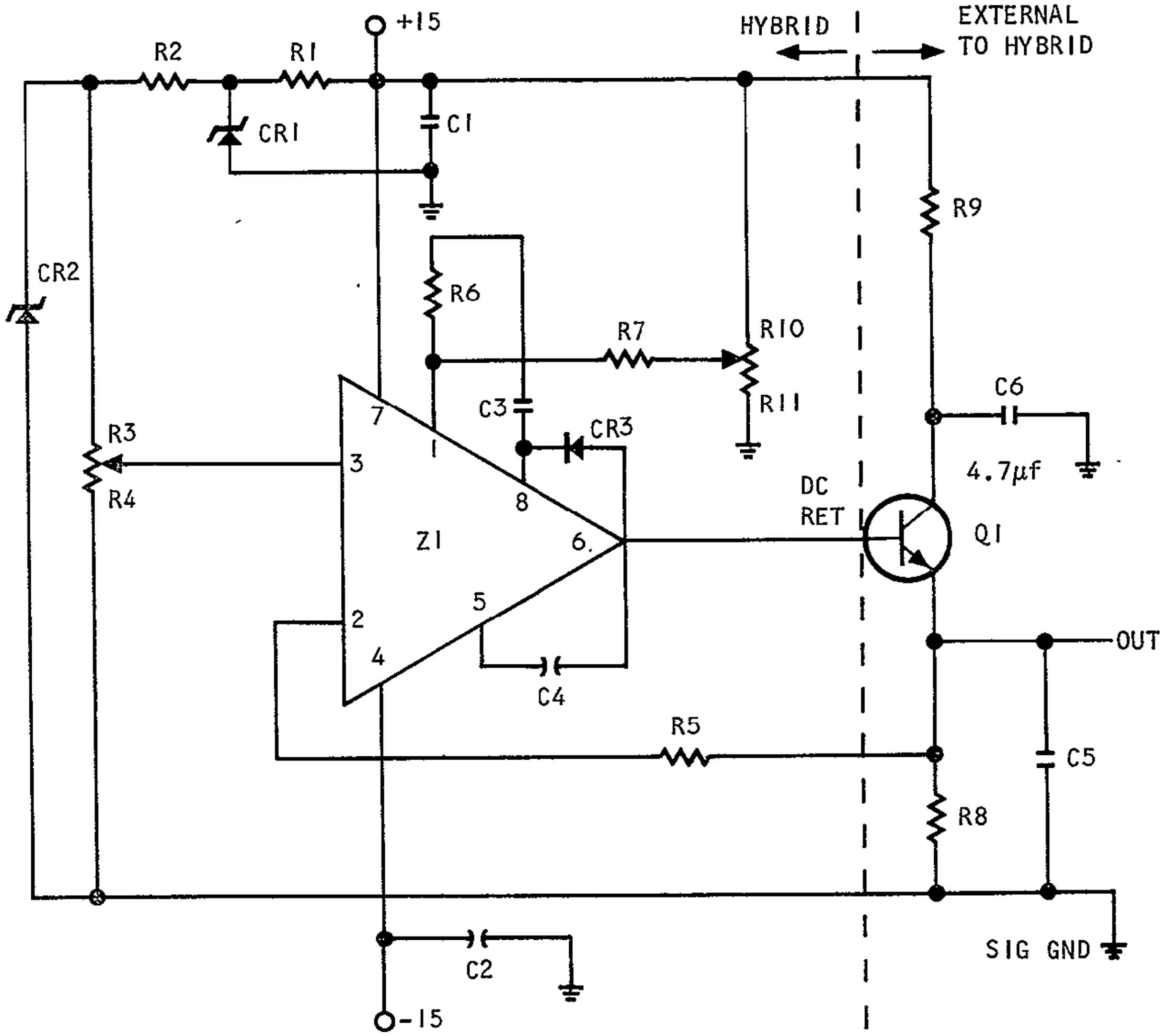
6.3.2.2 +5-v Reference Supply

The redesigned circuit is shown in Figure 6.3-4. This supply was redesigned to accommodate a total of five DACs and one ADC, all using AiResearch ladder switch PN 936516 as well as supplying an additional source loading of approximately 6 ma (4 ma to temperature control loop).

The redesign essentially consisted of changing the current sinking resistor, R8, adding R9 to reduce dissipation of Q1, and modifying the frequency compensation.

6.4 TEMPERATURE CONTROL

Since the last reporting period, the LM101 and LM102 operational amplifiers have been used to supplant μA709s. This resulted in a reduction in system power consumption to approximately a third of its previous value. This modification included the buffer stage, the sample and hold, and the storage circuit. The redesigned storage circuit is described in this report, along



R1 = 374Ω
R2 = 4.32K
R3 ≃ 5.6K } R3 AND R4 TRIMMED
R4 ≃ 20K } FOR V_{OUT} = 5V±10 MV
R5 = 4.32K
R6 = 1.5K
R7 = 200K
R8 = 100Ω 1/2W 5%
R9 = 120Ω 1/2W 5%

R10 ≃ 50K } TRIMMED FOR
R11 ≃ 50K } V_0 = 5V±1 MV
Q1 = 2N3501
Z1 = μA709
CR1 = 1N943B
CR2 = 1N4574A
CR3 = 1N914

C1, C2 = 1μf TANT
C3 = 5000 pf
C4 = 100 pf
C5 = 22μf TANT
C6 = 4.7μf

S-48830

Figure 6.3-4. +5-v Ladder Reference Supply with its performance tests. These tests show that the settling time has been reduced by a factor of 100, while signal droop was not appreciably increased.

Tests of the dump valve driver and the coolant regulating valve driver have been conducted at over-temperature conditions. These tests indicate a gain error of less than 0.1 percent, and an offset error of less than 2.5 ma, or less than 1.5 percent of full scale.

Appendix L displays the present status of the final breadboard circuitry for the temperature control.

6.4.1 Storage Circuit

Development of the storage circuit was originally reported in the fourth TDR. The original circuit diagram is shown in Figure 6.4-1, and the redesigned circuit is shown in Figure 6.4-2. The redesigned circuit is similar to the original circuit, except that an operational amplifier (Z1) now serves the dual purposes of (1) providing an output buffer for the storage capacitor (C2), and (2) operating as a feedback element for the input amplifier (Z2). The amplifier Z1 is an LM102, use of LM102 permits utilizing a smaller storage capacitor. The reduction in capacitor size has allowed the elimination of some of the circuitry previously used to discharge a large capacitor. This circuitry in Figure 6.4-1 includes components S2, R10, and C4. The reduction in the storage capacitance resulted in a 25-percent reduction in the size of those components.

The four capacitors (labelled C_p), which appear in Figure 6.4-2, but not in Figure 6.4-1, serve to decouple the storage circuit from the power supply.

The response of the new storage circuit is documented in Figures 6.4-3 through 6.4-5. Figure 6.4-3 shows the storage circuit response to a 5-volt step input. The response is underdamped, with an overshoot of 0.3 volts, or 6 percent. This implies a damping ratio of slightly less than 0.7. The settling is about 5 μsec; this compares with a settling time for the original circuit of about 500 μsec.

Droop of the stored voltage is shown in Figure 6.4-4. The signal decreases about 6 mv in 15 msec. This compares with a droop of 5 mv in 14 msec, as reported in the fourth TDR. The signal input was 10 volts, so the droop was 0.06 percent. Since the storage circuit may be called on to hold signals for up to 25 msec (1/40th of a second), a droop of about 0.1 percent may be expected.

Figure 6.4-5 shows that reset capability of the storage circuit. In this test, a signal of 10 volts is discharged through the FET switch. The reset time is about 150 μsec.

6.4.2 Sample and Hold Tests

The performance of the new sample and hold circuit is shown in Figures 6.4-6 and 6.4-7. Figure 6.4-6 shows the response of the sample and hold to a step input. The response is overdamped, with a settling time of about 130 μsec. The decay of the held signal is shown in Figure 6.4-7. The signal

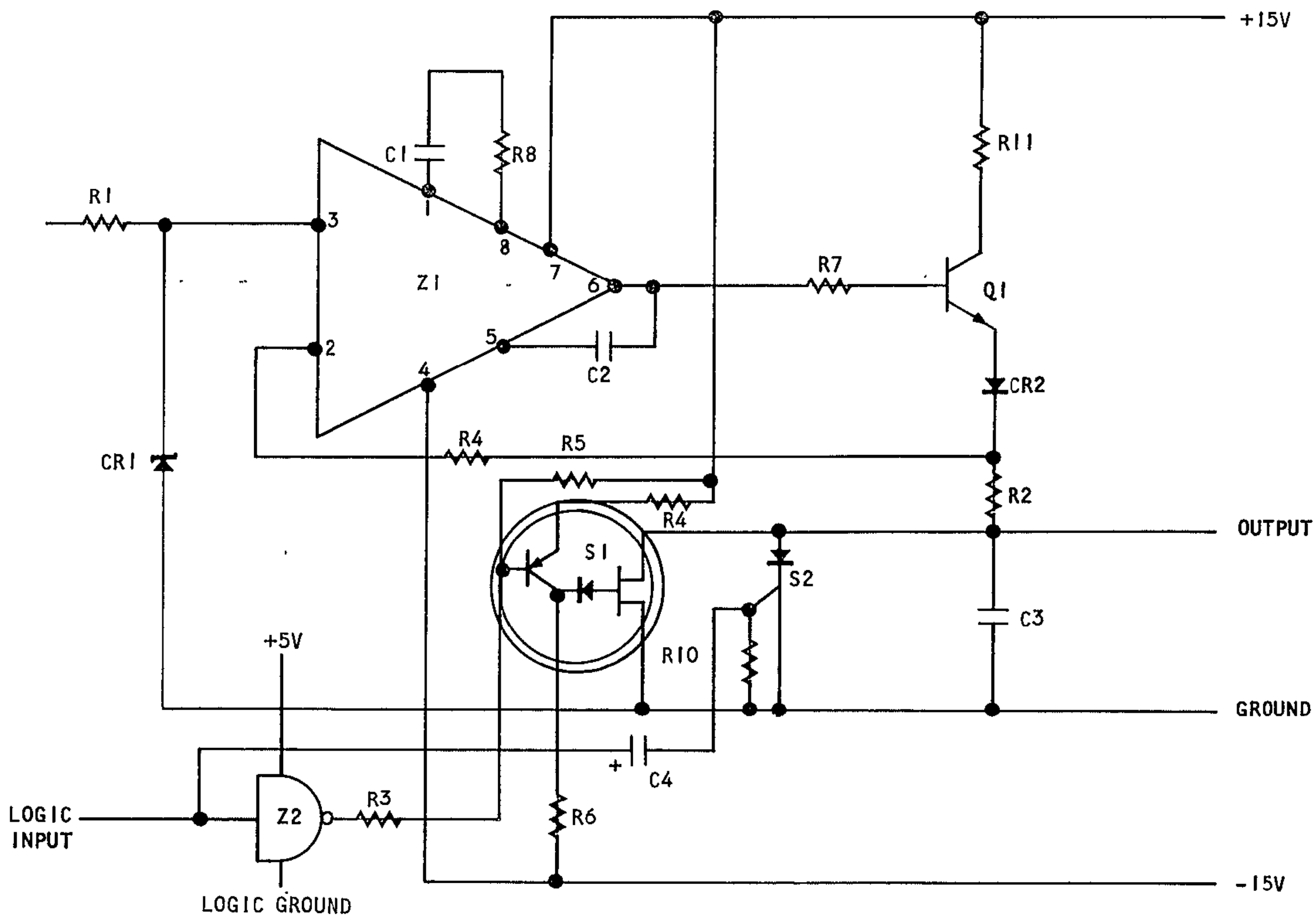


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Figure 6.4-1. Storage Device Schematic

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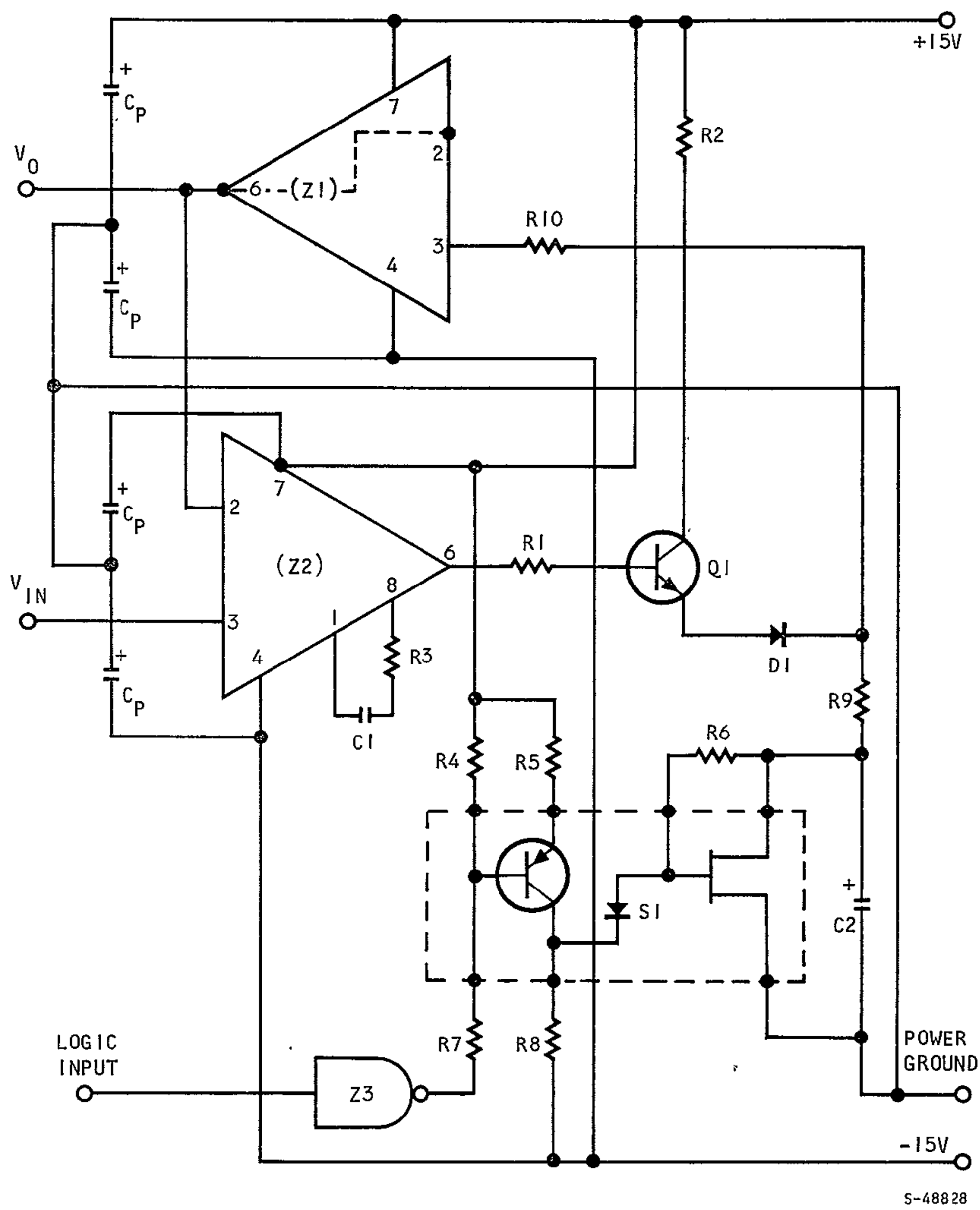
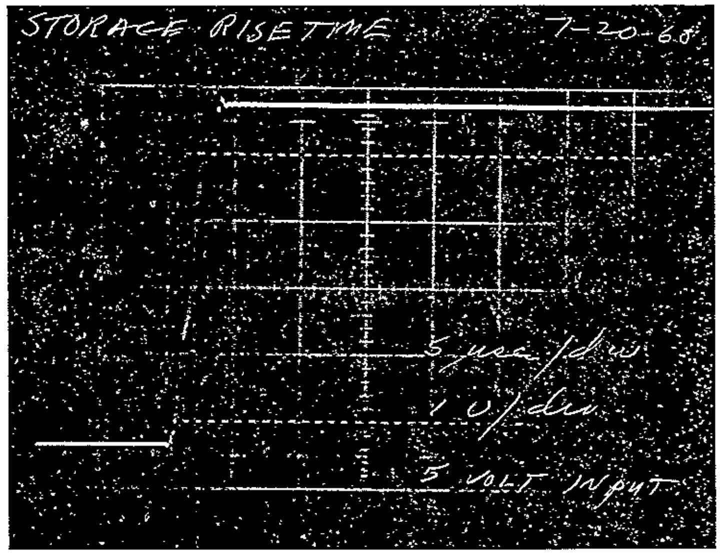


Figure 6.4-2. Storage Circuit



F-10883

Figure 6.4-3. Response of Storage Circuit to Step Input

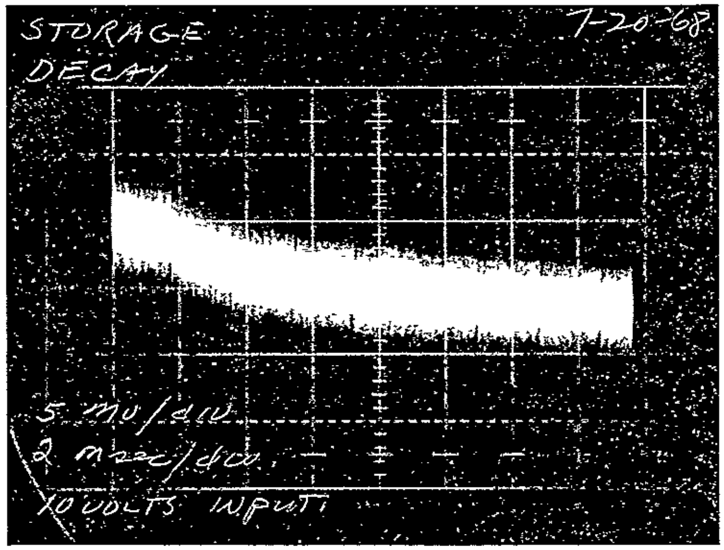


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Figure 6.4-4. Storage Circuit Droop (At Room Temperature)*

* The initial fast signal drop in the first 2 msec is due to a polarization phenomenon inherent in the storing capacitor.

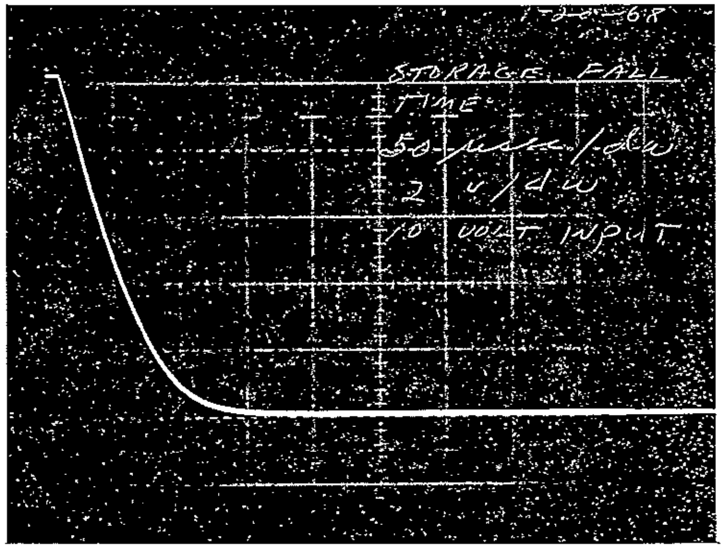

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Figure 6.4-5. Storage Circuit Reset Time

Scaling

V = 2 v/div

H = 50 μsec/div

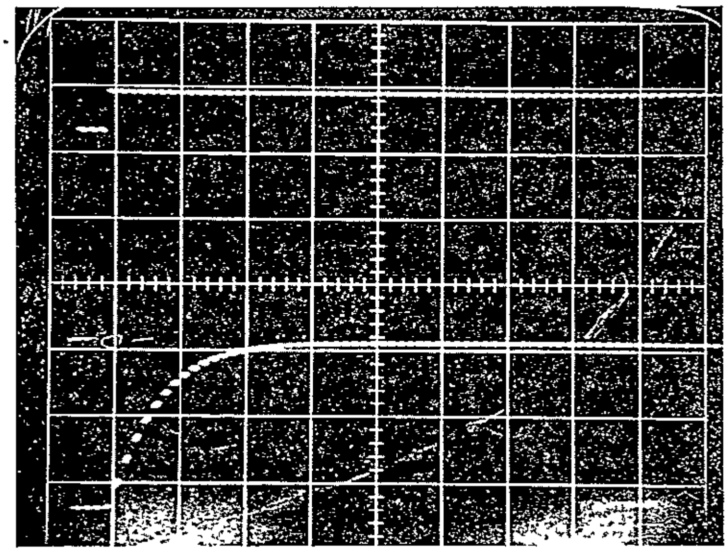

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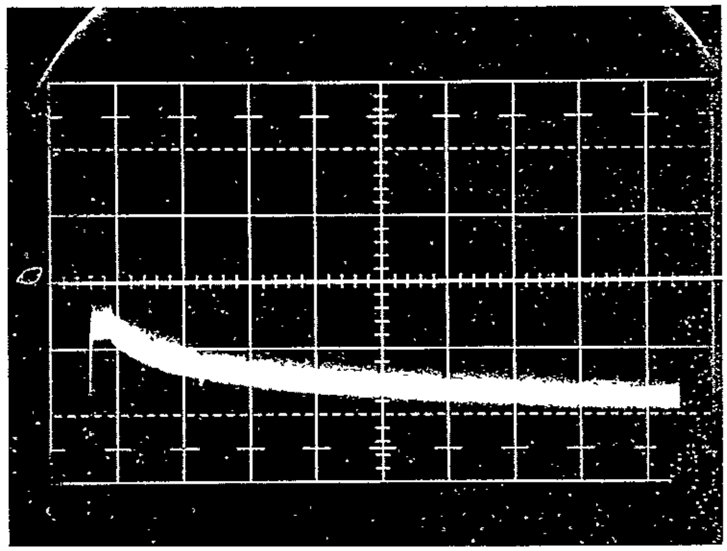
Figure 6.4-6. Response of Sample and Hold to Step Input

Scaling

V = 5 mv/div

H = 2 msec/div



F-10884

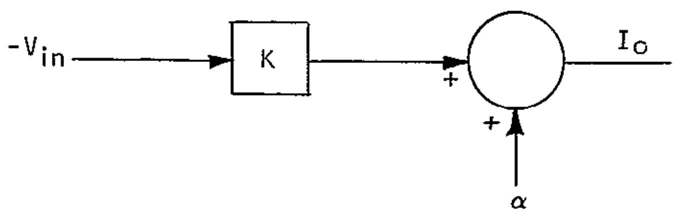
Figure 6.4-7. Storage Capability of Sample and Hold (Room Temperature)*

* The initial quick discharge of the signal shown is due to polarization phenomenon inherent in storing capacitor.

decays about 6 mv in 17 msec. In the fourth TDR, the original sample and hold was shown to have a signal decay of about 3 mv in 15 msec. The simplified sample and hold thus provides the same order of performance as the original.

6.4.3 Valve Driver Temperature Tests

The function of the CRV drivers is to provide a current output, which is related to its voltage input by a gain and an offset, as shown below.



A circuit diagram of the CRV driver is shown in Figure 6.4-8. In the temperature tests, this circuit was soaked for 1/2 hour at two different temperatures (-55°C and +125°C). At each of these temperatures, and at room temperature, the voltage output, V_o, is measured as a function of V_{in}, and this value is compared to the expected value. The error signal is plotted against input voltage in Figure 6.4-9. The predicted output voltage is, $V_o = b - m\ V_{in}$

Figure 6.4-9 can be used to find offset errors (Δb) and gain errors (ΔM). The offset errors are the intersections of the plotted straight lines with the V error axis.

$\Delta b = 21$ mv at -55°C

$= 32$ mv at 125°C

The slope of the error graph is the error in the voltage gain.

$$\Delta M = \frac{18 - 8 \text{ mv}}{2 \text{ v}} = 5 \text{ mv/v}$$

These errors can be directly related to errors in the current gain and offset of the valve driver. Referring to Figure 6.4-8, it can be seen that R8 (15 Ω) has a much lower resistance than R7 or R6. For this reasons, the load current is virtually equal to the current through R8. . Therefore,

$I_o = V_o/R8$

$\alpha = b/R8$

$K = M/R8$

$$i_0 R8 = V_0 = R7 \left[\left(\frac{R3}{R2\ R5} \right)^{(5V)} - V_{IN} \left(\frac{1}{R5} + \frac{1}{R6} + \frac{1}{R7} \right) \right]$$

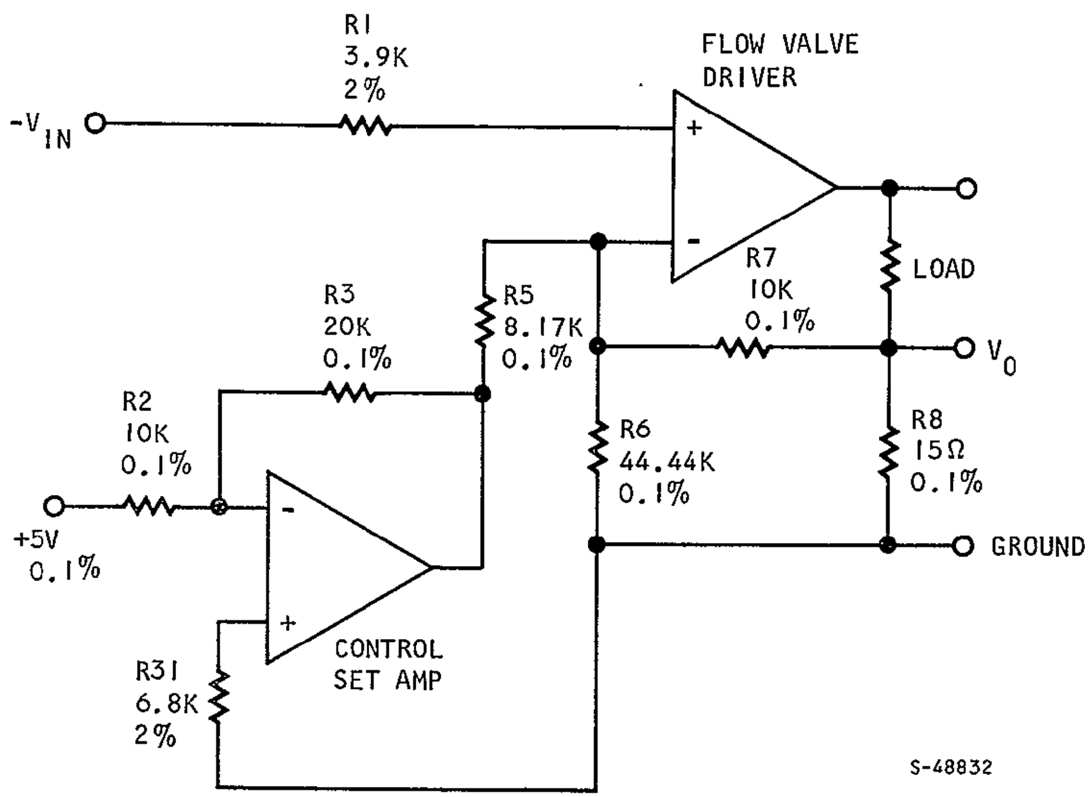


Figure 6.4-8. Circuitry for Flow Driver Temperature Test

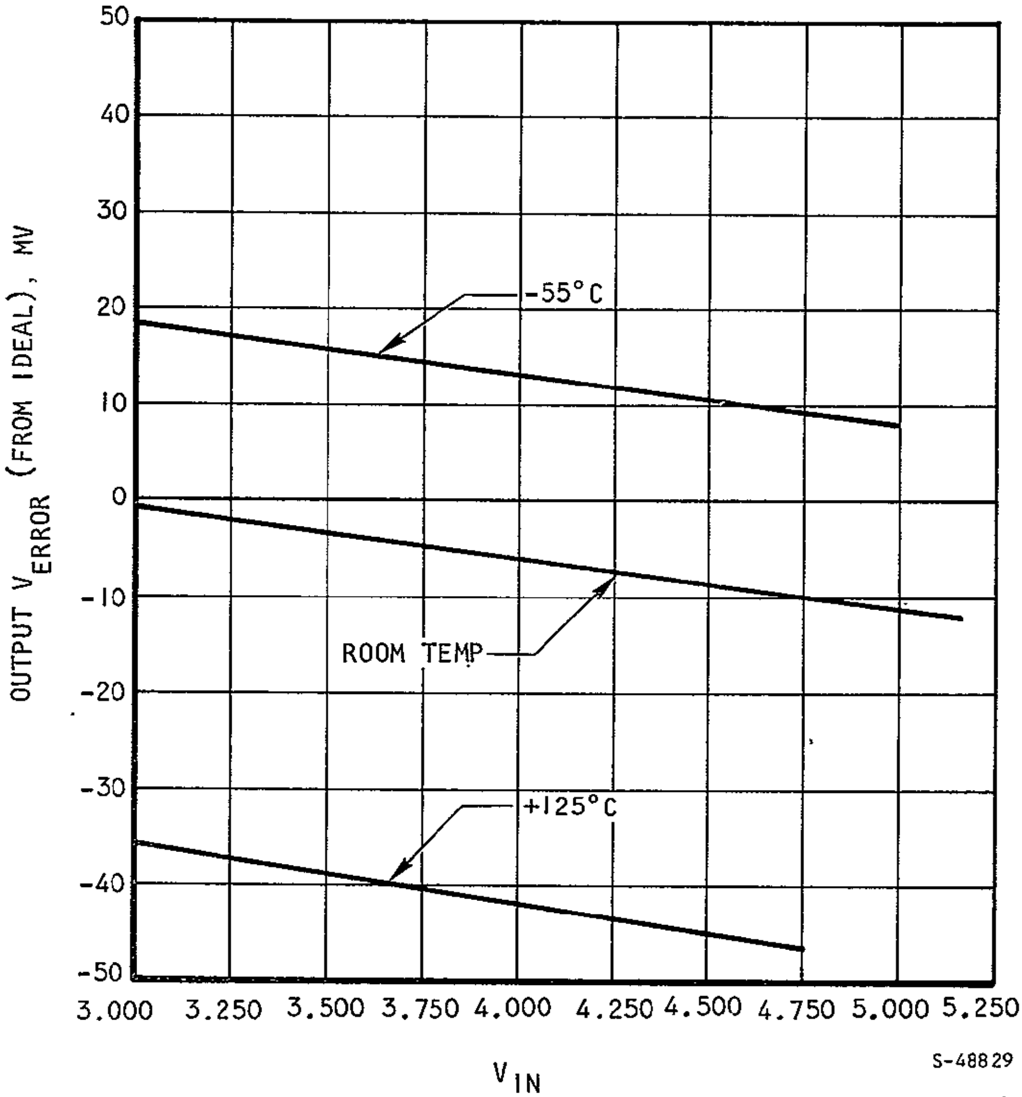


Figure 6.4-9. Flow Driver Temperature Test Results on Scaling Accuracy

The errors in offset and gain are

$$\Delta\alpha = 1.4 \text{ ma at } -55^{0}\text{C}$$

$$= -2.2 \text{ ma at } 125^{0}\text{C}$$

$$\Delta K = \frac{5}{15} = 0.333 \text{ ma/v}$$

$$\frac{\Delta K}{K} = 0.2 \text{ percent}$$

Since the full-scale current output is 175 ma, the current offset is about 1.3 percent of full scale.

The circuit for the dump valve driver is shown in Figure 6.4-10, and the temperature test results are shown in Figure 6.4-11. The dump valve driver showed a gain error of 0.62 percent, and a large offset error of -0.9 ma, or -0.51 percent of full-scale.

$$V_0 = R15 \left[V_{REF} \cdot \left(\frac{R3}{R2\,R17} + \frac{R11}{R13\,R9} \right) + V_{IN} \frac{R11}{R10\,R13} \right]$$

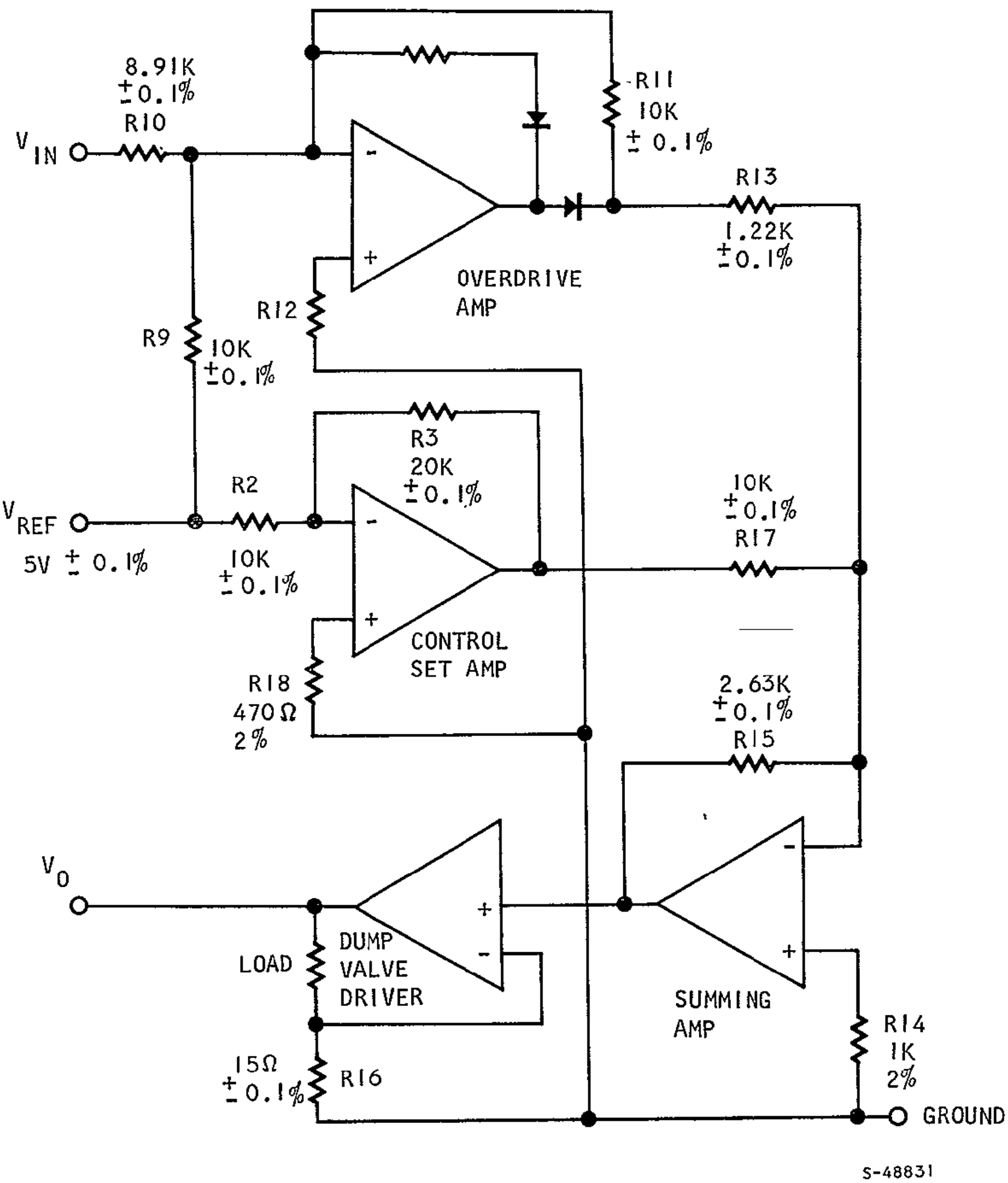


Figure 6.4-10. Circuitry for Dump Valve Driver Temperature Test

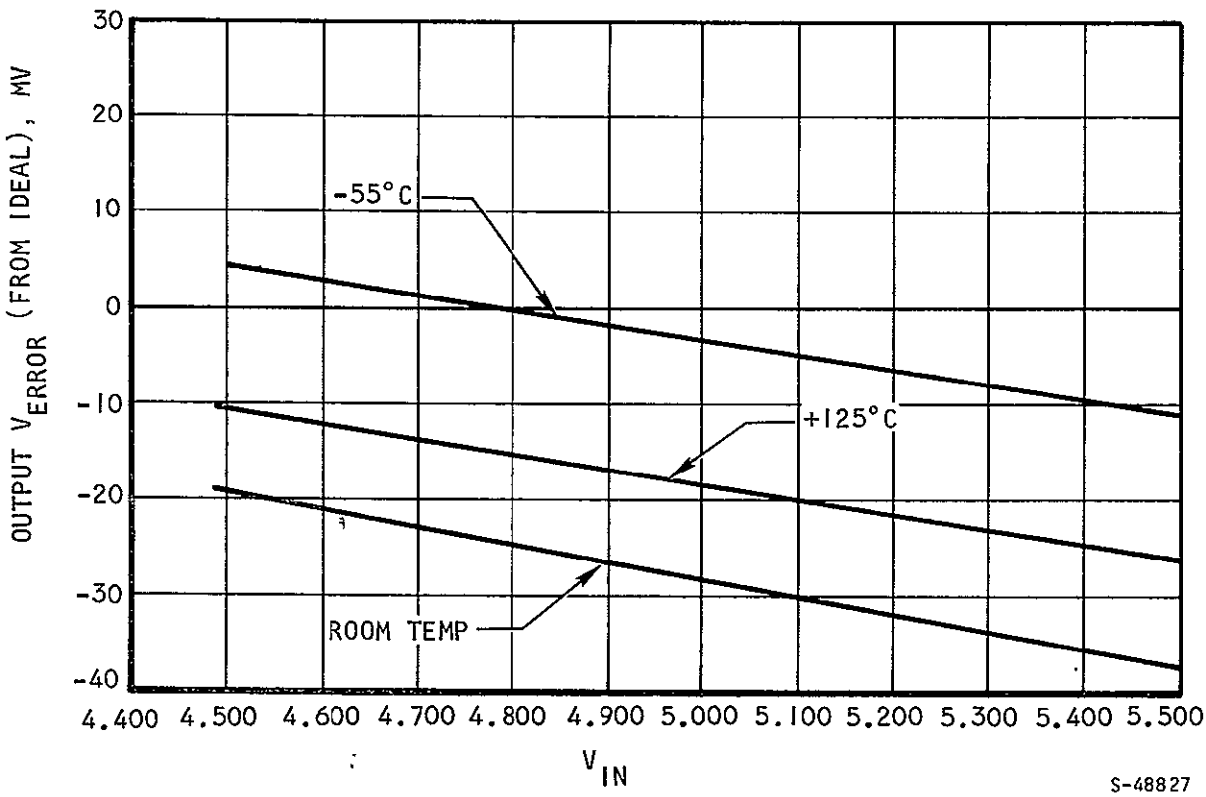


Figure 6.4-11. Dump Valve Driver Temperature Test of Scaling Accuracy

APPENDIX A

ANALOG COMPUTER MECHANIZATION

APPENDIX A

ANALOG COMPUTER MECHANIZATION

This appendix gives data for fuel injectors 2 and 3. Table A-1 lists the system constants. Table A-2 lists the expected maximum values of all the variables and the values over which they were scaled. The equations can then be written in scaled form as in Table A-3 (injector 2) and Table A-4 (injector 3).

The computer mechanization is shown in Figure A-1 for injector 2; injector 3 is identical, except for potentiometer values.

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TABLE A-1

SYSTEM CONSTANTS

Injector Number 2

K31	0.009544	lbm $\sqrt{^0R}$ in.^{2}/lbf-sec
K32	0.006232	lbm $\sqrt{^0R}$ in.^{2}/lbf-sec
K33	0.002080	lbm in.^{2}/lbf-sec
K34	0.002531	lbm in.^{2}/lbf-sec
K35	0.1402	$\sqrt{^0R}$ /sec
V31	109.4	in.^{3}
V32	77.3	in.^{3}
P21	500.0	psia
T21	740.0 and 1600.0	^0R
C	0.6	

Injector Number 3

K41	0.004607	lbm $\sqrt{^0R}$ in.^{2}/lbf-sec
K42	0.002543	lbm $\sqrt{^0R}$ in.^{2}/lbf-sec
K43	0.001467	lbm in.^{2}/lbf-sec
K44	0.002187	lbm in.^{2}/lbf-sec
K45	0.1402	$\sqrt{^0R}$ /sec
V41	60.4	in.^{3}
V42	61.1	in.^{3}
P21	500.0	psia
T21	990.0 and 1600.0	^0R
C	0.6	

TABLE A-2

SYSTEM VARIABLES

Injector Number 2

	Maximum Expected	Scaled Valve
W30	1.385 lb/sec	2 lb/sec
W31	0.734 lb/sec	1 lb/sec
W32	0.651 lb/sec	1 lb/sec
W33	0.734 lb/sec	1 lb/sec
P32	345.0 psia	500 psia
P33	313.0 psia	500 psia
P34	290.0 psia	500 psia
A31	2.46 $in.^2$	5 $in.^2$
N	1.0	1

Injector Number 3

	Maximum Expected	Scaled Valve
W40	0.75 lb/sec	1 lb/sec
W41	0.398 lb/sec	1 lb/sec
W42	0.352 lb/sec	1 lb/sec
W43	0.398 lb/sec	1 lb/sec
P42	290.0 psia	500 psia
P43	240.0 psia	500 psia
P44	182.0 psia	500 psia
A41	1.54 $in.^2$	2 $in.^2$
N	1	1

TABLE A-3

INJECTOR NO. 2 SCALED EQUATIONS

$$\left[\frac{W30}{2}\right] = (0.3866)\ (10)\ \left[\frac{P21}{500}\right]\left[\frac{A31}{5}\right]\left[\frac{N}{1}\right]$$

$$\left[\frac{P32}{500}\right]^2 = (0.1757)\left[\frac{W30}{2}\right]^2 + \left[\frac{P33}{500}\right]^2$$

$$\left[\frac{P33}{500}\right] = \left(\frac{8.658}{\beta^*}\right)\int\left(2\left[\frac{W30}{2}\right] - 10\left[\frac{W31}{10}\right] - \left[\frac{W32}{1}\right]\right) dt$$

$$\left[\frac{W32}{1}\right] = (0.1040)\ (10)\ \left[\frac{P33}{500}\right]$$

$$\left[\frac{W31}{1}\right] = (0.3116)\sqrt{\left[\frac{P33}{500}\right]^2 - \left[\frac{P34}{500}\right]^2}$$

$$\left[\frac{P34}{500}\right] = \left(\frac{12.25}{\beta^*}\right)\int\left(10\left[\frac{W31}{10}\right] - \left[\frac{W33}{1}\right]\right) dt$$

$$\left[\frac{W33}{1}\right] = (0.1265)\ (10)\ \left[\frac{P34}{500}\right]$$

* β = time scale factor

TABLE A-4

INJECTOR NO. 3 SCALED EQUATIONS

$$\left[\frac{W40}{1}\right] = (0.2674)\ (10)\left[\frac{P21}{500}\right]\left[\frac{A41}{2}\right]\left[\frac{N}{1}\right]$$

$$\left[\frac{P42}{500}\right]^2 = (0.4341)\left[\frac{W40}{1}\right]^2 + \left[\frac{P43}{500}\right]^2$$

$$\left[\frac{P43}{500}\right] = \left(\frac{20.98}{\beta *}\right)\int\left(\left[\frac{W40}{1}\right] - 10\left[\frac{W41}{10}\right] - \left[\frac{W42}{1}\right]\right) dt$$

$$\left[\frac{W42}{1}\right] = (0.7335)\left[\frac{P43}{500}\right]$$

$$\left[\frac{W41}{10}\right] = (0.1271)\sqrt{\left[\frac{P43}{500}\right]^2 - \left[\frac{P44}{500}\right]^2}$$

$$\left[\frac{P44}{500}\right] = \left(\frac{20.74}{\beta *}\right)\int\left(10\left[\frac{W41}{10}\right] - \left[\frac{W43}{1}\right]\right) dt$$

$$\left[\frac{W43}{1}\right] = (0.1094)\ (10)\left[\frac{P44}{500}\right]$$

* β = Time scale factor

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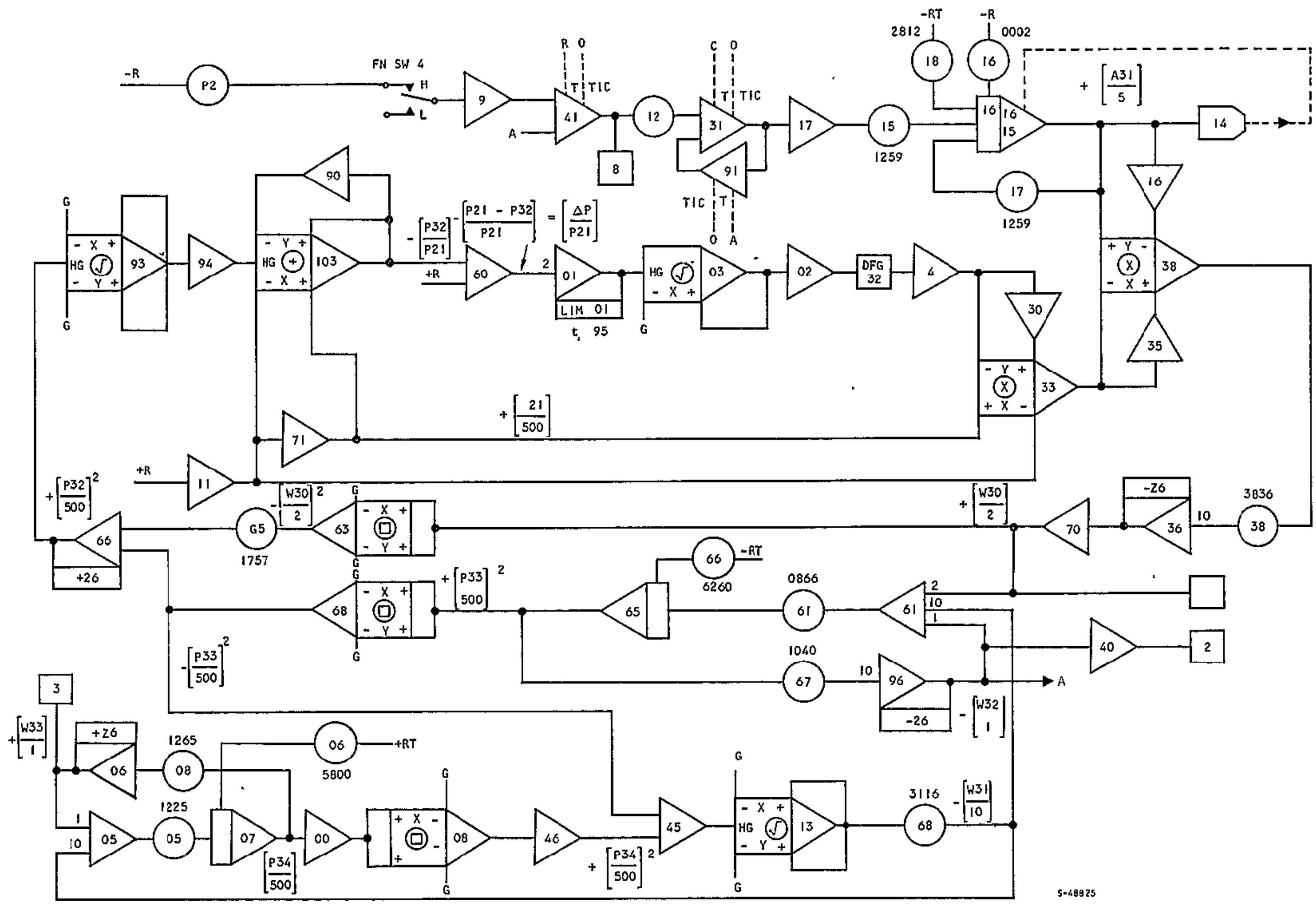
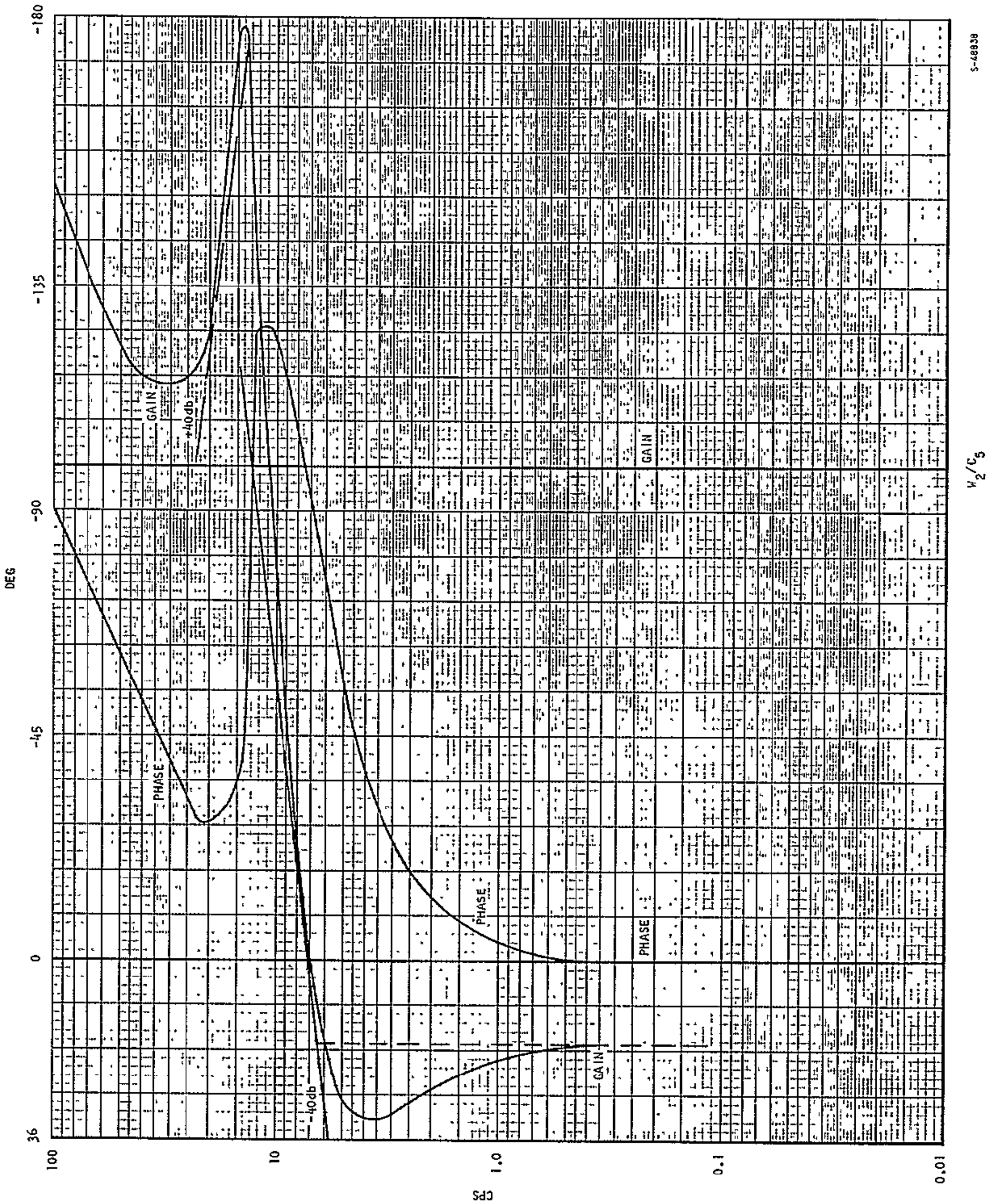


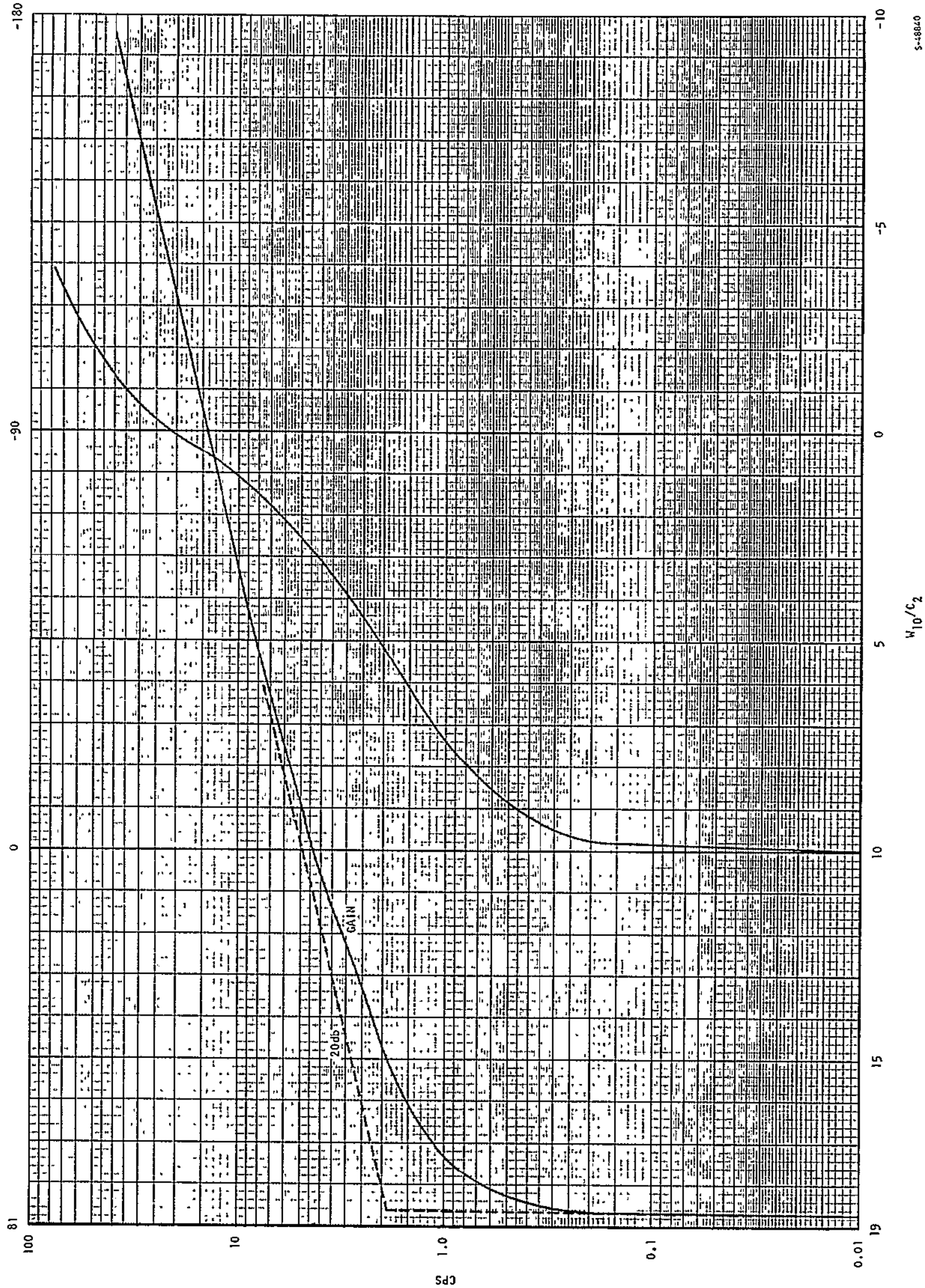
Figure A-1. HRE Injector No. 2

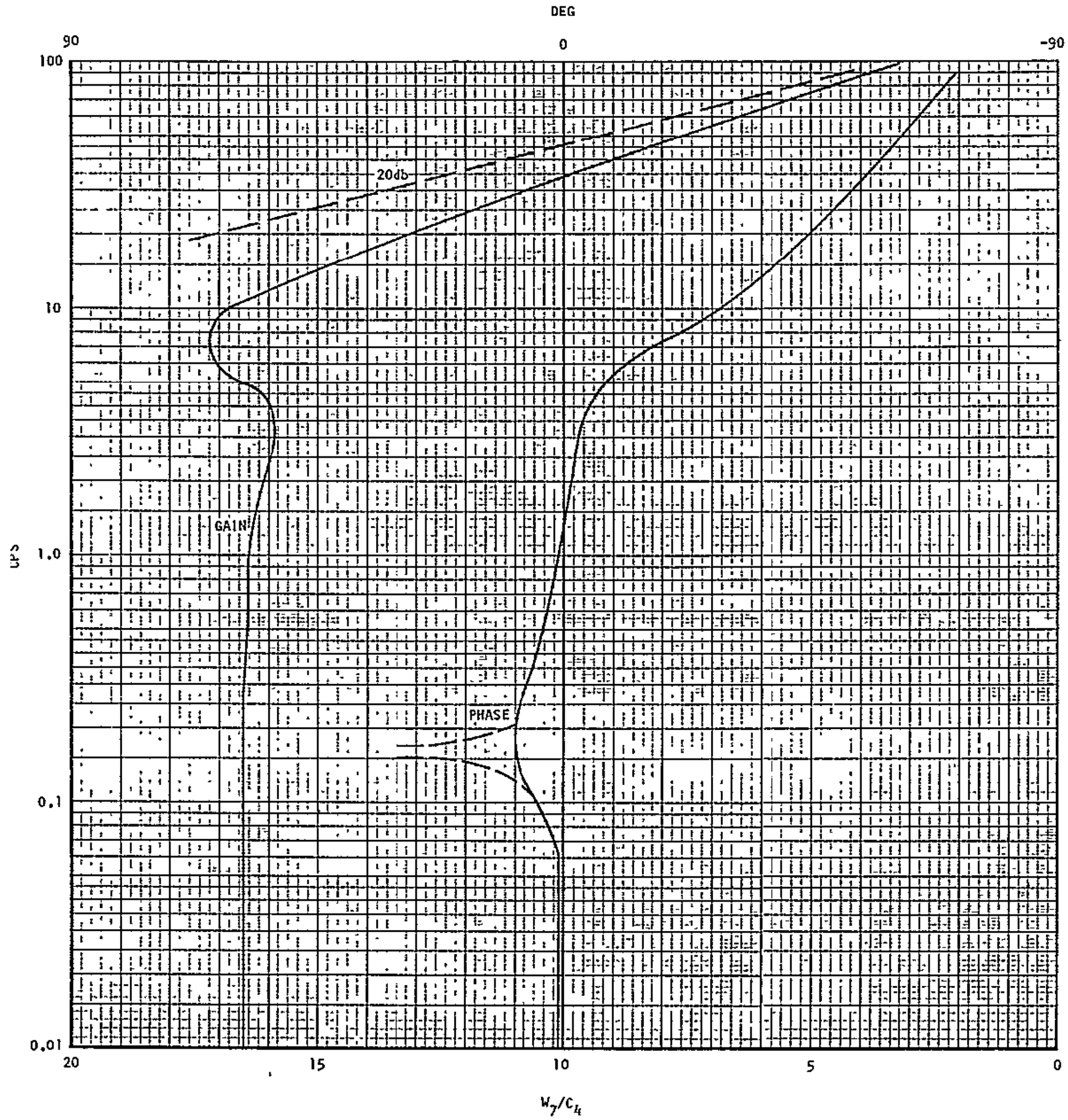
APPENDIX B

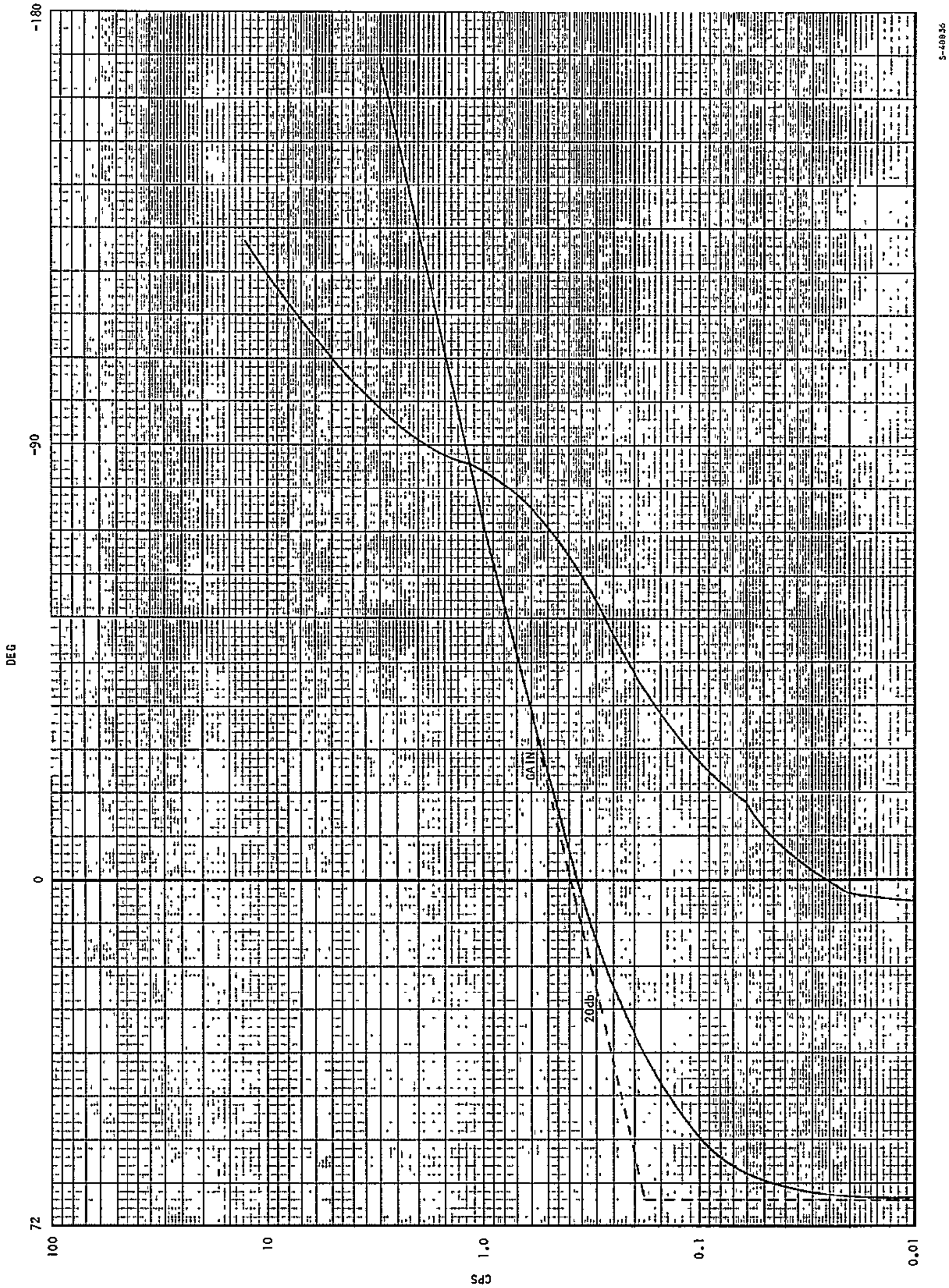
FREQUENCY RESPONSE TESTS

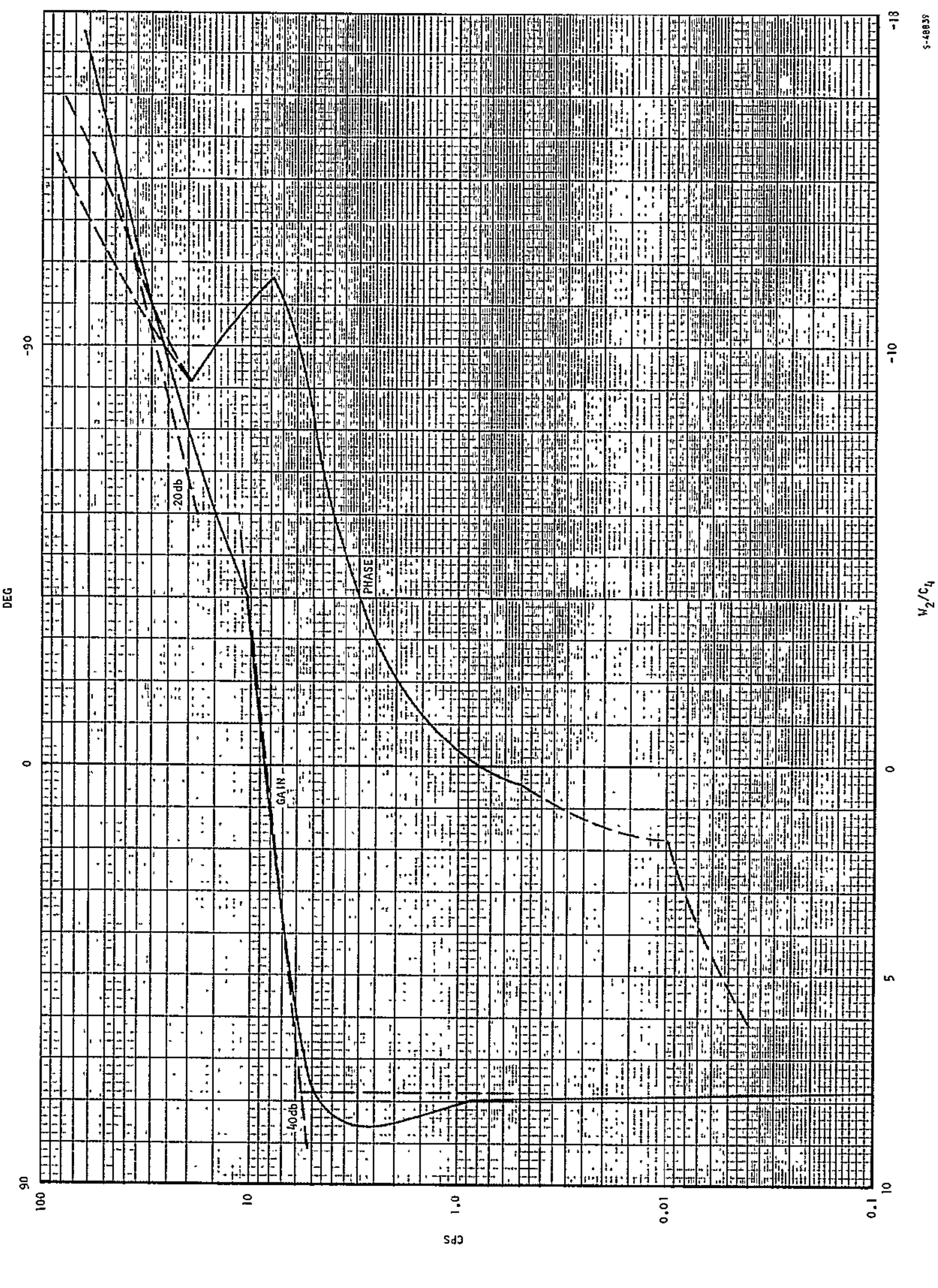


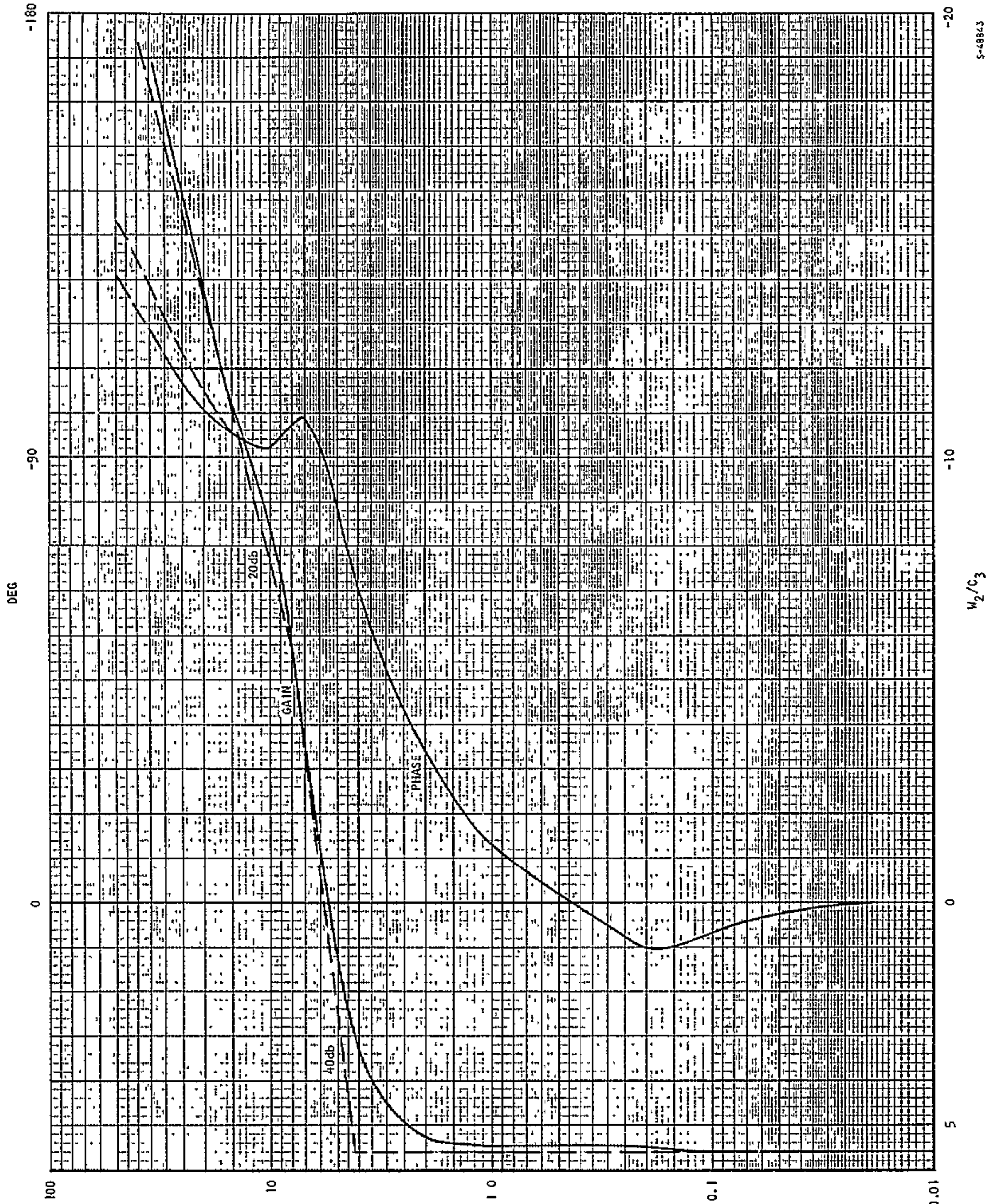
DEG
-180
-135
-90
-45
0
36
100
10
1.0
0.1
0.01
CPS
GAIN
+40db
PHASE
-40db
W_2/C_5
S-48838


DEG
-180
-90
0
CPS
100
10
1.0
0.1
0.01
W_{10}/C_2
-10
-5
0
5
10
15
19
GAIN
20db
S-48840

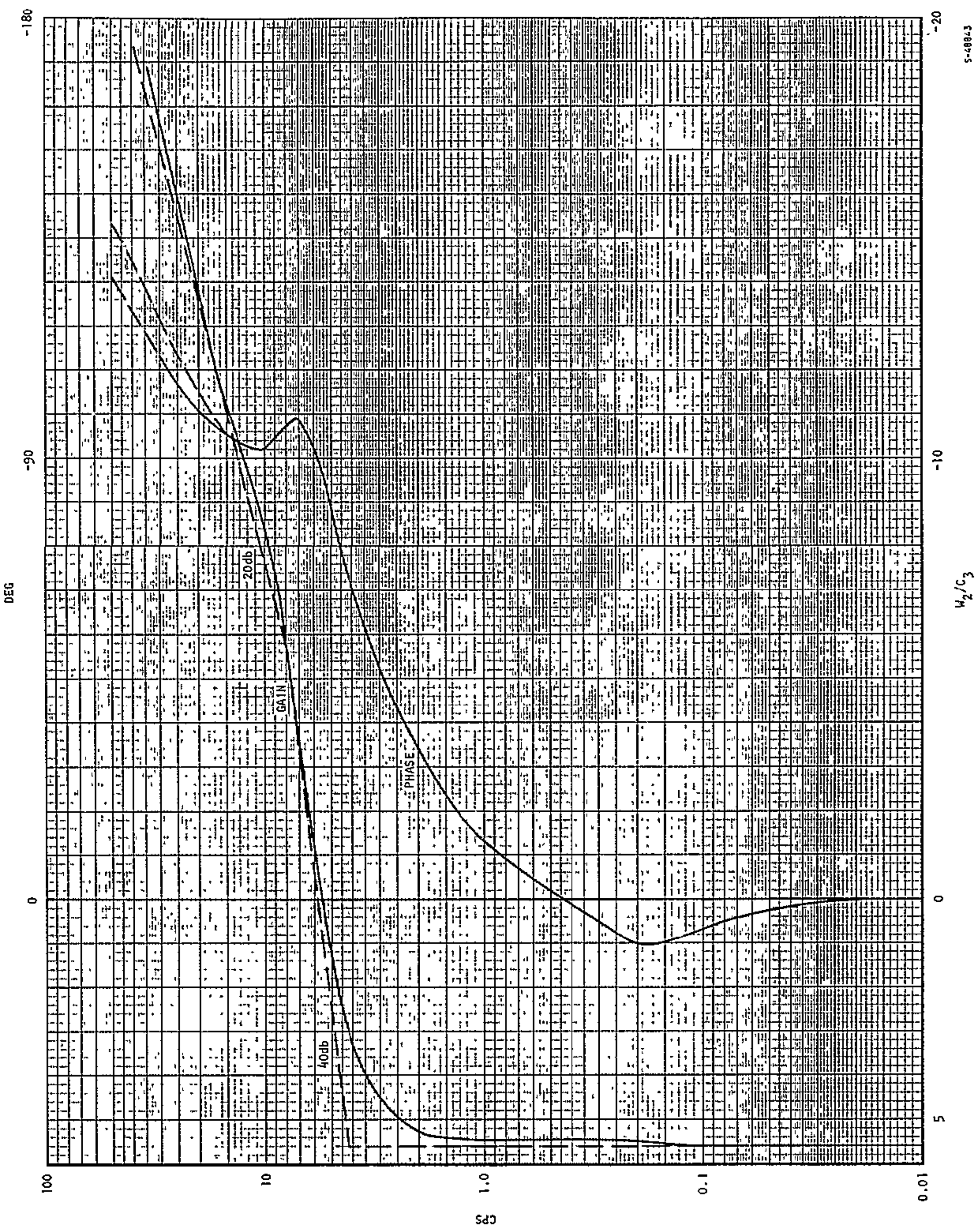

DEG
90
0
-90
100
10
1.0
0.1
0.01
CPS
20db
GAIN
PHASE
20
15
10
5
0
W_7/C_4

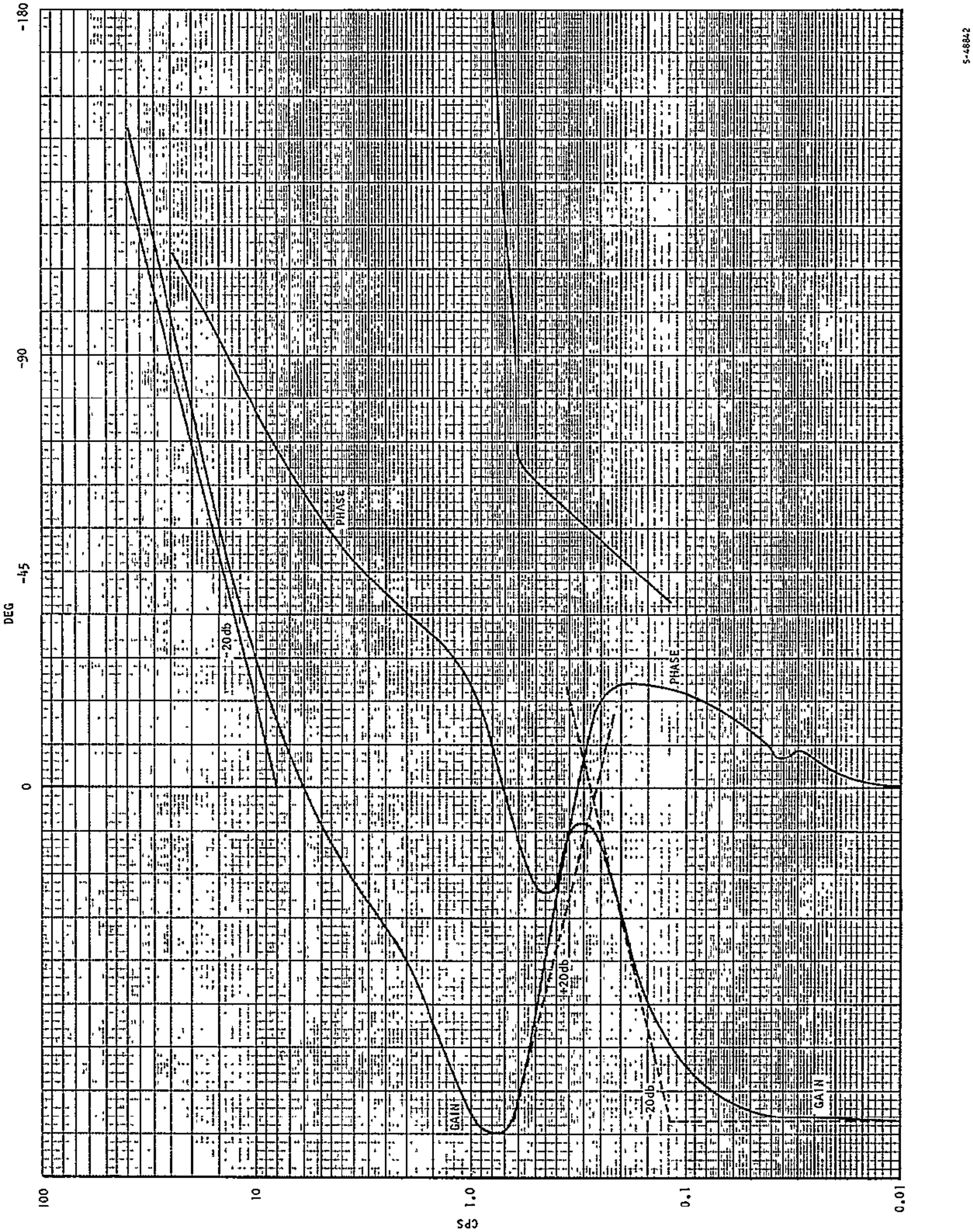

DEG
-180
-90
0
72
100
10
1.0
0.1
0.01
CPS
GAIN
20db
S-40836

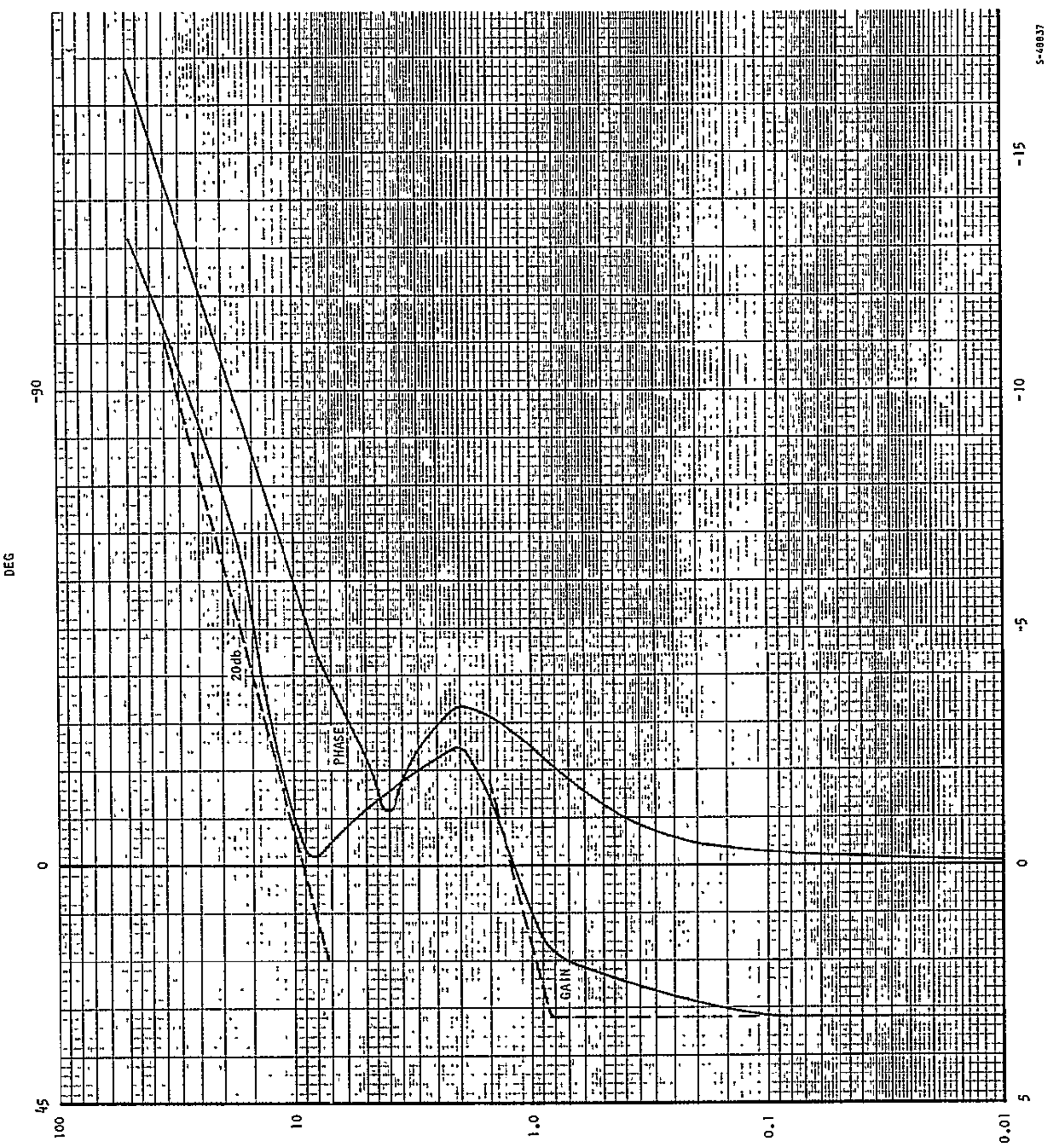

DEG
90
0
-90
CPS
100
10
1.0
0.01
0.1
10
5
0
-10
-18
W_2/C_4
GAIN
PHASE
20db
40db

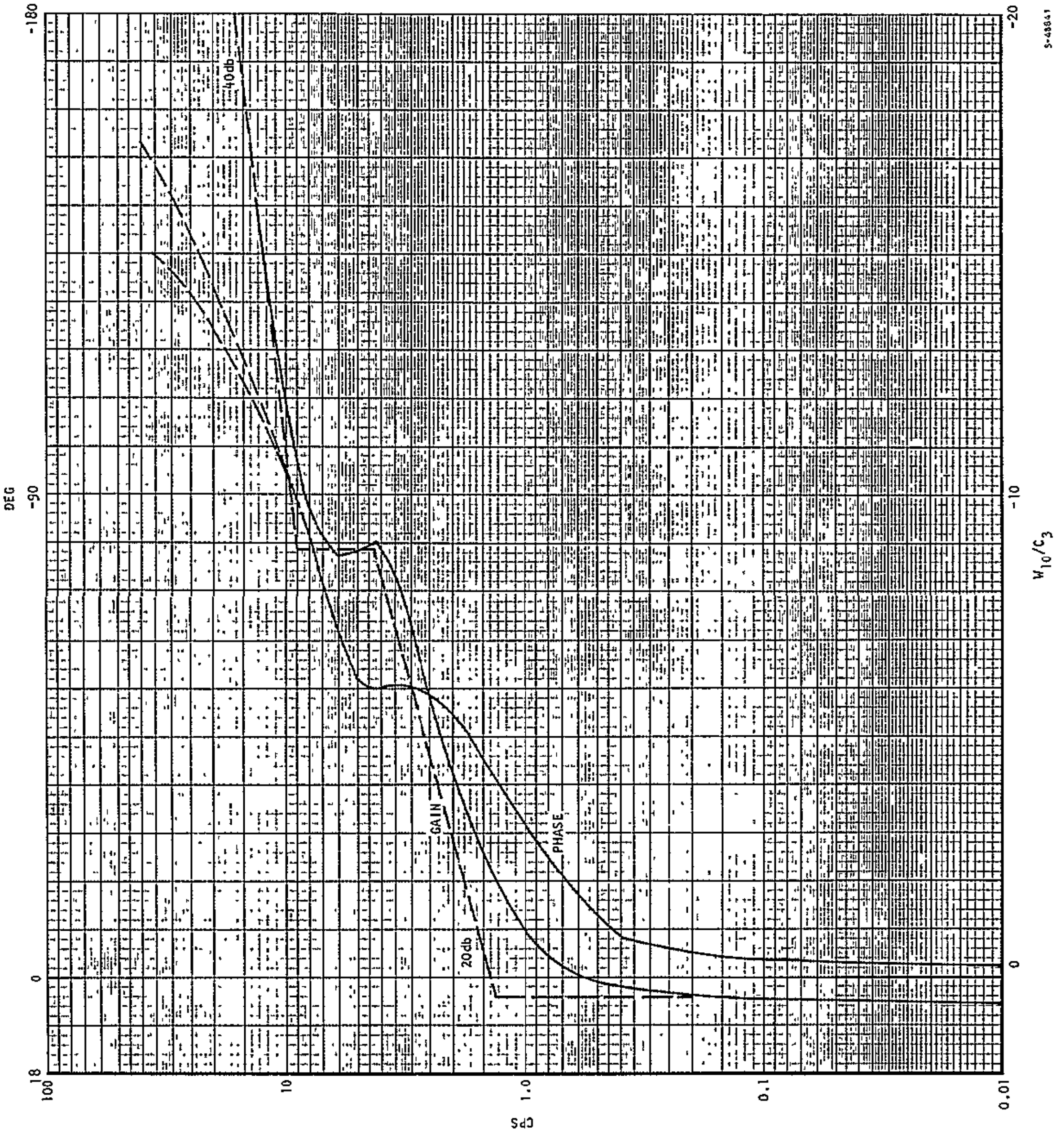


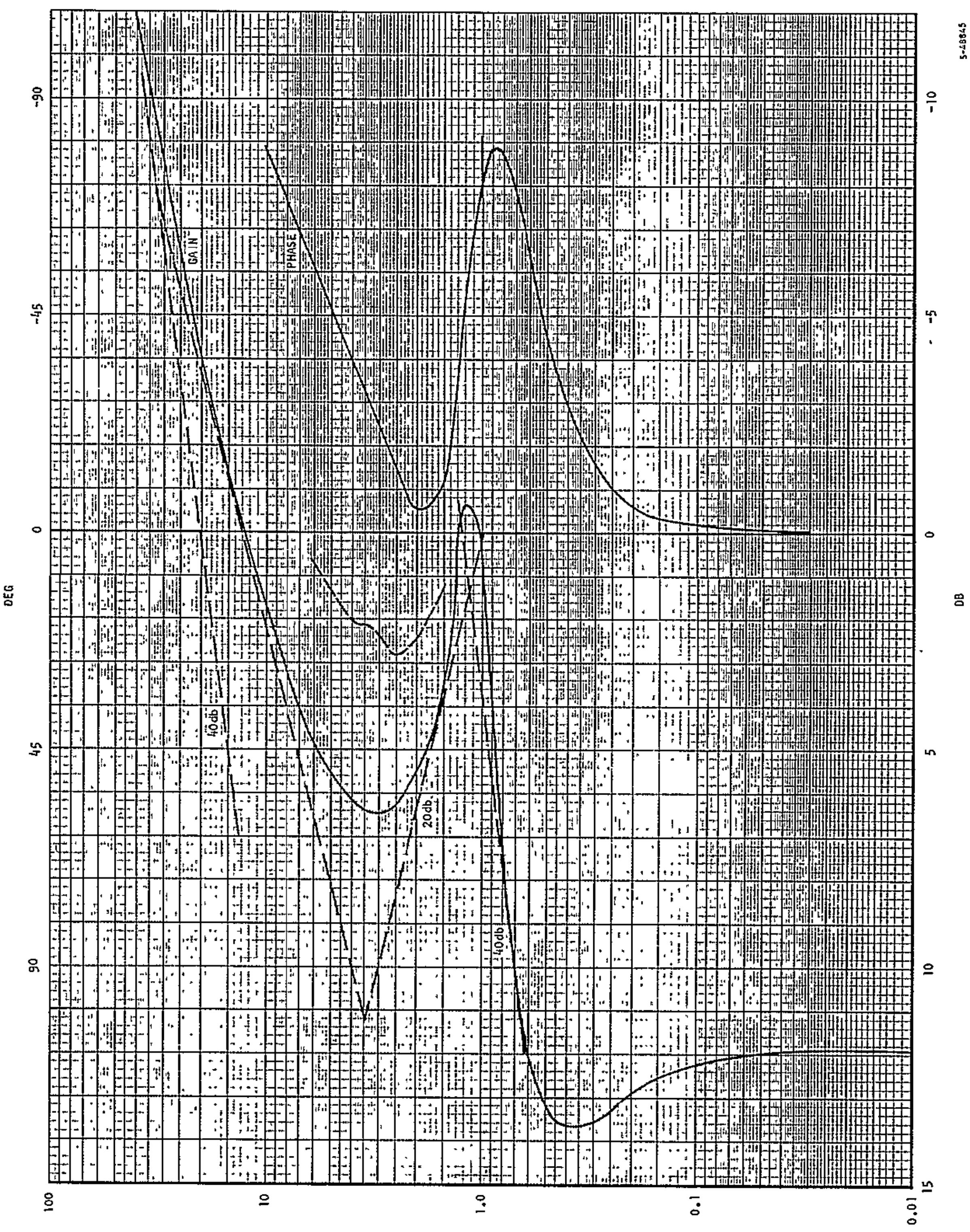
DEG
-180
-90
0
-20
-10
0
5
W2/C3
100
10
1.0
0.1
0.01
CPS
GAIN
PHASE
20db
40db
S-48843

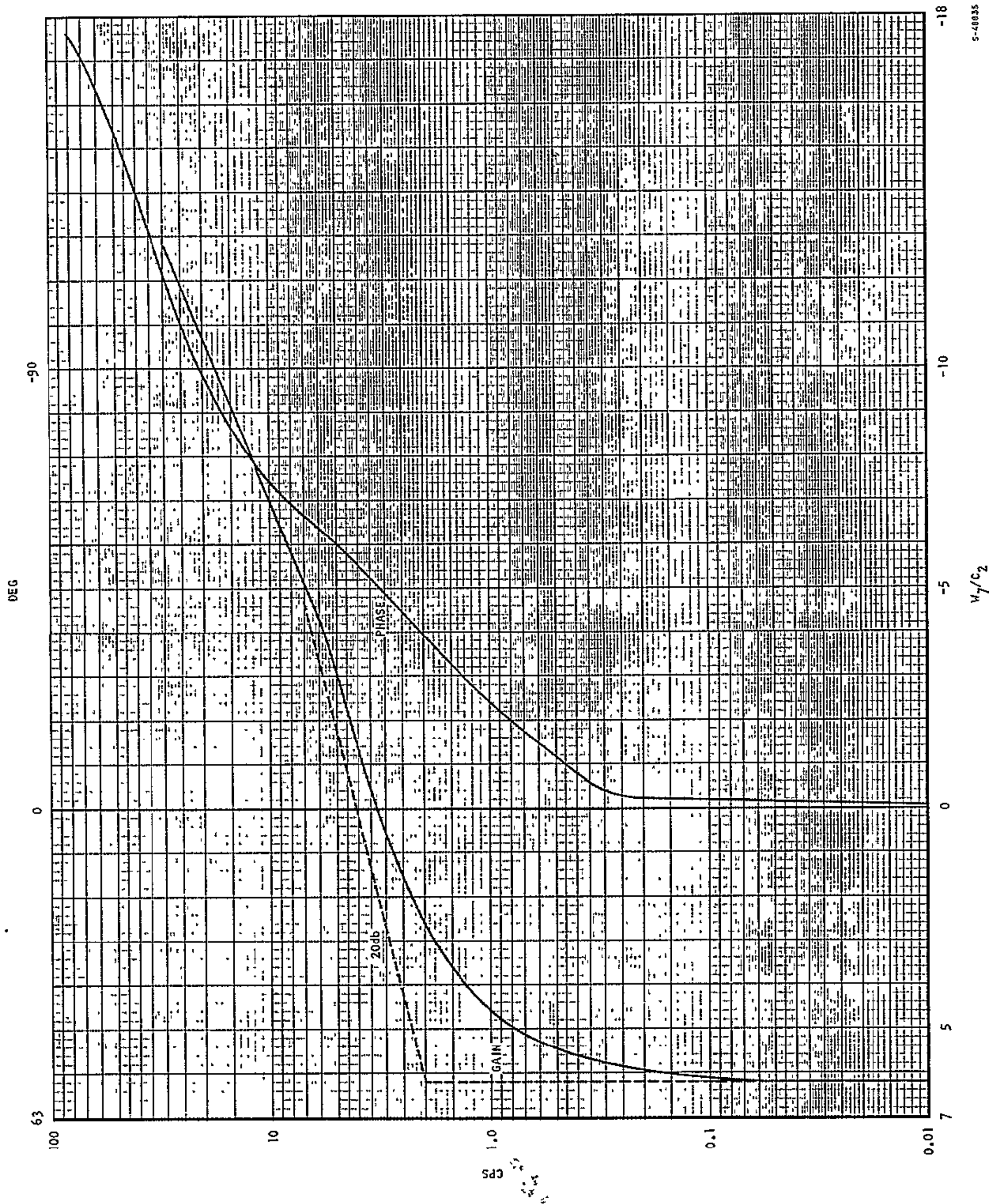

-180
-90
0
DEG
-20
-10
0
5
W_2/C_3
100
10
1.0
0.1
0.01
CPS
GAIN
PHASE
20db
40db
S-48843

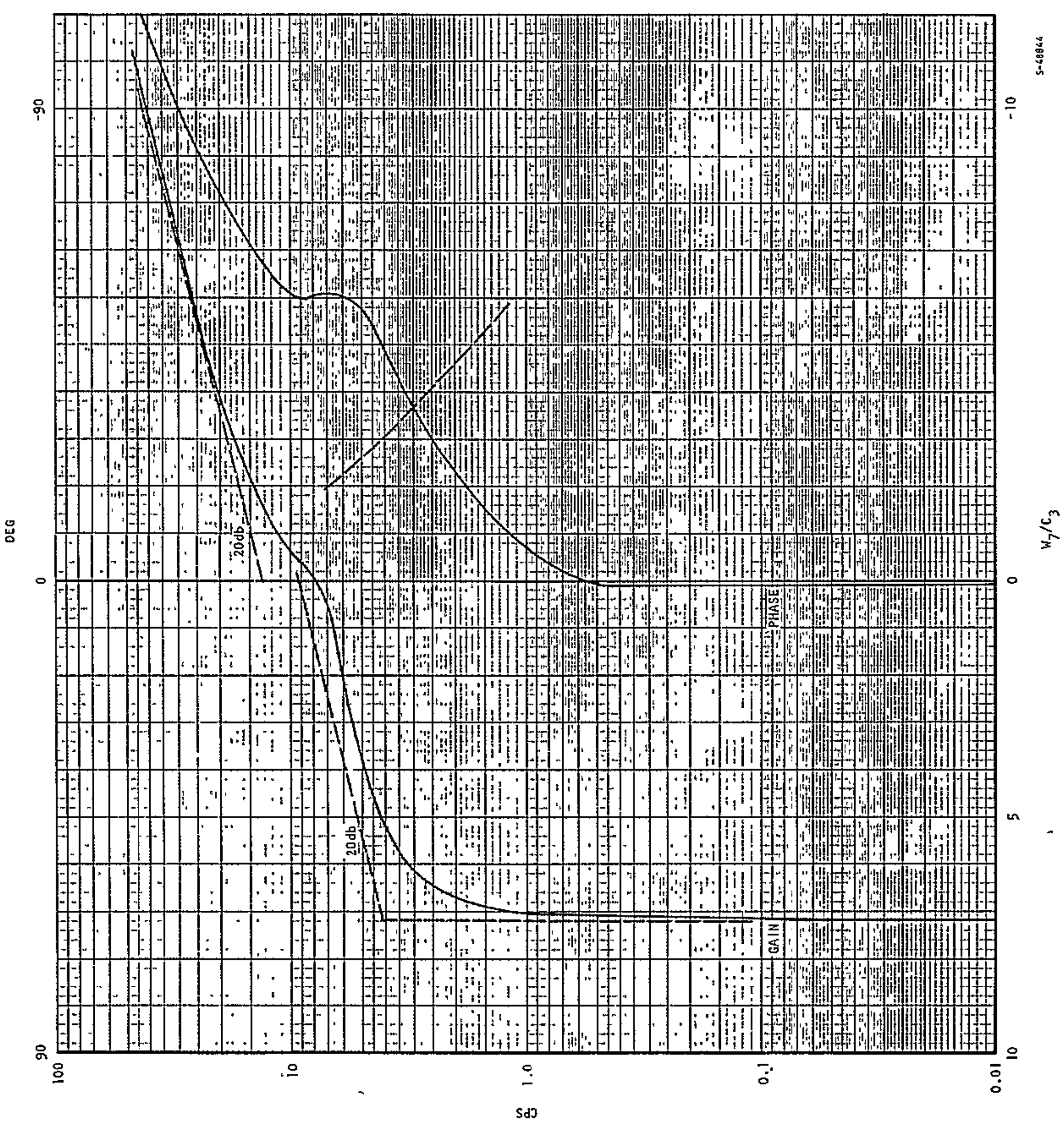

DEG
-180
-90
-45
0
PHASE
PHASE
GAIN
GAIN
-20db
+20db
-20db
100
10
1.0
0.1
0.01
CPS
S-48842


DEG
45
0
-90
-15
-10
-5
5
W_{10}/C_4
100
10
1.0
0.1
0.01
CPS
20db
PHASE
GAIN
S-49837


DEG
-180
-90
0
18
100
10
1.0
0.1
0.01
CPS
-20
-10
0
W_{10}/C_3
40db
20db
GAIN
PHASE
S-48841


DEG
-90
-45
0
45
90
GAIN
PHASE
40db
20db
40db
DB
-10
-5
0
5
10
15
CPS
100
10
1.0
0.1
0.01
S-48845


DEG
63
0
-90
100
10
1.0
0.1
0.01
CPS
7
5
0
-5
-10
-18
W_7/C_2
PHASE
GAIN
20db
S-40035


DEG
-90
0
90
100
10
1.0
0.1
0.01
CPS
10
5
0
-10
W7/C3
20db
20db
PHASE
GAIN
S-48844

APPENDIX C

FREQUENCY RESPONSE PERIPHERALS

APPENDIX C

FREQUENCY RESPONSE PERIPHERALS

This appendix contains a computer diagram of the frequency response peripherals (Figure C-1) and two calibration runs (Figures C-2 and C-3).

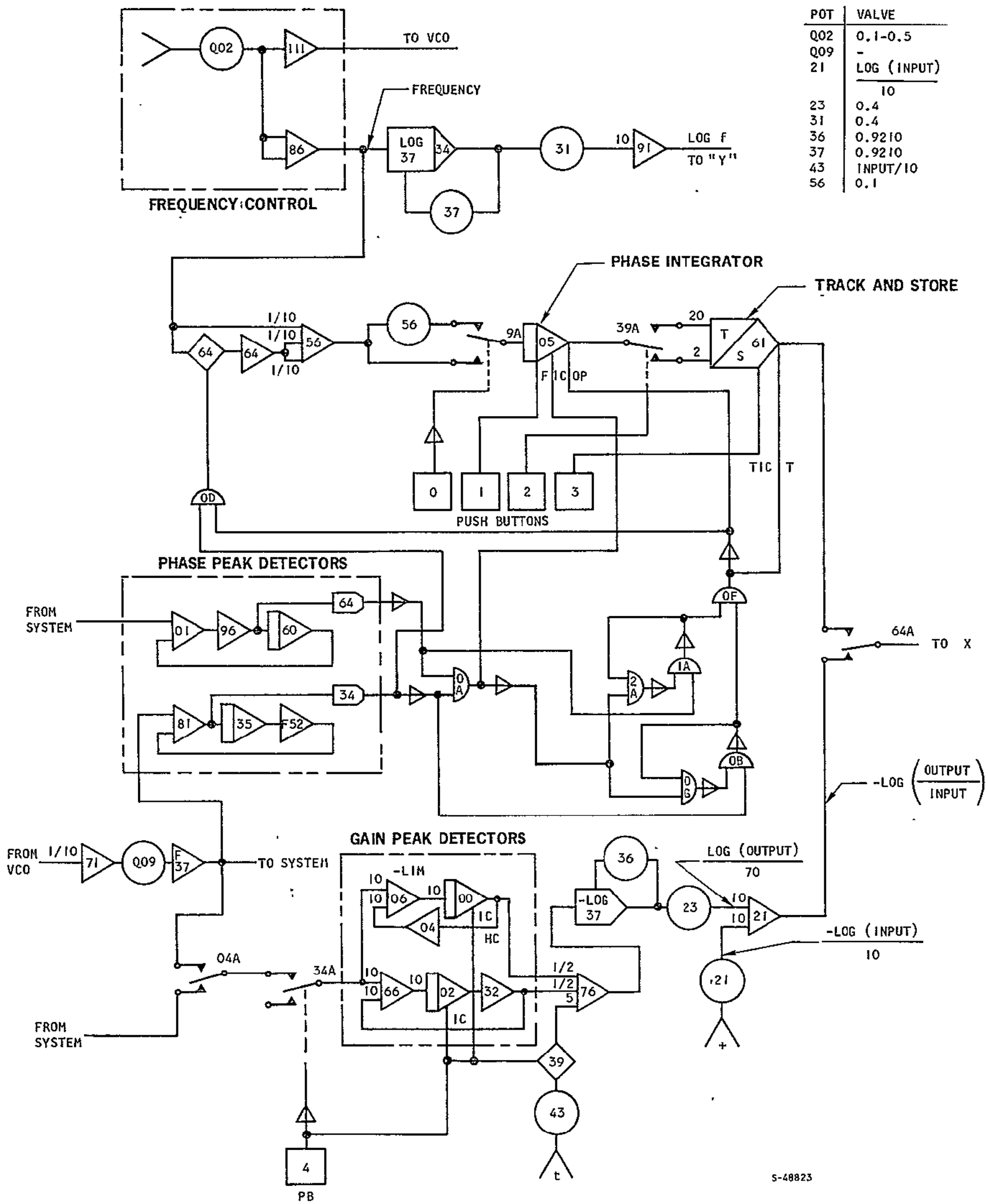
These frequency response peripherals are simpler than the previous peripherals, in that they are not very automatic. The user must select a frequency, decide when the system has settled out, and take a reading. These peripherals do, however, measure phase, thus giving us two criteria for the transfer functions which are derived.

The operation of the phase detector is relatively straightforward. For phase lag operation, integrator 05 will produce the following output.

$$E_o = \int_{T_1}^{T_2} f \, dt$$

Where f is the frequency, T_1 is the time of occurrence of the peak of the driving function, and T_2 is the time of occurrence of the peak in the response voltage. T_1 and T_2 are detected by comparators 34 and 64 in the "phase-peak detectors." The output of integrator 05 will be proportional to the phase. This output is held in track-and-store amplifier 61, while integrator 05 recalculates the phase from the next two peaks. The phase detector logic allows the phase detector to measure lags or leads of up to 180 deg.

Figure C-2 shows the measured frequency response of a lag system, and also the exact values (which are circled) of phase and gain for that system. The exact values were computed digitally. The gain measurement is accurate to within about 0.2 db, and a phase accuracy of within 2.5 degrees. Figure C-3, the frequency response of a lead system, shows a gain inaccuracy of about 0.7 db, and a phase inaccuracy of about 1.8 deg.



POT	VALVE
Q02	0.1-0.5
Q09	-
21	$\frac{\text{LOG (INPUT)}}{10}$
23	0.4
31	0.4
36	0.9210
37	0.9210
43	INPUT/10
56	0.1

Figure C-1. Frequency Response Peripherals

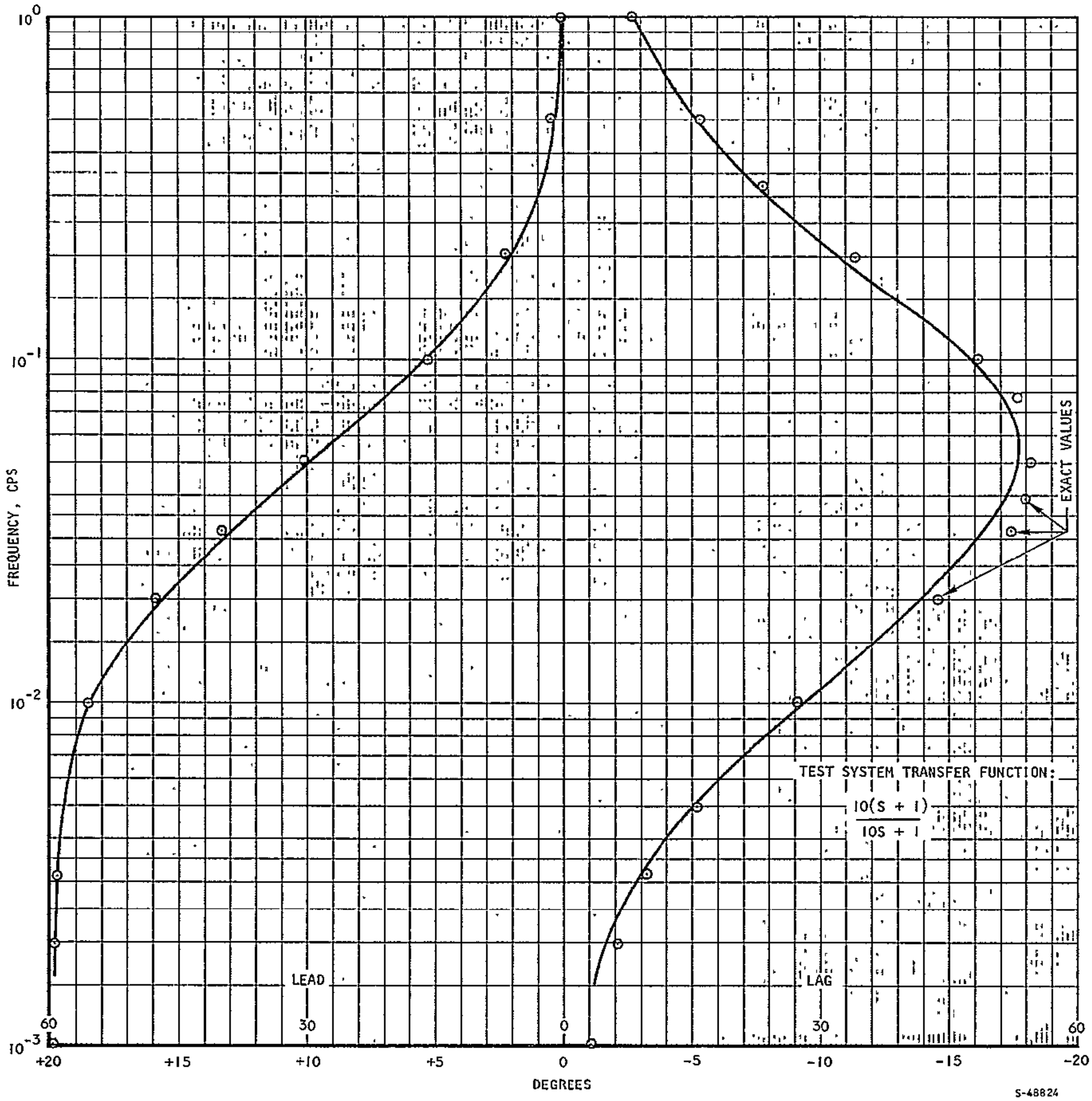


Figure C-2. Test Run on HRE Fuel System Bode Plot Analyzer

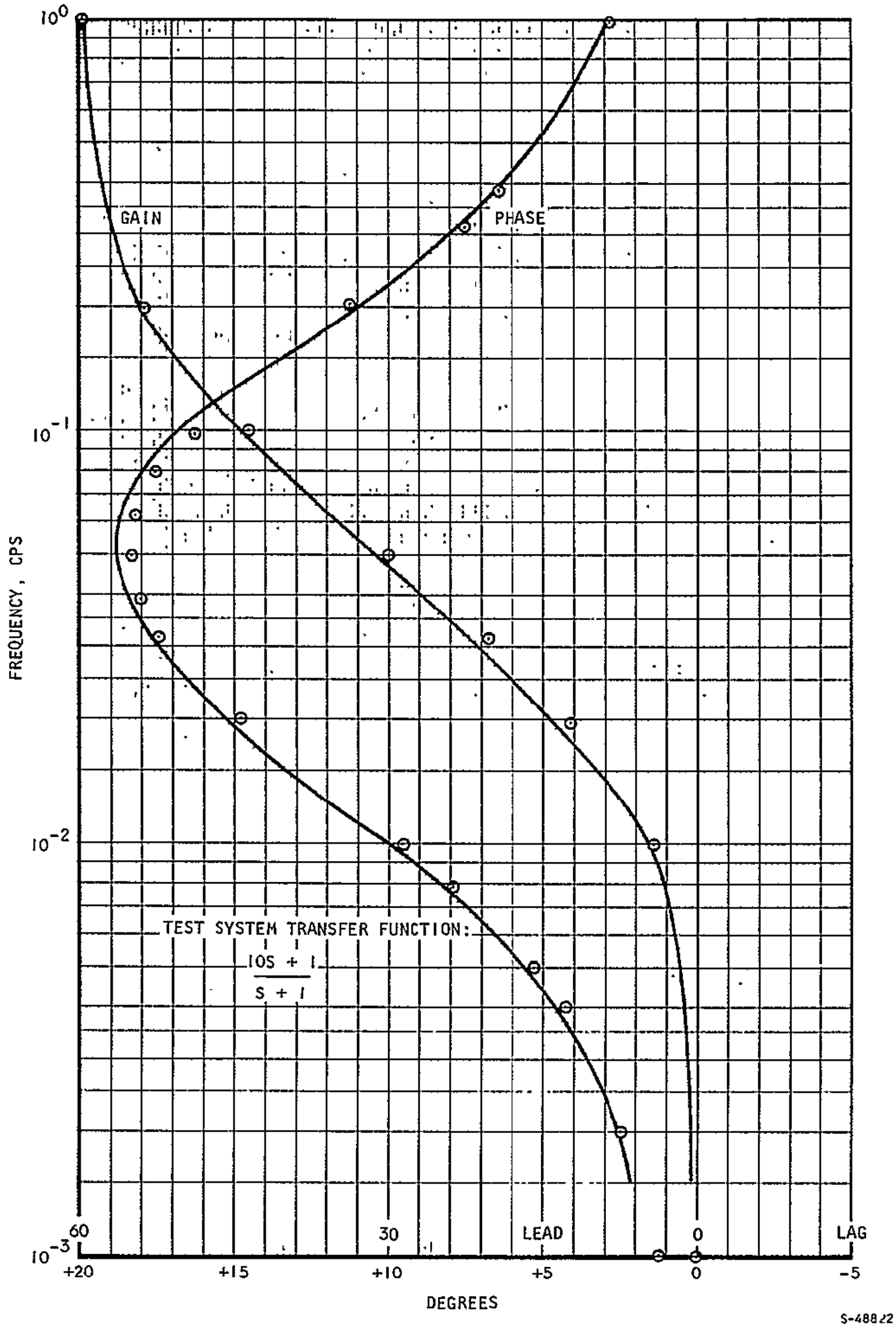


Figure C-3. Test Run on HRE Fuel System Bode Plot Analyzer

APPENDIX D

COMPUTER INTERFACE UNIT TEST PROGRAM LISTINGS

APPENDIX D

COMPUTER INTERFACE UNIT TEST PROGRAM LISTINGS

This appendix includes the listings for the computer interface unit test programs. These are as follows.

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COMPUTER INTERFACE UNIT TEST PROGRAM

```
         ORG 0401
         DOT S          SET JUMP TO WAIT S/R
         TRA J1,1
J1       PZE X2

         ORG  .
         WOT AL         LOCKOUT ADC INTERRUPT
         WOT GL         LOCKOUT TIMER INTERRUPT
         WOT EL         LOCKOUT EXTERNAL DEVICE INTERRUPT
         WOT TE         ENABLE TELETYPE INTERRUPT
S1       CLA C1         SET CHARACTER CTR TO 25
         STA CT
         WOT TA         CLEAR TTY INTERRUPT
         DOT S          SET SR TO PRINT DATA
         CLA W1         SET DATA - SELECT TEST NUMBER
         STA T2
         TRA TO         GO TO TYPE OUT S/R - PRINT DATA
         TRA CC         GO TO CHAR CTR S/R
         TRA WS         GO TO WAIT S/R
         CLA IP
         ANA MK         MASK
         SUB C2         SUBTRACT OCTAL 60
         TMI S1         NOT 0 - 7
         ALS 1
         STA G1         SAVE
         SUB MK
         TMI S2
         TRA S1         NOT 0 - 7
S2       TRA WS         GO TO WAIT S/R
         CLA IP
         ANA MK         MASK
         SUB C2         SUBTRACT OCTAL 60
         TMI S1         NOT 0 - 7
         ADD G1         FORM TEST NUMBER
         STA G1
         SUB MK
         TMI S3
         TRA S1         NOT 0 - 7
S3       DOT RI         RESET MASTER INHIBIT
         CLA R2         SET WAIT S/R RETURN ADDRESS TO S1
         STA WA
         CLA G1
         ANA ON         MASK FOR SINGLE CYCLE
         TZE S4
         CLA G1         YES,SET FOR MULTIPLE CYCLE
         SUB ON
         STA G1
         CLA R1         SET RETURN JUMP TO S5
         STA RJ
```

```
        TRA S5
S4      CLA R2          SET RETURN JUMP TO S1
        STA RJ
S5      TRA LF          GO TO LF AND CR S/R
        CLA G1
        SUB TW
        TZE RA          GO TO PROGRAM 02
        SUB TW
        TZE RB          GO TO PROGRAM 04
        SUB TW
        TZE RC          GO TO PROGRAM 06
        SUB TW
        TZE RD          GO TO PROGRAM 10
        SUB TW
        TZE RE          GO TO PROGRAM 12
        SUB TW
        TZE RF          GO TO PROGRAM 14
        SUB TW
        TZE RG          GO TO PROGRAM 16
        SUB TW
        TZE RH          GO TO PROGRAM 20
        SUB TW
        TZE RP          GO TO PROGRAM 22
        SUB TW
        TZE RK          GO TO PROGRAM 24
        SUB TW
        TZE RL          GO TO PROGRAM 26
        SUB TW
        TZE RM          GO TO PROGRAM 30
        SUB TW
        TZE RN          GO TO PROGRAM 32
        SUB TW
        TZE RO          GO TO PROGRAM 34
        TRA S1

P1      OCT 000215   CR
        OCT 000012   LF
        OCT 000012   LF
        OCT 000215   CR
        OCT 000215   CR
KS      OCT 000123   S
        OCT 000305   E
        OCT 000314   L
        OCT 000305   E
        OCT 000303   C
KT      OCT 000324   T
        OCT 000240
        OCT 000324   T
        OCT 000305   E
        OCT 000123   S
        OCT 000324   T
```

```
         OCT 000240
         OCT 000116     N
         OCT 000125     U
         OCT 000115     M
         OCT 000102     B
         OCT 000305     E
KR       OCT 000322     R
P8       OCT 000240
         OCT 000240

                        TYPE OUT SUBROUTINE

TO       STM SR
         CLA ZE         SET DELAY COUNT ZERO
         STA G2
T1       DIN836,1       WAIT TTY READY
         TMI T3
         WOT TA         TTY OUTPUT ADDRESS
T2       BSS 1          DATA
         DIN836,1       TEST TTY READY
         TZE T4
         RJP SR
T3       CLA G2         ADD ONE TO DELAY COUNT
         ADD ON
         STA G2
         SUB EC
         TMI T1         DELAY TOO LONG
         DOT HT         HALT
         TRA S1         PROCEED TO START
T4       DOT HT         HALT
         TRA S1         PROCEED TO START
SR       BSS 1          RETURN ADDRESS WL
TA       OCT 030040     TTY OUTPUT ADDRESS

                        CHARACTER COUNTER SUBROUTINE

CC       STM SR
         CLA T2         UPDATE DATA ADDRESS
         ADD ON
         STA T2
         CLA CT         ALL TYPED
         SUB ON
         STA CT
         TZE CR
         CLA SR         NO - MODIFY RETURN JUMP
         SUB TW
         STA SR
CR       RJP SR
CT       BSS 1          CHARACTER COUNTER WL
```

WAIT SUBROUTINE

```
WS      STM WA
        DOT RI       RESET MASTER INHIBIT
X1      CLA SR       WAIT INTERRUPT
        TRA X1
X2      WOT TI       INPUT DATA
        DIN IP
        RJP WA
IP      BSS 1        INPUT DATA WORKING LOCATION
TI      OCT 020003   TTY INPUT ADDRESS
WA      BSS 1        RETURN ADDRESS WL
```

LINE FEED AND CARRIAGE RETURN SUBROUTINE

```
LF      STM SS
        CLA C3       SET CHARACTER CTR TO 5
        STA CT
        DOT S        SET SR TO PRINT DATA
        CLA W1       SET DATA - SELECT PROGRAM NUMBER
        STA T2
        TRA TO       GO TO TYPE OUT S/R LF AND CR
        TRA CC       GO TO CHAR CTR S/R
        RJP SS
SS      BSS 1        RETURN ADDRESS WL
```

PRINT WORD SUBROUTINE

```
PW      STM SS
        CLA W6       SET DATA - PRINT WORD WL
        STA T2
        CLA SI       SET INITIAL SHIFT INSTRUCTION
        STA PY
PX      CLA WD       FORM OCTAL INTO TTY CODE
PY      BSS 1
        ANA K2       MASK DIGIT
        ADD BS       ADD BASE OCTAL 260
        STA P7
        TRA TO       GO TO TYPE OUT S/R
        CLA CT       ALL CHARACTERS TYPED
        SUB ON
        STA CT
        TZE PZ
        CLA PY       NO - MODIFY SHIFT INSTRUCTION
        SUB TH
        STA PY
        TRA PX
```

```
PZ      RJP SS

                   SPACE TWO SUBROUTINE

SP      STM SS
        CLA TW     SET CHARACTER CTR TO 2
        STA CT
        DOT S      SET SR TO PRINT DATA
        CLA W7     SET DATA - 2 SPACES
        STA T2
        TRA TO     GO TO TYPE OUT S/R
        TRA CC     GO TO CHAR CTR S/R
        RJP SS


                   ANALOG INPUT-OUTPUT SUBROUTINE

SA      STM SC
        CLA ZE     SET SWITCH FOR ANALOG IN
        TRA SE
SB      STM SC
        CLA ON     SET SWITCH FOR ANALOG OUT
SE      STA SD
SF      TRA LF     GO TO LF AND CR S/R
        CLA C6     SET CHARACTER COUNT TO 14
        STA CT
        DOT S      SET SR TO PRINT DATA
        CLA W4     SET DATA - SELECT ANALOG
        STA T2
        TRA TO     GO TO TYPE OUT S/R
        TRA CC     GO TO CHAR CTR S/R
        CLA SD     ANALOG IN
        TZE SG
        CLA TH     NO - SET CHARACTER CTR TO 3
        STA CT
        DOT S      SET SR TO PRINT DATA
        CLA W9     SET DATA - OUT
        TRA SH
SG      CLA TW     SET CHARACTER CTR TO 2
        STA CT
        DOT S      SET SR TO PRINT DATA
        CLA W8     SET DATA -IN
SH      STA T2
        TRA TO     GO TO TYPE OUT S/R
        TRA CC     GO TO CHAR CTR S/R
        TRA SP     GO TO SPACE 2 S/R
        TRA WS     GO TO WAIT S/R
        CLA IP
        ANA MK     MASK
```

```
         SUB C2        SUBTRACT OCTAL 60
         TMI SF        NOT 0 - 7
         ALS 1
         STA G3        SAVE
         SUB MK
         TMI SJ
         TRA SF        NOT 0 - 7
SJ       TRA WS        GO TO WAIT S/R
         CLA IP
         ANA MK        MASK
         SUB C2        SUBTRACT OCTAL 60
         TMI SF        NOT 0 - 7
         ADD G3        FORM ANALOG NUMBER
         STA G3
         CLA SD        ANALOG IN OR OUT
         TZE SK        ANALOG IN
         CLA G3        ANALOG OUT
         TZE SM        ANALOG 00 SELECTED
         SUB K3
         TZE SF        05 NOT VALID FOR ANALOG OUT
         SUB K4
         TMI SL
         TRA SF        ANALOG OUT NUMBER GREATER THAN 12
SL       CLA G3        SET TO ANALOG OUT
         STA G6
         TRA SQ
SK       CLA G3
         TZE SM        ALL ANALOG INPUTS
         SUB C7
         TMI SN
         TRA SF        NOT VALID NUMBER
SN       CLA G3
         SUB C8        SUBTRACT OCTAL 17
         TZE SF
         SUB C9        SUBTRACT OCTAL 10 (27)
         TZE SF
         SUB C9        SUBTRACT OCTAL 10 (37)
         TZE SF
         CLA G3        SET TO ANALOG IN
         STA G5
SQ       CLA SC
         ADD ON
         STA SC
SM       RJP SC

P5       OCT 000123    S
         OCT 000305    E
         OCT 000314    L
         OCT 000305    E
         OCT 000303    C
         OCT 000324    T
```

```
         OCT 000240
         OCT 000101    A
         OCT 000116    N
         OCT 000101    A
         OCT 000314    L
         OCT 000317    O
         OCT 000107    G
         OCT 000240
P9       OCT 000311    I
         OCT 000116    N
PA       OCT 000317    O
         OCT 000125    U
         OCT 000324    T
PC       OCT 000303    C
         OCT 000110    H
         OCT 000101    A
         OCT 000116    N
         OCT 000116    N
         OCT 000305    E
         OCT 000314    L
         OCT 000240
P6       OCT 000303    C
         OCT 000131    Y
         OCT 000303    C
         OCT 000314    L
         OCT 000305    E
         OCT 000240
         OCT 000305    E
         OCT 000116    N
         OCT 000104    D

                       TELETYPE OUTPUT TEST  02 AND 03

MA       STM RJ
RA       TRA LF        GO TO LF AND CR S/R
         CLA C4        SET CHARACTER COUNTER TO 22
         STA CT
         DOT S         SET SR TO PRINT DATA
         CLA W2        SET DATA - TTY REPERTOIRE PART 1
         STA T2
         TRA TO        GO TO TYPE OUT S/R
         TRA CC        GO TO CHAR CTR S/R
         TRA LF        GO TO LF AND CR S/R
         CLA C5        SET CHARACTER COUNTER TO 42
         STA CT
         DOT S         SET SR TO PRINT DATA
         CLA W3        SET DATA - TTY REPERTOIRE PART 2
         STA T2
         TRA TO        GO TO TYPE OUT S/R
         TRA CC        GO TO CHAR CTR S/R
```

```
        RJP RJ

P2      OCT 000261    1
        OCT 000262    2
        OCT 000063    3
        OCT 000264    4
        OCT 000065    5
        OCT 000066    6
        OCT 000267    7
        OCT 000270    8
        OCT 000071    9
        OCT 000060    0
        OCT 000072    COLON
        OCT 000055    HYPHEN
        OCT 000321    Q
        OCT 000327    W
        OCT 000305    E
        OCT 000322    R
        OCT 000324    T
        OCT 000131    Y
        OCT 000125    U
        OCT 000311    I
        OCT 000317    O
        OCT 000120    P
        OCT 000012    LF
        OCT 000215    CR
P3      OCT 000101    A
        OCT 000123    S
        OCT 000104    D
        OCT 000306    F
        OCT 000107    G
        OCT 000110    H
        OCT 000312    J
        OCT 000113    K
        OCT 000314    L
        OCT 000273    SEMI COLON
        OCT 000132    Z
        OCT 000330    X
        OCT 000303    C
        OCT 000126    V
        OCT 000102    B
        OCT 000116    N
        OCT 000115    M
        OCT 000254    COMMA
        OCT 000056    PERIOD
        OCT 000257    /
        OCT 000240
        OCT 000041    EXCLAMATION
        OCT 000042    INVERTED COMMAS
        OCT 000243    PART/WEIGHT
        OCT 000044    DOLLAR
```

```
          OCT 000245     PERCENT
          OCT 000246     AMPLICAND
          OCT 000047     APOSTROPHE
          OCT 000050     OPEN PARENTHESIS
          OCT 000251     CLOSE PARENTHESIS
          OCT 000252     ASTERISK
          OCT 000275     EQUALS
          OCT 000137     LEFT ARROW
          OCT 000300     AT
          OCT 000333     OPEN BRACKET (VT.)
          OCT 000134     SLASH (FORM)
          OCT 000053     PLUS
          OCT 000336     UPWARD ARROW
          OCT 000335     CLOSE BRACKET
          OCT 000074     LESS THAN
          OCT 000276     GREATER THAN
          OCT 000077     QUESTION MARK
P4        PZE P3&42

                         TELETYPE INPUT TEST  04

RB        CLA IT         SET TEST FOR FIRST CHARACTER
          STA I2
I1        TRA WS         GO TO WAIT S/R
          CLA IP         COMPARE CHARACTERS
I2        BSS 1
          TZE I3         EQUAL
          TRA LF         GO TO LF AND CR S/R
          CLA I2
          ADD CX         SET TO INSTRUCTION
          STA T2
          TRA TO         TYPE REQUIRED CHARACTER
          TRA I1
I3        CLA I2         UPDATE REQUIRED CHARACTER
          ADD ON
          STA I2
          SUB IF         ALL TYPED
          TZE S1         YES
          TRA I1         NO

                         ANALOG INPUT TEST 06

A2        CLA ON         SET SWITCH TO ONE FOR TEST ALL
          STA SW
          CLA AI         SET FOR FIRST ANALOG INPUT
          STA WO
A1        TRA WS         GO TO WAIT S/R
AB        CLA IP
          SUB KT
```

```
        TZE S1        KEY T
        CLA IP
        SUB KR
        TZE A5        KEY R
RC      TRA SA        GO TO ANALOG IN S/R
        TRA A2        ALL ANALOG INPUTS REQUIRED
        CLA ZE        SET SWITCH TO ZERO FOR SINGLE TEST
        STA SW
        CLA AS        FORM INPUT OPCODE
        ADD G5
        STA WO
        TRA A1
A5      DOT RI        RESET MASTER INHIBIT
        CLA A9        SET WAIT S/R RETURN ADDRESS TO A8
        STA WA
        WOT WO        INPUT ANALOG
        ALS 6         DELAY 7 WORD TIMES
        DIN IP
        CLA IP        SAVE FIRST VALUE OF ANALOG INPUT
        STA G4
A6      TRA LF        GO TO LF AND CR S/R
        CLA TW        SET CHARACTER CTR TO 2
        STA CT
        CLA WO        SET ANALOG NUMBER IN PRINT WORD WL
        SUB AS
        STA WD
        TRA PW        GO TO PRINT WORD S/R
        TRA SP        GO TO SPACE TWO S/R
        CLA FR        SET CHARACTER CTR TO 4
        STA CT
        CLA IP        SET ANALOG INPUT IN PRINT WORD WL
        STA WD
        TRA PW        GO TO PRINT WORD S/R
        CLA SW        SINGLE TEST
        TZE A1        YES
A7      CLA WO        UPDATE ANALOG AND CHECK SEQUENCE
        ADD ON
        STA WO
        SUB AS        SUBTRACT OPCODE BASE
        SUB C8        SUBTRACT OCTAL 17
        TZE A7
        SUB C9        SUBTRACT OCTAL 10 (27)
        TZE A7
        SUB C9        SUBTRACT OCTAL 10 (37)
        TZE A7
        SUB K1        SUBTRACT OCTAL 11 (50)
        TZE A8
        WOT WO        INPUT ANALOG
        ALS 6         DELAY
        DIN IP
        CLA G4        COMPARE ANALOG WITH FIRST VALUE
```

```
        SUB IP
        TZE A7      EQUAL
        TRA A6      NO
A8      TRA LF      GO TO LF AND CR S/R
        CLA K1      SET CHARACTER CTR TO 9
        STA CT
        DOT S.      SET SR TO PRINT DATA
        CLA W5      SET DATA - CYCLE END
        STA T2
        TRA TO      GO TO TYPE OUT S/R
        TRA CC      GO TO CHAR CTR S/R
        TRA A1

                    ANALOG INPUT-OUTPUT TEST 10

RD      TRA SA      GO TO SELECT ANALOG IN S/R
        TRA RD      ANALOG 00 SELECTED
AA      TRA SB      GO TO SELECT ANALOG OUT S/R
        TRA AA      ANALOG 00 SELECTED
        CLA AS      FORM INPUT OPCODE
        ADD G5
        STA WO
        CLA OI      FORM OUTPUT OPCODE
        ADD G6
        STA AO
        DOT RI      RESET MASTER INHIBIT
        CLA PB      SET WAIT S/R RETURN TO A4
        STA WA
A3      WOT WO      INPUT ANALOG
        ALS 6
        DIN IP
        WOT AO      OUTPUT ANALOG
        WOT IP
        TRA A3
A4      CLA IP      TERMINATE
        SUB KT
        TZE S1      YES
        TRA RD      NO

                    ANALOG OUTPUT TEST 12 AND 13

RE      DOT RI      RESET MASTER INHIBIT
        CLA BB      SET WAIT S/R RETURN ADDRESS TO BI
        STA WA
        CLA O1      SET FOR ANALOG OUTPUT NUMBER 1
        STA AO
        CLA I4      SET FOR ANALOG INPUT NUMBER 60
        STA WO
        CLA V1      SET MAXIMUM VALUE FOR ANALOG OUTPUT NO 1
```

```
        STA MV
        CLA LM      SHIFT LIMIT FOR CHANNELS 1,2 AND 3 (FCV)
        ALS 2
        STA LM
B1      CLA ON      SET FOR POSITIVE UPDATE
        STA UD
        CLA ZE      SET INITIAL VALUE OF DATA TO ZERO
        STA DT
B2      WOT AO      OUTPUT DATA TO CHANNEL
        WOT DI
        WOT WO      INPUT DATA FROM CHANNEL
        ALS 6
        DIN IP
        CLA IP
        SUB DT
        TZE B4      INPUT EQUALS OUTPUT
        TMI B3      NO,CHECK LIMITS
        SUB LM      SUBTRACT LIMIT
        TMI B4      OK
        TRA BA      OVER LIMIT
B3      ADD LM      ADD LIMIT
        TMI BA      UNDER LIMIT
B4      CLA DT      UPDATE OUTPUT
        ADD UD
        STA DT
        TMI B6      CHANNEL TEST COMPLETED
        SUB MV
        TZE B5      MAXIMUM VALUE
        TRA B2
B5      CLA MO      SET NEGATIVE UPDATE
        STA UD
        TRA B4
B6      CLA WO      UPDATE ANALOG INPUT CHANNEL
        ADD ON
        STA WO
        CLA AO      UPDATE OUTPUT CHANNEL
        ADD ON
        STA AO
        SUB O2      SPIKE CHANNEL
        TZE B8      YES
        SUB ON      FIRST TEMPERATURE CHANNEL
        TZE B9      YES
        SUB O3      LAST CHANNEL
        TZE B7      YES
        TRA B1
B7      RJP RJ
B8      CLA LM      RESET LIMIT FOR REMAINING CHANNELS
        ARS 2
        STA LM
        CLA V2      SET MAXIMUM VALUE FOR REMAINING CHANNELS
        STA MV
```

```
        TRA B1
B9      CLA A0      UPDATE OUTPUT FOR FIRST TEMPERATURE CHANNEL
        ADD ON
        STA A0
        CLA W0      UPDATE INPUT FOR FIRST TEMPERATURE CHANNEL
        ADD FR
        STA W0
        TRA B1
BA      TRA LF      GO TO LF AND CR S/R
        CLA 03      SET CHARACTER CTR TO 8
        STA CT
        DOT S       SET SR TO PRINT DATA
        CLA WL      SET DATA - CHANNEL
        STA T2
        TRA TO      GO TO TYPE OUT S/R
        TRA CC      GO TO CHAR CTR S/R
        CLA A0      MASK TO OBTAIN CHANNEL ADDRESS
        ANA M1
        STA WD      STORE AS OUTPUT WORD
        CLA TW      SET CHARACTER CTR TO 2
        STA CT
        TRA PW      GO TO PRINT WORD S/R
        TRA SP      GO TO SPACE TWO S/R
        CLA FR      SET CHAR CTR TO 4
        STA CT
        CLA DT      SET OUTPUT DATA IN PRINT WORD
        STA WD
        TRA PW      GO TO PRINT WORD S/R
        TRA SP      GO TO SPACE TWO S/R
        CLA FR      SET CHAR CTR TO 4
        STA CT
        CLA IP      SET INPUT DATA IN PRINT WORD
        STA WD
        TRA PW      GO TO PRINT WORD S/R
        TRA B4      CONTINUE
BI      CLA IP
        SUB KS      KEY S
        TZE B6      YES - SKIP PRESENT CHANNEL
        CLA IP
        SUB KT      KEY T
        TZE S1      YES - GO TO PROGRAM SELECT
BC      TRA LF      GO TO LF AND CR S/R
        CLA K5      SET CHARACTER CTR TO 10
        STA CT
        DOT S       SET SR TO PRINT DATA
        CLA WE      SET PRINT DATA - SET LIMIT
        STA T2
        TRA TO      GO TO TYPE OUT S/R
        TRA CC      GO TO CHAR CTR S/R
        TRA WS      GO TO WAIT S/R
        CLA IP
```

```
        ANA MK        MASK FOR NUMERIC
        SUB C2
        STA LM        STORE LIMIT
        SUB 03
        TMI RE
        TRA BC        NOT NUMERIC 0-7

PD      OCT 000123    S
        OCT 000305    E
        OCT 000324    T
        OCT 000240
        OCT 000314    L
        OCT 000311    I
        OCT 000115    M
        OCT 000311    I
        OCT 000324    T
        OCT 000240

                      OUTPUT DISCRETE TEST 14 AND 15

MF      STM RJ
RF      CLA ON        SET SWITCH FOR TEST 14
        STA SU
DU      WOT TA        CLEAR TTY INTERRUPT
        WOT AD        CLEAR ADC INTERRUPT
        WOT EX        CLEAR EXTERNAL DEVICE INTERRUPT
        WOT TC        CLEAR TIMER INTERRUPT
        CLA DF        RESET ALL DISCRETES
        STA DR
D1      WOT DR        RESET DISCRETE
        CLA DR        UPDATE DISCRETE
        ADD ON
        STA DR
        SUB DE        ALL DONE
        TZE D2        YES
        TRA D1        NO
D2      CLA DX        SET DISCRETE INSTRUCTION
        STA D4
        CLA DY        RESET DISCRETE INSTRUCTION
        STA D6
DK      CLA DG        SET FOR FIRST DISCRETE
        STA DS
D3      CLA DS        UPDATE DISCRETES
        ADD ON
        STA DS
        ADD AD
        STA DR
        SUB DH        FIRST DISCONTINUITY
        TZE D3
        SUB DJ        SECOND DISCONTINUITY
```

```
        TZE D3
        SUB TW
        TZE D7       END OF SEQUENCE
D4      WOT DS
        CLA SU       TEST 20
        TZE F1       YES
DV      CLA DL       SET DELAY
D5      ADD ON
        TMI D5
D6      WOT DR
        TRA D3
D7      CLA D4
        SUB DX
        TZE DB       FIRST RUN THROUGH
        CLA DF       NO.RESET ALL DISCRETES
        STA DR
D8      WOT DR
        CLA DR
        ADD ON
        STA DR
        SUB DE
        TZE D9
        TRA D8
D9      WOT TA       CLEAR TTY INTERRUPT
        WOT DN       SET TTY INTERRUPT ENABLE DISCRETE
        RJP RJ
DB      CLA DG       SET ALL DISCRETES
        ADD ON
        STA DS
DC      WOT DS
        CLA DS
        ADD ON
        STA DS
        ADD AD
        SUB DE
        TZE DD
        TRA DC
DD      CLA DX       CHANGE SET AND RESET INSTRUCTIONS
        STA D6
        CLA DY
        STA D4
        TRA DK


                     DISCRETE INPUT TEST 16

RG      CLA DM       SET FOR FIRST DISCRETE
        STA DS
        CLA DF
        STA DR
        WOT DI       INPUT DISCRETES
```

```
        ALS 7          DELAY
        DIN IP
I5      CLA IP
        ANA ON         MASK FOR LSB
        TZE I6
        WOT DS         SET DISCRETE
        TRA I7
I6      WOT DR         RESET DISCRETE
I7      CLA IP         RIGHT SHIFT INPUT DISCRETES 1 PLACE
        ARS 1
        STA IP
        CLA DS         UPDATE OUTPUT DISCRETE OPCODES
        ADD ON
        STA DS
        ADD AD
        STA DR
        SUB DQ         LAST OUTPUT
        TZE RG         YES - REPEAT
        TRA I5         NO - CONTINUE

                       CONSTANTS AND WORKING LOCATIONS

ZE      OCT 000000     CONSTANT ZERO
ON      OCT 000001     CONSTANT ONE
TW      OCT 000002     CONSTANT TWO
TH      OCT 000003     CONSTANT THREE
FR      OCT 000004     CONSTANT FOUR
A9      PZE AB
AD      OCT 010000     OPCODE CLEAR ADC INTERRUPT
AI      OCT 010001     INITIAL VALUE OF ANALOG IN ADDRESS
AL      OCT 060015     RESET ADC INT
AS      OCT 010000     ANALOG INPUT BASE
BB      PZE BI         INTERRUPT ADDRESS
BS      OCT 000260     TTY BASE FOR NUMERIC
C1      OCT 000031     CONSTANT 25
C2      OCT 000060     CONSTANT FOR NUMERIC
C3      OCT 000005     CONSTANT 5
C4      OCT 000026     CONSTANT 22
C5      OCT 000052     CONSTANT 42
C6      OCT 000016     CONSTANT 14
C7      OCT 000051     CONSTANT FOR ANALOG IN
C8      OCT 000017     CONSTANT OCTAL 17
C9      OCT 000010     CONSTANT OCTAL 10
DE      OCT 060031     OPCODE RESET DISCRETE 30 PLUS 1
DF      OCT 060001     OPCODE RESET DISCRETE 1
DG      OCT 050000     OPCODE SET DISCRETE BASE
DH      OCT 060017     OPCODE AT FIRST DISCONTINUITY
DI      OCT 020001     OPCODE INPUT DISCRETES - SET 1
DJ      OCT 000010     INCREMENT FOR DISCONTINUITIES
DL      OCT 040000     DELAY COUNT
DN      OCT 050016     OPCODE SET TTY ENABLE DISCRETE
```

```
DM      OCT 050001   OPCODE SET DISCRETE 1
DQ      OCT 060015   OPCODE RESET DISCRETE 14 PLUS 1
DR      BSS 1        OPCODE RESET DISCRETE WL
DS      BSS 1        OPCODE SET DISCRETE WL
DT      BSS 1        OUTPUT DATA WL
DX      WOT DS       OUTPUT INSTRUCTION SET DISCRETE
DY      WOT DR       OUTPUT INSTRUCTION RESET DISCRETE
EC      OCT 001433   TO CONSTANT 795
EL      OCT 060020   RESET EXT DEV INT
EX      OCT 020040   OPCODE CLEAR EXTERNAL DEVICE INTERRUPT
G1      BSS 1        PROGRAM NO WL
G2      BSS 1        DELAY COUNT TO S/R WL
G3      BSS 1        ANALOG NUMBER WL
G4      BSS 1        FIRST VALUE OF ANALOG INPUT
G5      BSS 1        ANALOG INPUT NUMBER WL
G6      BSS 1        ANALOG OUT NUMBER WL
GL      OCT 060021   RESET TIMER INT
HT      OCT 000400   HALT
I4      OCT 010060   OPCODE FOR ANALOG INPUT 60
IF      SUB P4       FINAL VALUE OF I2
IO      OCT 030000   ANALOG OUT OPCODE BASE
IT      SUB P2       INITIAL VALUE OF I2
K1      OCT 000011   CONSTANT OCTAL 11
K2      OCT 000007   CONSTANT OCTAL 7
K3      OCT 000005   CONSTANT 5
K4      OCT 000006   CONSTANT 6
K5      OCT 000012   CONSTANT TEN
LM      BSS 1        LIMIT VALUE
ML      OCT 000077   MASK FOR OUTPUT CHANNEL
MK      OCT 000077   MASK FOR NUMERIC
MV      BSS 1        MAXIMUM VALUE OF OUTPUT
O1      OCT 030001   OPCODE FOR ANALOG OUTPUT 1
O2      OCT 030004   OPCODE FOR ANALOG OUTPUT SPIKE CHANNEL
O3      OCT 000010   DIFFERENCE FOR OPCODES FOR LAST ANALOG OUTPUT
P7      BSS 1
PB      PZE A4
RI      OCT 000040   MASTER INHIBIT RESET
RJ      BSS 1        TEST PROGRAM RETURN ADDRESS
R1      PZE S5
R2      PZE S1
SC      BSS 1        SELECT ANALOG S/R RETURN ADDRESS
SD      BSS 1        SWITCH WL
SI      OCT 400017   INITIAL VALUE OF SHIFT INSTRUCTION
SW      BSS 1        SWITCH
TC      OCT 040000   OPCODE CLEAR TIMER INTERRUPT
TE      OCT 050016   SET TTY INT
UD      BSS 1        UPDATE VALUE WL
V1      OCT 000775   MAXIMUM VALUE FOR FCV CHANNELS
V2      OCT 002000   MAXIMUM VALUE FOR REMAINING CHANNELS
W1      WOT P1,1     DATA - SELECT PROGRAM NO
W2      WOT P2,1     DATA - TTY REPERTOIRE PART 1
```

```
W3      WOT P3,1      DATA - TTY REPERTOIRE PART 2
W4      WOT P5,1      DATA - SELECT ANALOG IN
W5      WOT P6,1      DATA - CYCLE END
W6      WOT P7        DATA PRINT WORD
W7      WOT P8,1      DATA - 2 SPACES
W8      WOT P9,1      DATA - IN
W9      WOT PA,1      DATA - OUT
WD      BSS 1         PRINT WORD WL
WE      WOT PD,1
WL      WOT PC,1
WO      BSS 1         OUTPUT COMMAND TO CIU
```

APPENDIX E

HRE INTERFACE SIGNALS

APPENDIX E

HRE INTERFACE SIGNALS

The complete list of interface signals is shown in Table E-I. The following set of comments is provided to clarify the use of the various signals.

Aircraft Velocities X, Y, and Z - Velocity components obtained from an inertial platform on the X-15 used in air mass flow computation to determine aircraft true airspeed.

Aircraft Velocity Reference - Reference voltage used to verify the accuracy of the aircraft velocity components x, y, and z.

Spike Total Pressure, High and Low Range - Total pressure measured at the tip of the spike used in air mass flow computation. Range is considered too broad for one sensor.

Inlet Vertical and Horizontal Differential Pressures - Pressure differentials used in the air mass flow computation to determine engine local angle of attack and yaw.

Shock Position Pressure - Pressure in inlet to determine shock position for detection of shock expulsion and buzz.

Combustor Pressures - Each combustor has four pressure sensors arranged around the periphery of the combustor chamber. Four measurements are made to compensate for flow distortions in the combustion chamber. The pressure are used in the combustor limit computation.

Fuel Total Pressure - Pressure measured at a venturi placed in the manifold for fuel flow computation. Manifold one, has two venturis because of installation restrictions.

Fuel Differential Pressure - Pressure measured across a venturi placed in the manifold for fuel flow computation. Manifold one, has two venturis because of installation constraints. The range expected for manifold three is considered too broad for one sensor.

Fuel Total Temperature - Temperature measured at a venturi placed in the manifold for fuel flow computation. Manifold one has two sensors.

Spike Position - Monitoring signal. Used to check functioning of spike control loop.

Spike Actuator Current - Monitoring signal. Used to check functioning of spike control loop.

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Fuel Control Valve Currents - Monitoring signals. Used to check functioning of fuel valve control loops.

Local Environment Temperatures - Optional signals. The LVDT in the spike control loop may require temperature compensation. The pressure sensors used throughout the engine may also need temperature compensation. The local environment of the control electronics will be monitored.

Temperature Controller Channel, Temperature Outputs - Monitoring signals. Output of each channel temperature signal conditioner sampled to check operation of channel temperature sensors.

Temperature Controller Channel, Control and Dump Valve Currents - Monitoring signals. Used to check functioning of temperature control and dump valves.

Reference Power Supplies - Monitoring signals. Reference supply levels directly effect accuracy of sensor measurements.

Main Power Supplies - Monitoring signals. Signals are multiplexed to reduce input lines. Failure of the power supply is detected in the power supply and not in the computer. These voltages will be recorded, via the computer to provide trending information.

Fuel Control Valve Outputs - Command signals from computer to fuel control valves.

Spike Control Output - Command signal proportional to required spike position.

Temperature Controller Channel Offsets - Offsets, setting control levels supplied by the computer to each channel of the temperature controller. Offsets are changed as required for each position of the temperature controller multiplexer.

Temperature Controller Multiplexer Position - Indicates sensor selected as input to the signal conditioner on each channel enabling the computer to select the required temperature offset.

Pilot's Engine On/Off Switch - Pilot may select engine ON or OFF at any time. However, engine start will not be attempted until a purge cycle has been completed and engine is within operating range. Engine run will be terminated by run duration if not previously terminated by pilot switching to OFF.

Low Gas Supplies - Control system will terminate engine run before fuel or actuation gas pressures become too low to safefy complete flight let down.

Fuel Plenum Pressure - Optional monitoring signal. Included to check functioning of fuel pressurizing system, turbopump, etc.

Fire Indication - Fire detection in engine. Routed to computer for orderl shutdown. (Possibly directly to pilot - see engine fire indicator.)

Predrop Signal - Signal to computer before X-15 is dropped from mother ship to enable computer to change mode and verify system.

Ground Test Signal - Indicates to computer that the teletype is connected and available for use. Programs can be exercised under external control.

Reset After Failure - After a system shuts down due to failure, a reset may be desirable in the event that the failure was transitory.

Zero the Spike Integrator - Integrator used in the spike control loop must have any drift errors removed upon release of the spike.

Fire Spike Actuator Nitrogen Squib 1 and 2 - Redundant squibs to release the nitrogen supply for both spike and control valve actuators.

Subsonic and Supersonic Igniters - Ignition signals for the two modes of combustion. Duration of ignitor signals to be determined.

Turn On Solenoids 1 and 2 Purge Shut Off Valve - Sequence signals for controlling the purge and shut off valve solenoids.

Engine On/Off Indicator - Indication from computer to X-15 pilot that engine is running satisfactorily.

Engine Go/No-Go Indicator - Indication from computer to X-15 pilot that engine operating system is go or no go.

Engine Fire Indicator - Indication to X-15 pilot that a fire has been detected inside the engine. Signal may be derived directly from the engine fire detection system or from the computer.

Enable Signals to Computer Peripherals - Control signals from the computer to the computer interface unit for operating the peripheral devices.

System Failure Indicator - System failure can be detected by the failure monitor. If the computer detects a failure a faster shut down can be obtained by activating this line to the power supply.

Data Available to External Device - Control signal from computer interface unit to external device indicating that signals on the external device data bit lines are valid.

Peripheral Busy and Interrupt Lines - Signals from the computer interface unit to the computer for operating the peripheral devices.

Output to Failure Monitor - Fixed pattern generated by the computer and recognized by the failure monitor as a good signal. Nonrecognition or absence of the pattern indicates a failure.

External Device Data Bits 1 to 12 Input - Twelve parallel data bits transmitting data from external device to the computer. The external device will raise its interrupt line when the data is valid.

External Device Data Bits 1 to 12 Output - Twelve parallel data bits transmitting data from the computer to the external device. The computer interface unit raises the data available line to the external device when the data is valid. The external device raises its busy line while it is processing the data.

TABLE E-I

HRE INPUT/OUTPUT SIGNAL LIST AUGUST 26 1968

TYPE	SOURCE	DESTINATION	SIGNAL
ANALOG	X-15	COMPUTER	AIRCRAFT ANGLE OF ATTACK
ANALOG	X-15	COMPUTER	AIRCRAFT VELOCITY X
ANALOG	X-15	COMPUTER	AIRCRAFT VELOCITY Y
ANALOG	X-15	COMPUTER	AIRCRAFT VELOCITY Z
ANALOG	X-15	COMPUTER	AIRCRAFT VELOCITY REFERENCE SIGNAL
ANALOG	ENGINE	COMPUTER	SPIKE TOTAL PRESSURE - LOW RANGE
ANALOG	ENGINE	COMPUTER	SPIKE TOTAL PRESSURE - HIGH RANGE
ANALOG	ENGINE	COMPUTER	INLET VERTICAL DIFFERENTIAL PRESSURE
ANALOG	ENGINE	COMPUTER	INLET HORIZONTAL DIFFERENTIAL PRESSURE
ANALOG	ENGINE	COMPUTER	SHOCK POSITION PRESSURE
ANALOG	ENGINE	COMPUTER	COMBUSTOR 1 PRESSURE PORT 1/UNSTART PRESS.
ANALOG	ENGINE	COMPUTER	COMBUSTOR 1 PRESSURE PORT 2
ANALOG	ENGINE	COMPUTER	COMBUSTOR 1 PRESSURE PORT 3
ANALOG	ENGINE	COMPUTER	COMBUSTOR 1 PRESSURE PORT 4
ANALOG	ENGINE	COMPUTER	COMBUSTOR 2 PRESSURE PORT 1
ANALOG	ENGINE	COMPUTER	COMBUSTOR 2 PRESSURE PORT 2
ANALOG	ENGINE	COMPUTER	COMBUSTOR 2 PRESSURE PORT 3
ANALOG	ENGINE	COMPUTER	COMBUSTOR 2 PRESSURE PORT 4
ANALOG	ENGINE	COMPUTER	COMBUSTOR 3 PRESSURE PORT 1
ANALOG	ENGINE	COMPUTER	COMBUSTOR 3 PRESSURE PORT 2
ANALOG	ENGINE	COMPUTER	COMBUSTOR 3 PRESSURE PORT 3
ANALOG	ENGINE	COMPUTER	COMBUSTOR 3 PRESSURE PORT 4
ANALOG	ENGINE	COMPUTER	FUEL TOTAL PRESSURE MANIFOLD 1A
ANALOG	ENGINE	COMPUTER	FUEL TOTAL PRESSURE MANIFOLD 1B
ANALOG	ENGINE	COMPUTER	FUEL TOTAL PRESSURE MANIFOLD 2
ANALOG	ENGINE	COMPUTER	FUEL TOTAL PRESSURE MANIFOLD 3
ANALOG	ENGINE	COMPUTER	FUEL DIFF. PRESSURE MANIFOLD 1A
ANALOG	ENGINE	COMPUTER	FUEL DIFF. PRESSURE MANIFOLD 1B
ANALOG	ENGINE	COMPUTER	FUEL DIFF. PRESSURE MANIFOLD 2
ANALOG	ENGINE	COMPUTER	FUEL DIFF. PRESSURE MANIFOLD 3 -LOW RANGE
ANALOG	ENGINE	COMPUTER	FUEL DIFF. PRESSURE MANIFOLD 3 -HIGH RANGE
ANALOG	ENGINE	COMPUTER	FUEL TOTAL TEMPERATURE MANIFOLD 1A
ANALOG	ENGINE	COMPUTER	FUEL TOTAL TEMPERATURE MANIFOLD 1B
ANALOG	ENGINE	COMPUTER	FUEL TOTAL TEMPERATURE MANIFOLD 2
ANALOG	ENGINE	COMPUTER	FUEL TOTAL TEMPERATURE MANIFOLD 3
ANALOG	SPIKE	COMPUTER	SPIKE POSITION
ANALOG	SPIKE	COMPUTER	SPIKE ACTUATOR CURRENT
ANALOG	F.C.V.1	COMPUTER	FUEL CONTROL VALVE 1 CURRENT
ANALOG	F.C.V.2	COMPUTER	FUEL CONTROL VALVE 2 CURRENT
ANALOG	F.C.V.3	COMPUTER	FUEL CONTROL VALVE 3 CURRENT
ANALOG	CONTROL SYS.	COMPUTER	LOCAL ENVIRONMENT TEMPERATURE 1 - OPTIONAL
ANALOG	CONTROL SYS.	COMPUTER	LOCAL ENVIRONMENT TEMPERATURE 2 - OPTIONAL
ANALOG	ENGINE	COMPUTER	LOCAL ENVIRONMENT TEMPERATURE 3 - OPTIONAL
ANALOG	ENGINE	COMPUTER	LOCAL ENVIRONMENT TEMPERATURE 4 - OPTIONAL
ANALOG	TEMP. CONTROL	COMPUTER	TEMPERATURE OUTPUT CHANNEL 1
ANALOG	TEMP. CONTROL	COMPUTER	TEMPERATURE OUTPUT CHANNEL 2
ANALOG	TEMP. CONTROL	COMPUTER	TEMPERATURE OUTPUT CHANNEL 3
ANALOG	TEMP. CONTROL	COMPUTER	TEMPERATURE OUTPUT CHANNEL 4
ANALOG	TEMP.CONTROL	COMPUTER	CHANNEL 1 CONTROL VALVE CURRENT
ANALOG	TEMP.CONTROL	COMPUTER	CHANNEL 2 CONTROL VALVE CURRENT
ANALOG	TEMP.CONTROL	COMPUTER	CHANNEL 3 CONTROL VALVE CURRENT
ANALOG	TEMP.CONTROL	COMPUTER	CHANNEL 4 CONTROL VALVE CURRENT
ANALOG	TEMP.CONTROL	COMPUTER	DUMP VALVE CURRENT

TABLE E-I (Continued)

TYPE	SOURCE	DESTINATION	SIGNAL
ANALOG	POWER SUPPLY	COMPUTER	10V REF 1 SUPPLY
ANALOG	POWER SUPPLY	COMPUTER	10V REF 2 SUPPLY
ANALOG	POWER SUPPLY	COMPUTER	5V REF 3 SUPPLY
ANALOG	POWER SUPPLY	COMPUTER	5V REF 4 SUPPLY
ANALOG	POWER SUPPLY	COMPUTER	+25V SUPPLY)
ANALOG	POWER SUPPLY	COMPUTER	+15V SUPPLY)SUB-MULTIPLEXED
ANALOG	POWER SUPPLY	COMPUTER	+5V SUPPLY)
ANALOG	POWER SUPPLY	COMPUTER	-15V SUPPLY)
ANALOG	COMPUTER	FUEL C.V.1	OUTPUT TO FUEL CONTROL VALVE MANIFOLD 1
ANALOG	COMPUTER	FUEL C.V.2	OUTPUT TO FUEL CONTROL VALVE MANIFOLD 2
ANALOG	COMPUTER	FUEL C.V.3	OUTPUT TO FUEL CONTROL VALVE MANIFOLD 3
ANALOG	COMPUTER	SPIKE ACT.	OUTPUT TO SPIKE ACTUATOR
ANALOG	COMPUTER	TEMP.CONTROL	TEMPERATURE OFFSET CHANNEL 1
ANALOG	COMPUTER	TEMP.CONTROL	TEMPERATURE OFFSET CHANNEL 2
ANALOG	COMPUTER	TEMP.CONTROL	TEMPERATURE OFFSET CHANNEL 3
ANALOG	COMPUTER	TEMP.CONTROL	TEMPERATURE OFFSET CHANNEL 4
DISCRETE	TEMP.CONTROL	COMPUTER	TEMP.CONTROL MULTIPLEXER POSITION BIT 1
DISCRETE	TEMP.CONTROL	COMPUTER	TEMP.CONTROL MULTIPLEXER POSITION BIT 2
DISCRETE	TEMP.CONTROL	COMPUTER	TEMP.CONTROL MULTIPLEXER POSITION BIT 3
DISCRETE	TEMP.CONTROL	COMPUTER	TEMP.CONTROL MULTIPLEXER POSITION BIT 4
DISCRETE	X-15	COMPUTER	PILOT'S ENGINE ON/OFF SWITCH
DISCRETE	X-15	COMPUTER	LOW HYDROGEN GAS SUPPLY
DISCRETE	X-15	COMPUTER	LOW HELIUM GAS SUPPLY
DISCRETE	X-15	COMPUTER	LOW NITROGEN GAS SUPPLY
DISCRETE	ENGINE	COMPUTER	FUEL PLENUM PRESSURE - OPTIONAL
DISCRETE	ENGINE	COMPUTER	FIRE INDICATION
DISCRETE	B-52	COMPUTER	PRE-DROP SIGNAL
DISCRETE	EXTERNAL	COMPUTER	GROUND TEST SIGNAL
DISCRETE	X-15	CONTROL SYS.	RESET AFTER FAILURE
DISCRETE	COMPUTER	SPIKE CTRL	ZEROISE SPIKE INTEGRATOR
DISCRETE	COMPUTER	ENGINE	FIRE SPIKE ACTUATOR NITROGEN SQUIB 1
DISCRETE	COMPUTER	ENGINE	FIRE SPIKE ACTUATOR NITROGEN SQUIB 2
DISCRETE	COMPUTER	ENGINE	SUBSONIC IGNITER
DISCRETE	COMPUTER	ENGINE	SUPERSONIC IGNITER
DISCRETE	COMPUTER	ENGINE	TURN ON SOLENOID 1 PURGE/SHUT-OFF VALVE
DISCRETE	COMPUTER	ENGINE	TURN ON SOLENOID 2 PURGE/SHUT-OFF VALVE
DISCRETE	COMPUTER	X-15	ENGINE ON/OFF INDICATOR
DISCRETE	COMPUTER	X-15	ENGINE GO-NO GO INDICATOR
DISCRETE	COMPUTER	X-15	ENGINE FIRE INDICATOR
DISCRETE	COMPUTER	C.I.U.	ENABLE TELETYPE INTERRUPT
DISCRETE	COMPUTER	C.I.U.	ENABLE ADC CONVERSION INTERRUPT
DISCRETE	COMPUTER	C.I.U.	ENABLE EXTERNAL DEVICE INTERRUPT
DISCRETE	COMPUTER	C.I.U.	ENABLE TIMER INTERRUPT
DISCRETE	COMPUTER	C.I.U.	ENABLE TEMPERATURE CONTROLLER INTERRUPT
DISCRETE	COMPUTER	POWER SUPPLY	SYSTEM FAILURE INDICATOR (FAST SHUT-DO...)
DISCRETE	C.I.U.	EXTERNAL	DATA AVAILABLE TO EXTERNAL DEVICE
SERIAL	C.I.U.	COMPUTER	TELETYPE BUSY LINE
SERIAL	C.I.U.	COMPUTER	TELETYPE INTERRUPT LINE
SERIAL	C.I.U.	COMPUTER	ADC CONVERSION BUSY LINE
SERIAL	C.I.U.	COMPUTER	ADC CONVERSION INTERRUPT LINE
SERIAL	C.I.U.	COMPUTER	TIMER BUSY LINE
SERIAL	C.I.U.	COMPUTER	TIMER INTERRUPT LINE
SERIAL	TEMP.CTRL	COMPUTER/CIU	TEMPERATURE CONTROL INTERRUPT LINE
SERIAL	EXTERNAL	COMPUTER/CIU	TELETYPE DATA LINE
SERIAL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE BUSY LINE

TABLE E-I (Continued)

TYPE	SOURCE	DESTINATION	SIGNAL
SERIAL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE INTERRUPT LINE
SPECIAL	COMPUTER	FAILURE MON.	OUTPUT TO FAILURE MONITOR
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 1
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 2
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 3
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 4
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 5
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 6
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 7
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 8
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 9
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 10
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 11
PARALLEL	EXTERNAL	COMPUTER/CIU	EXTERNAL DEVICE DATA BIT 12
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 1
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 2
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 3
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 4
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 5
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 6
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 7
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 8
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 9
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 10
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 11
PARALLEL	COMPUTER/CIU	EXTERNAL	EXTERNAL DEVICE DATA BIT 12

APPENDIX F

ENGINEERING SOFTWARE

APPENDIX F

ENGINEERING SOFTWARE

Three programs have been written for use on the MICRO D computer using the teletypewriter as an input/output device. These input/output programs are (1) MONITOR KEY, a program which permits the memory contents to be inputted or outputted via the teletypewriter keyboard; (2) OVERWRITER, a program that writes STOP commands throughout unused areas of store; and (3) MICRO D ASSEMBLER, a program which assembles programs and produces a loadable paper tape. Each of these programs is detailed in this appendix, with flow charts and coding.

In addition, a function table generator has been written, which uses an IBM 1130 computer to generate the points required for the function tables used throughout the engine control programs.

MONITOR KEY PROGRAM

Object

The object of the MONITOR KEY program is to provide facilities via the teletype keyboard, for outputting memory contents in the form of six character octal words, or paper tape suitable for reentry of the memory contents; for loading memory in the form of six character octal words; and to enable entry and exit to and from programs stored in the computer.

Operation

When controlling the input/output operation, the program types out MONITOR KEY. The operator selects and presses the appropriate key for the required operation. The keys are as follows:

(KEY) 1: Type Out Memory Contents in Six Character Octal Words

The program types out START. The operator types the starting address required in four octal characters (0000 - 7777). The program types out END. The operator types the end address required in four octal characters. After the end address is given, the program types out the contents of the memory, from the start address up to and including the end address, eight words per line plus the address of the first word of the line.

ERRORS: If an error is made in the selection of the key or in the selection of the start or end addresses, depressing key X will return the program to MONITOR KEY. If an invalid key is selected, the program returnes to MONITOR KEY.

INTERRUPT: If the type out is to be discontinued, depressing any key will cause the program to return to MONITOR KEY (NOTE: It may be necessary to depress the key several times to obtain the interrupt).

(KEY) 2: <u>Produce Paper Tape for Reloading</u>

The operator selects the start and end address as per KEY 1. After the end address is selected, the program switches on the tape punch, punches delete, and produces a leader (of carriage returns) before punching out the program. The contents of the memory are reproduced by four teletype characters per word typed out at 16 words per line. When the last character is typed, the punch is switched off, and a delete character punched. (It is necessary to release the paper tape from the punch.) This tape may be loaded into the computer by the paper tape reader on the console or on the teletype by the normal methods. (If the optical reader is used, ensure that the leader is placed under the read head.)

ERRORS AND INTERRUPT: As KEY 1.

(KEY) 3: <u>Load Memory With Six Character Octal Words</u>

The operator selects the start address as per KEY 1. A line of data is typed with the program providing the location of the first data word. The operator types in six octal characters per word up to eight words per line, and the process is then repeated. Each word is stored as it is typed.

ERRORS: If an error is made in the selection of the key or during the selection of the start address depressing key X will return the program to MONITOR KEY. If the start address is incorrect the operation must be terminated. If the contents of the data word are incorrect, depressing key X causes the program to form a new line, starting with the print out of the address of the error word. If key X is depressed for the first character in the word, this indicates to the program that the previous word was in error.

TERMINATE: Depressing key T causes the program to exit to MONITOR KEY. Only words that are complete will have been stored.

RESTRICTED AREAS: Attempts to load data into the monitor key program are inhibited and cause the program to jump to MONITOR KEY.

(KEY) 4: <u>Enter Program at Specified Location</u>

The operator selects the start address as per KEY 1. Depressing key E causes the program to jump to the location specified by the start address.

ERRORS: As for KEY 1. Note: If a key other than E is depressed for execute, the program returns to MONITOR KEY.

INTERRUPT: Providing locations 0377, 0401, 402 and the program area are not destroyed, depressing any key will cause an exit from the current program to MONITOR KEY.

Program Storage

The program uses octal locations 0377, 0401, 402, and 7140 - 7777 inclusive.

Program Load

The program is loaded by placing the tape in the tape reader on the console. Set the start location to 7140. Depress the STANDBY/LOAD button. Depress the LOC button and observe that the L address reads 007140. Depress the TAPE button. The tape will be read in and the L register will count up. When all characters are read, the L address should be 000001. Depress STAND/BY load. Depress LOC button. Depress PROGRAM and the program is entered at MONITOR KEY on the teletypewriter.

Program Reentry

Reenter program at 7142. NOTE: If location 0377 has been used for another program, this must be reset to 000741.

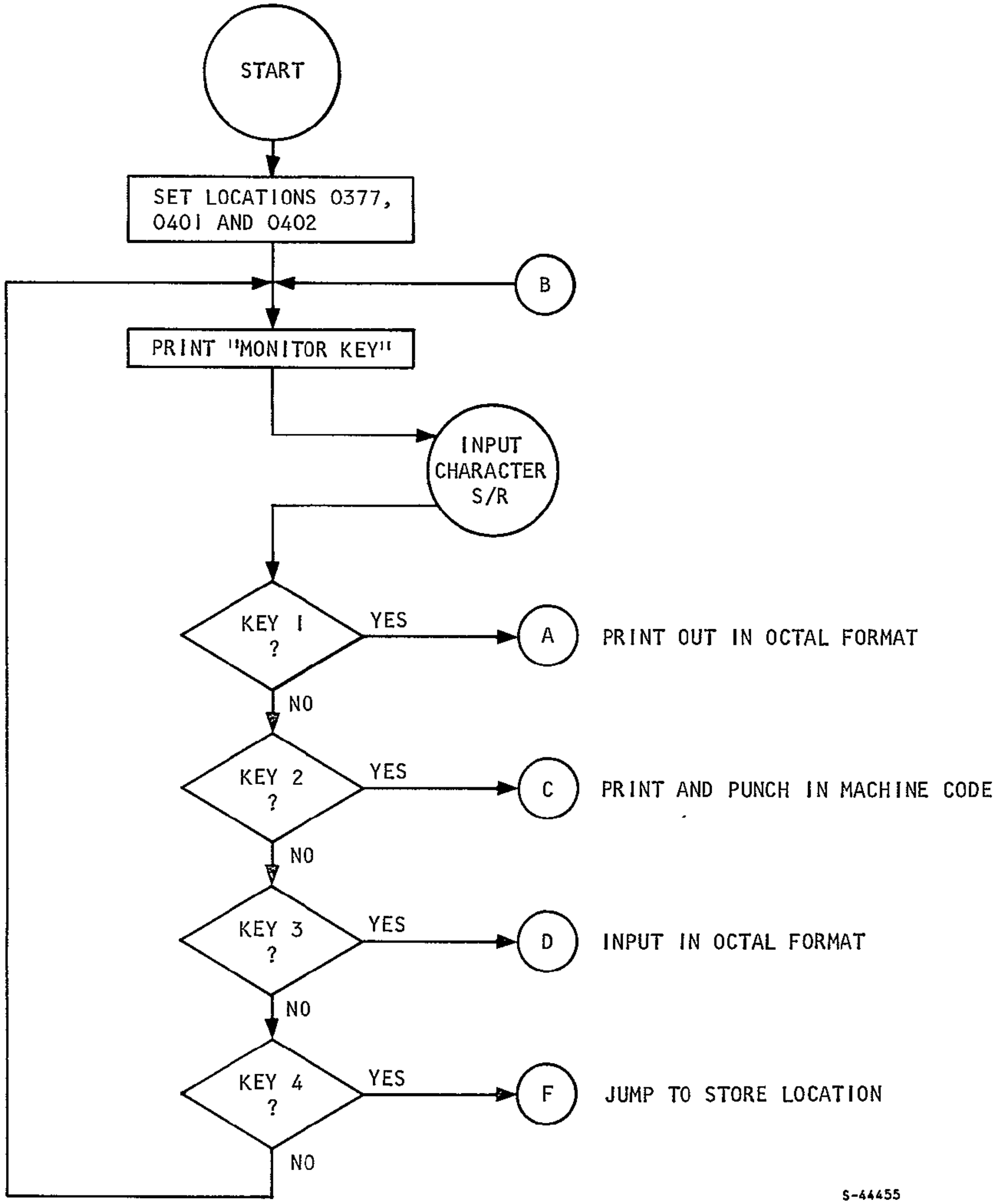

Figure F-1. Monitor Key Program - Key Selection

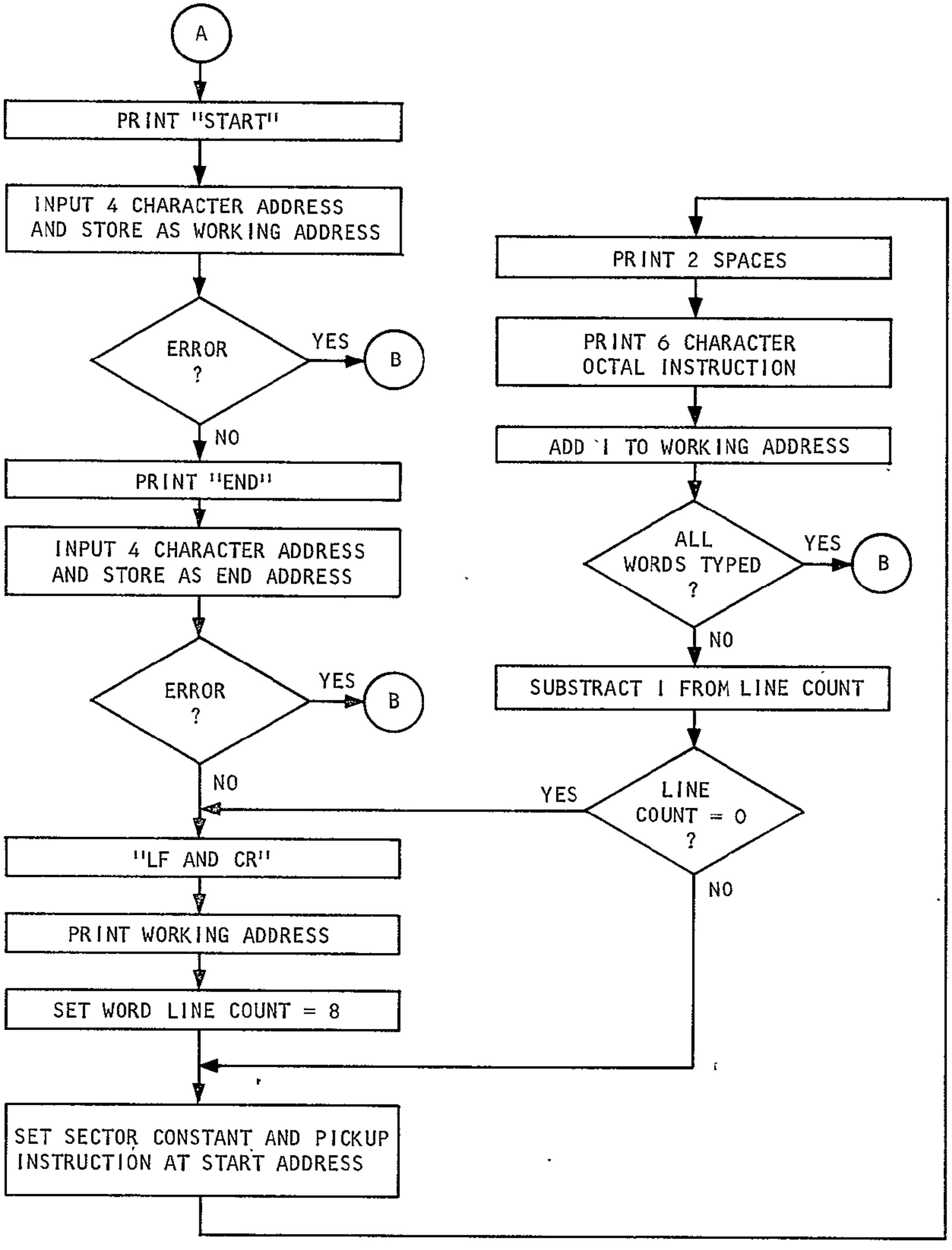

Figure F-2. Monitor Key Program, Key 1- Print Out in Octal Format

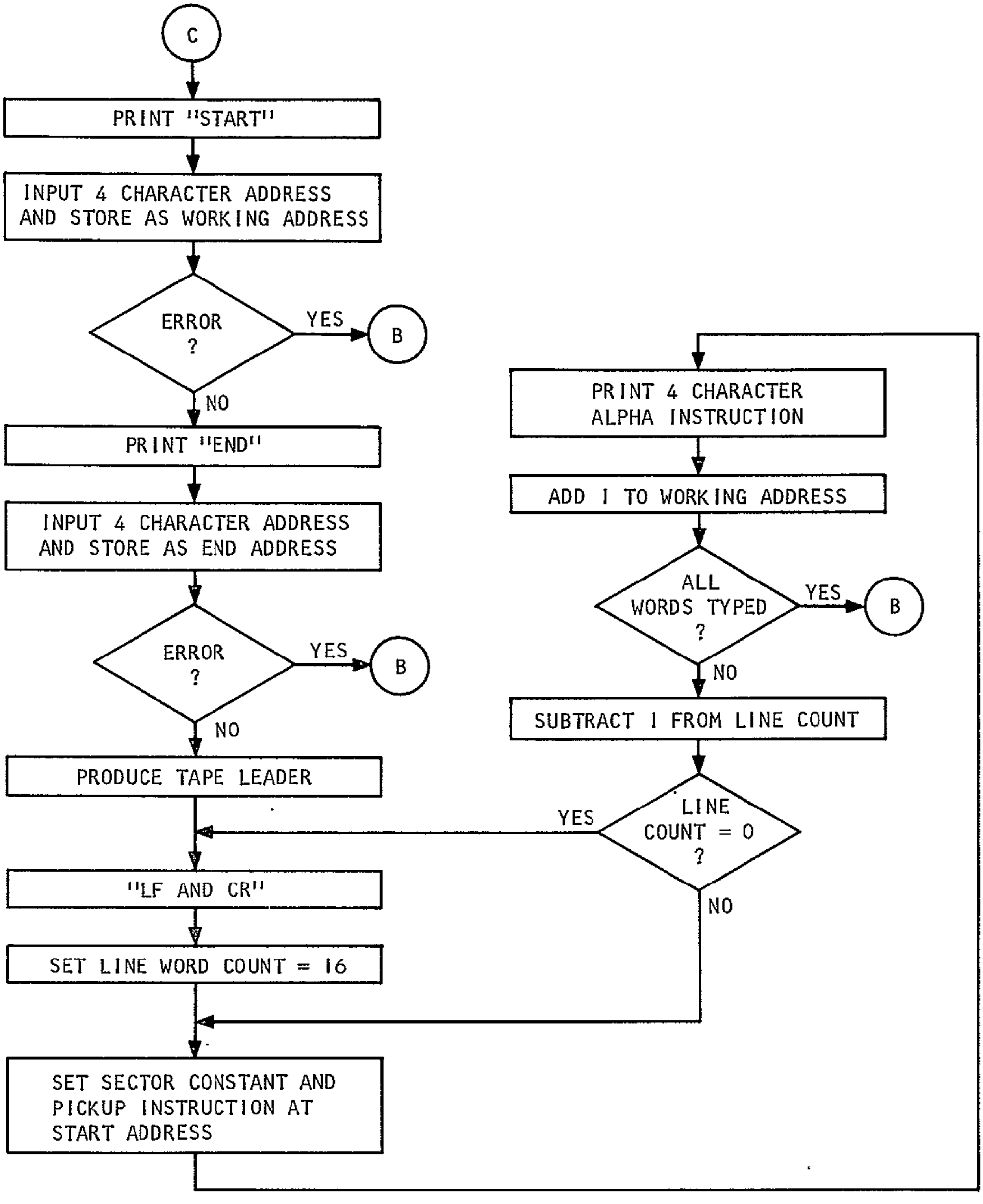

Figure F-3. Monitor Key Program, Key 2- Print and Punch in Machine Code

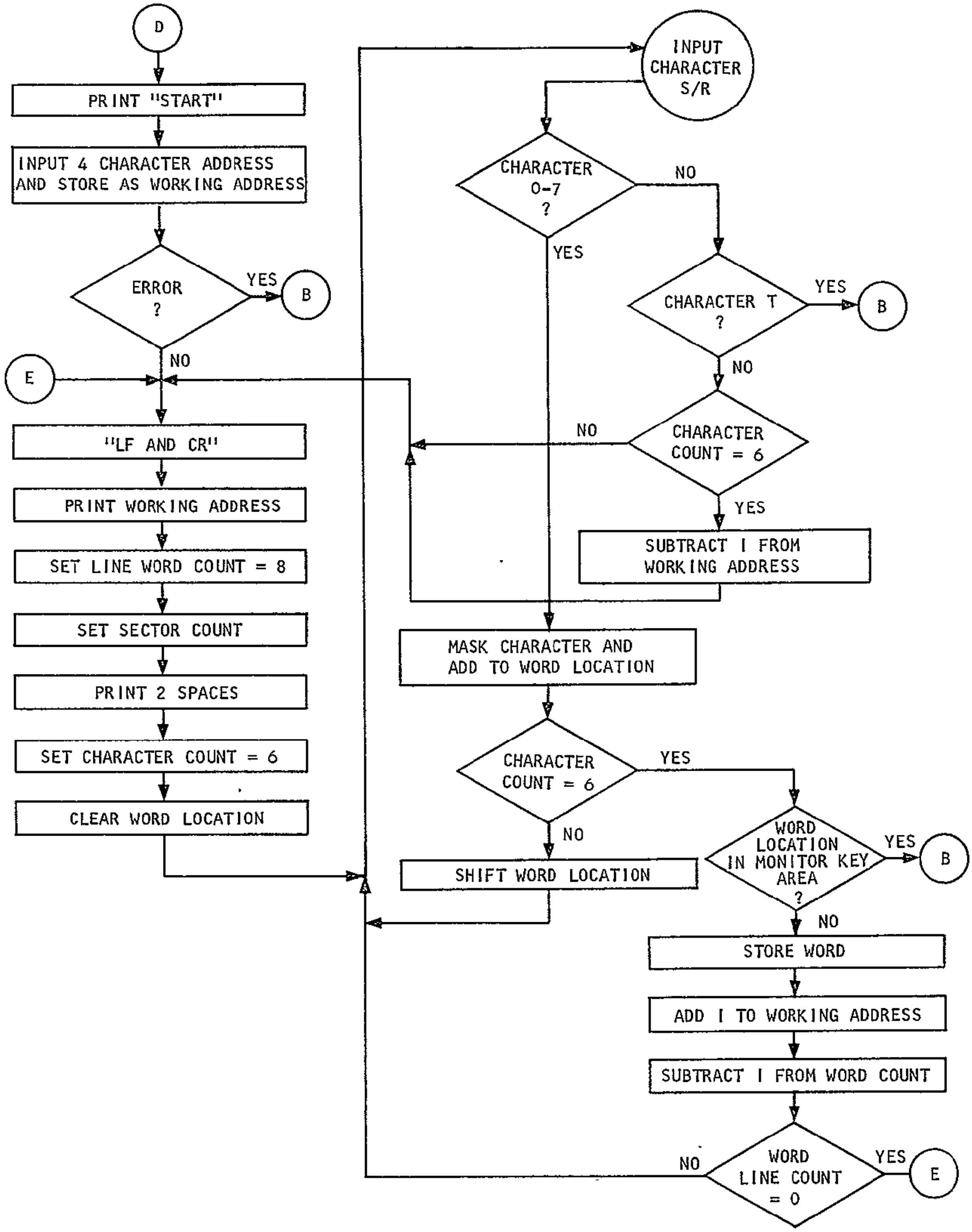

Figure F-4. Monitor Key Program, Key 3- Input in Octal Format

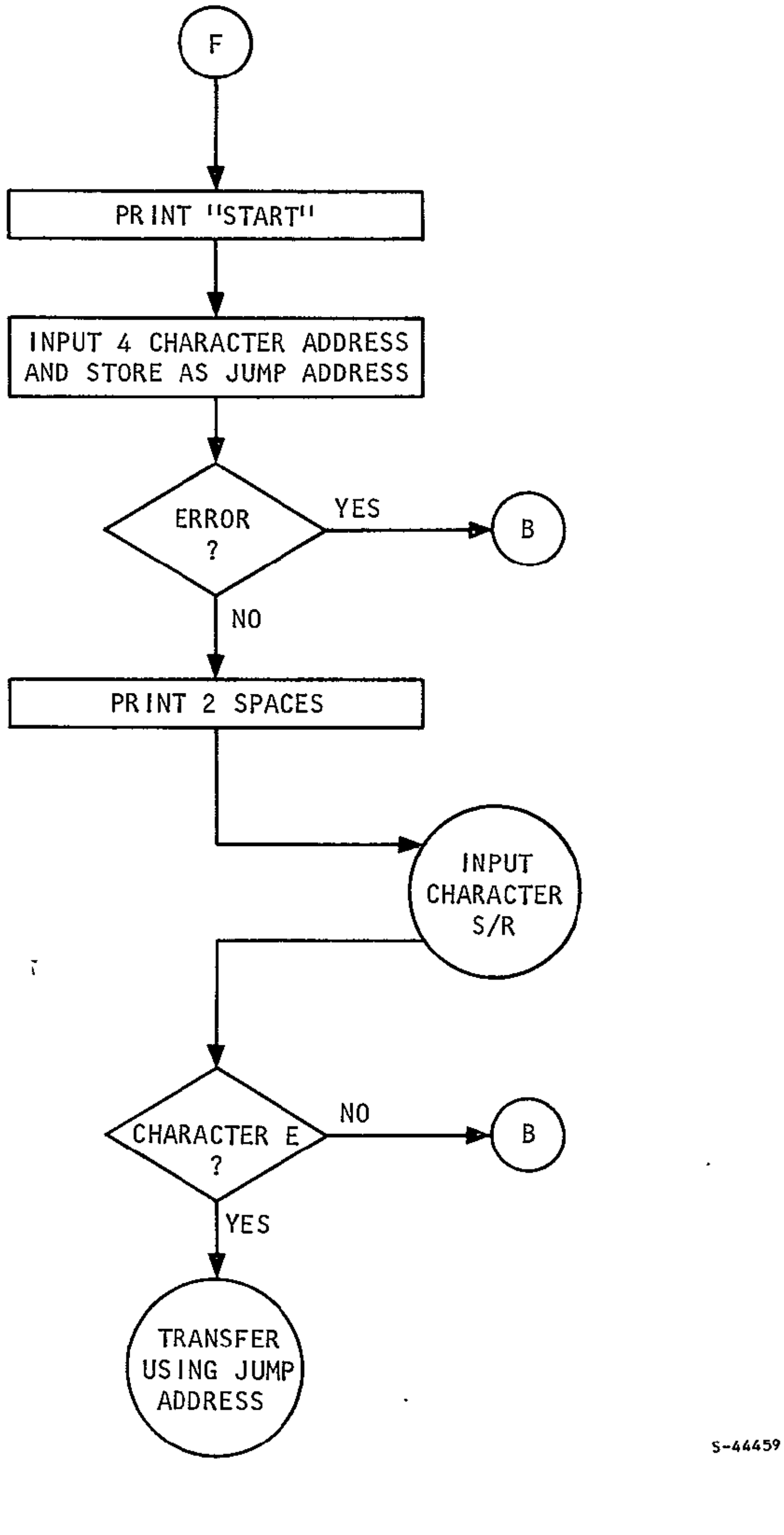

Figure F-5. Monitor Key Program, Key 4- Jump to Store Location

MONITOR KEY 1 START 7100 END 7777 *LOCATION 0000 – 000741*

Overwrite

7100	360247	720130	620121	720121	320135	620121	120137	040103
7110	120131	040125	720121	400003	520132	320135	620154	720133
7120	360154	627100	340377	360247	640103	720134	600376	660136
7130	617777	006501	000740	340376	000400	000001	007142	620377
Monitor Key Rev A.								
7140	700000	600377	340377	720071	360015	620001	340377	720025
7150	360015	620002	340377	640201	000701	000000	000000	000000
7160	220362	720014	620055	720033	620374	660054	720055	120001
7170	620055	040173	640165	760362	220377	720026	620367	360014
7200	760377	720065	620367	720012	620055	720030	620374	660054
7210	660044	660053	520007	120001	040224	120001	040246	120001
7220	040316	120001	040366	640203	660052	660045	640174	660040
7230	720010	620057	660041	660042	660047	720006	620055	660046
7240	660043	720057	120001	620057	040227	640232	660052	660045
7250	640174	020017	240251	720132	360023	640160	660050	720011
7260	620057	660041	660042	520007	440002	660037	720034	620374
7270	660054	720003	620055	720060	400003	620060	520013	660027
7300	660054	720055	120001	620055	040310	720060	400005	640275
7310	660043	720057	120001	620057	040256	640261	660052	660040
7320	720010	620057	660041	660047	720006	620055	660051	640353
7330	720061	120066	240334	640201	720061	320024	620070	720060
7340	660314	000000	000000	720061	320001	620061	720057	120001
7350	620057	040317	640322	720056	120120	040201	720055	120006
7360	040362	640317	720061	120001	620061	640317	660052	660047
7370	660053	120126	040374	640201	640174	660061	000000	000000
7400	000000	000001	000002	000003	000004	000005	000006	000007
7410	000010	000020	000023	000037	000040	000041	000200	000260
7420	000270	000300	000740	400017	620000	660036	660035	720000
7430	720073	720115	720124	720075	720063	007201	007767	007533
7440	007546	007560	007567	007600	007610	007633	007650	007674
7450	007704	007716	007747	007763	007771	000000	000267	000001
7460	746000	007461	010000	000260	000741	020060	0071/0 (4)	360064
7470	627124	340377	660315	000024	000377	000215	000012	000012

Figure F-6. Monitor Key and Overwrite Program Coding

7500	000215	000215	000115	000317	000116	000311	000324	000317
7510	000322	000240	000113	000305	000131	000240	000240	000123
7520	000324	000101	000322	000324	000240	000240	000305	000116
7530	000104	000240	000022	220362	620063	120014	240142	720063
7540	320016	640144	720063	320021	620063	760362	220362	640304
7550	720061	440006	620060	720004	620055	640250	640274	760362
7560	220377	720061	400003	520022	320001	620064	760377	220377
7570	720061	320027	620174	360064	727574	340377	620060	760377
7600	220377	720061	320001	620061	120062	240207	660035	760377
7610	220377	720374	320001	620374	720055	120001	620055	040223
7620	720377	120002	620377	760377	220232	720004	620055	640316
7630	660035	760232	007550	220362	720006	620055	720032	620374
7640	640371	640210	640224	720060	320001	620062	760362	000701
7650	220346	720034	620374	720023	620256	720060	400000	520007
7660	320017	620063	640371	720055	120001	620055	040273	720256
7670	120003	620256	640255	760346	220346	720002	620055	720031
7700	620374	640371	640210	760346	220232	720005	620055	720033
7710	620374	640371	640210	760232	007467	007343	220346	720000
7720	620060	640363	620056	120020	240326	640345	720056	520007
7730	320060	620060	720055	120001	620055	040342	720060	440003
7740	620060	640321	720346	320001	620346	760346	007240	220362
7750	720010	620055	720031	620374	640371	640210	640224	720060
7760	620061	760362	007230	220377	720061	361014	640364	660035
7770	760377	220377	020017	240372	720063	360023	760377	007234

Figure F-6. (Continued)

OVERWRITE PROGRAM

Object

Write halt instructions throughout the store from location 0000 to 7077 octal inclusive, except locations 0376 and 0377 octal. This facility enables a test program to stop immediately if an error in coding causes the test program to jump outside its prescribed operating range.

Operation

Enter the program at location 7100 octal via KEY 4 on MONITOR KEY. Control returns to MONITOR KEY when writing is complete.

Description

The instruction 340376, DOT HALT, is written throughout the store. Location 0376 contains the halt operation 000400, and location 0377 in undisturbed to allow operation of MONITOR KEY.

Program Storage

The program uses locations 7100-7137 inclusive. Location 7154 in the MONITOR KEY area is used as a working location. Location 7647 in the MONITOR KEY area stores the constant for setting the sector register to 16.

Program Load

The program is loaded via the tape reader starting at location 7100. For loading procedures see MONITOR KEY program. A combination tape is available, which contains both the overwrite and monitor key programs. This program is loaded at 7100, but must be entered at the monitor key starting location (7140).

MICRO D ASSEMBLER PROGRAM

Object

To convert programs written in the symbolic assembly language into a machine coded loadable paper tape. The program is divided into two basic routines each having two parts.

The first routine is the Tape Format Routine. This routine enables the operator to produce a paper tape of the programs to be assembled, via the teletype keyboard, which is compatible with the required input for the Assembler Routine. The routine produces new or revised tapes.

The second routine is the Assembler Routine. The program is assembled in two passes. On pass one, a tag table of operand addresses is accumulated in storage. On pass two, the resulting machine coded program is printed on the teletype, and then punched out on the paper tape punch.

Operation - Tape Format Routine

Enter the program at location 5400 octal via KEY 4 on MONITOR KEY, or via KEY F on the assembler routine. The program types out FORMAT. The operator selects and presses the appropriate key for the required operation. The keys are as follows.

(KEY) N: Prepare New Tape

The program produces a leader on the paper tape, and sets the teletype for the first line of the program. The format for each type of instruction is fixed, and is reproduced as per Table F-1. The first instruction must be an ORG mnemonic specifying the octal starting address of the program. Untagged instructions require two spaces in the tag field. Spaces and commas are automatically included by the program. Illegal nmemonics are treated as per an ADD instruction. The program continues placing one instruction per line until an END mnemonic is typed, then the program returns to the FORMAT type-out.

(KEY) R: Revise Previously Punched Tape

NOTE: Prior to pressing the R key, load the tape to be revised in the paper tape reader on the teletypewriter.

The program reads the leader of the old tape, produces a leader on a new tape, and then types out MODE. The operator selects and presses the appropriate key for the required style of revision. The keys are as follows.

(KEY) S: SKIP NN

The program completes the word SKIP and awaits operator input of the two octal characters NN. The program reads this number of instructions off the old tape and reproduces them on the new tape. After reproducing the NN instructions the program returns to MODE.

(KEY) D: DELETE NN

The program completes the word DELETE, and awaits operator input of the two octal characters NN. The program reads this number of instructions off the old tape, but does not reproduce them on the new tape. After NN instructions the program returns to MODE.

(KEY) A: ADD NN

The program completes the word ADD, and awaits operator input of the two octal characters NN. The operator types in the instructions to be added in the format used for a new tape. When NN instructions have been added the program returns to MODE.

TABLE F-I

INSTRUCTION FORMAT

Characters

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
T	T	b	b	A	D	D	b	b	T	T	,	S		
T	T	b	b	A	N	A	b	b	T	T	,	S		
T	T	b	b	A	L	S	b	b	b	b	b	b	N	N
T	T	b	b	A	R	S	b	b	b	b	b	b	N	N
T	T	b	b	B	S	S								
T	T	b	b	C	L	A	b	b	T	T	,	S		
T	T	b	b	D	I	N	b	b	D	D	,	S		
T	T	b	b	D	O	T	b	b	T	T	,	S		
T	T	b	b	E	N	D								
T	T	b	b	M	P	Y	b	b	T	T	,	S		
T	T	b	b	O	C	T	b	b	X	X	X	X	X	X
T	T	b	b	P	Z	E	b	b	b	b	b	b	T	T
T	T	b	b	R	J	P	b	b	T	T	,	S		
T	T	b	b	S	T	A	b	b	T	T	,	S		
T	T	b	b	S	T	M	b	b	T	T	,	S		
T	T	b	b	S	U	B	b	b	T	T	,	S		
T	T	b	b	T	M	I	b	b	T	T	,	S		
T	T	b	b	T	R	A	b	b	T	T	,	S		
T	T	b	b	T	Z	E	b	b	T	T	,	S		
T	T	b	b	W	O	T	b	b	T	T	,	S		

b = space (typed by program)

T T tag field = any character except space-space

S = sector bit 1 or 0

X = any numeric 0 - 7

N N = octal count 00 - 77

D D = numeric oo - 77 with S = 1
any character tag field with S = 0

, = comma (typed by program)

When an END instruction is encountered during an ADD or SKIP mode the program returns to FORMAT. If an END instruction is encountered during a DELETE mode it is ignored.

(KEY) A: Go to Assembler Routine

The program leaves the tape format routine and enters the assembler routine.

(KEY) T: Go to MONITOR KEY

The program leaves the tape format routine and enters the monitor key routine.

OPERATION - ASSEMBLER ROUTINE

Enter the program at location 6000 octal via KEY 4 on MONITOR KEY, or via KEY A on the tape format routine. The program types out ASSEMBLER PASS. The operator selects and presses the appropriate key for the required operation. The keys are as follows.

NOTE: Before each pass the format tape must be loaded in the teletype reader.

(KEY) 1: Assembler Pass 1

The program reads the format tape and accumulates a tag table in storage. When the program reads an END statement it returns to ASSEMBLER PASS.

ERRORS: Type out NO ORG
The first instruction of the program must be an ORG mnemonic. The program returns to ASSEMBLER PASS.

Type out DUP TG
This tag is a duplicate of one used earlier in the program. In assembly the address used is that of the first encountered tag. The program continues with the assembly of pass 1.

NOTE: Reload format tape before pass 2.

(KEY) 2: Assembler Pass 2

The program reads the format tape, and reproduces the machine code alongside each instruction. The program accumulates the machine coded program in storage until one of the following occurs:

1. END instruction. The program punches out the stored machine coded program preceded by a leader. The program returns to ASSEMBLER PASS.

2. 256 instructions assembled. The program punches out the 256 stored machine coded instructions preceded by a leader. The program then continues assembling the program.

3. Further ORG instruction. The program punches out the stored machine coded program up to the next ORG instruction preceded by a leader. The program then continues assembling the program.

ERRORS: Type out NO ORG
The first instruction of the program must be an ORG instruction. The program returns to ASSEMBLER PASS.

MN after machine coded instruction.
Illegal mnemonic: Program substitutes all zeros for instruction and continues.

TG after machine coded instruction.
Tag not defined in program. Program substitutes address zero and continues.

Program Storage

The program is stored in octal locations 5200 - 7077 inclusive, and uses octal locations 0000 - 0071 for working locations, 0740 - on for tag field locations and 4400 - 4777 for the assembled program storage. A maximum of 912 tags are permitted.

The program also uses subroutines contained in the MONITOR KEY program.

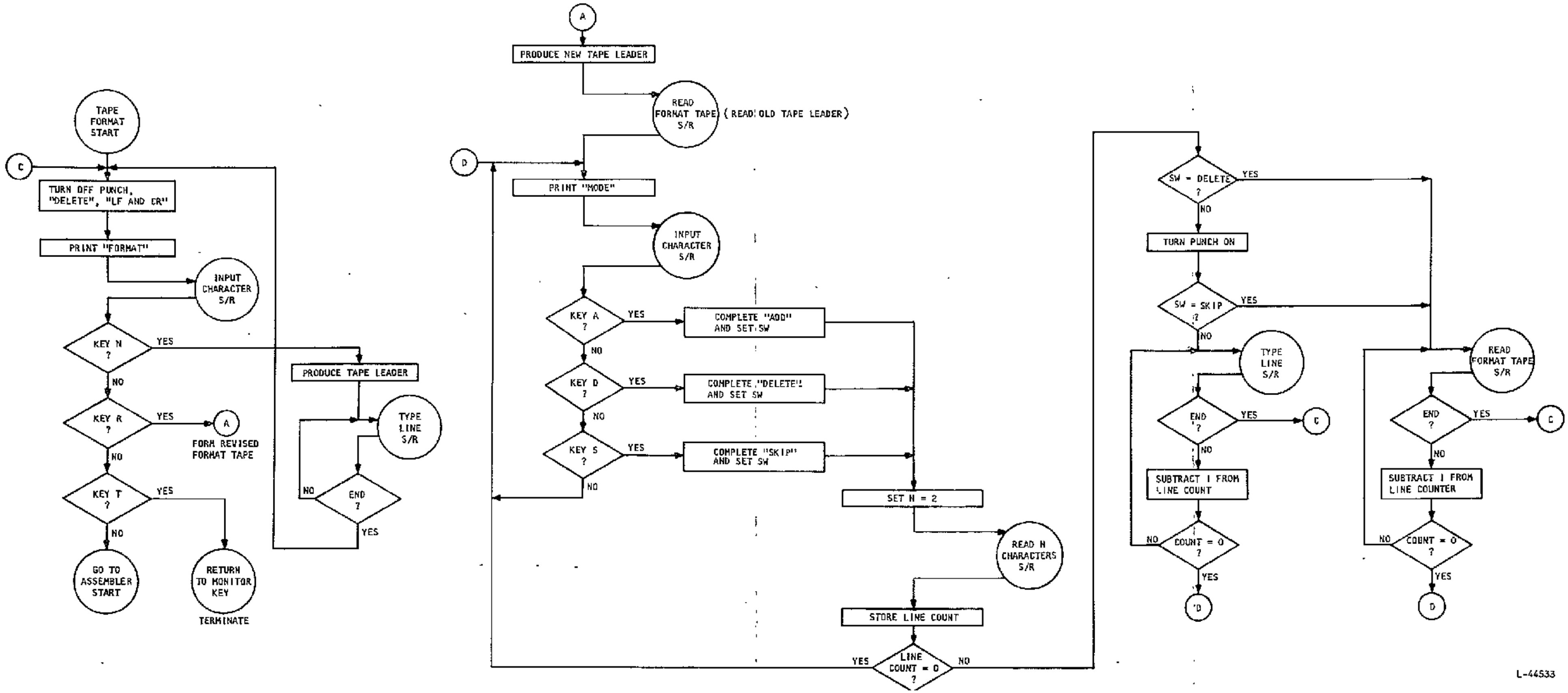

Figure F-7. Tape Format Program

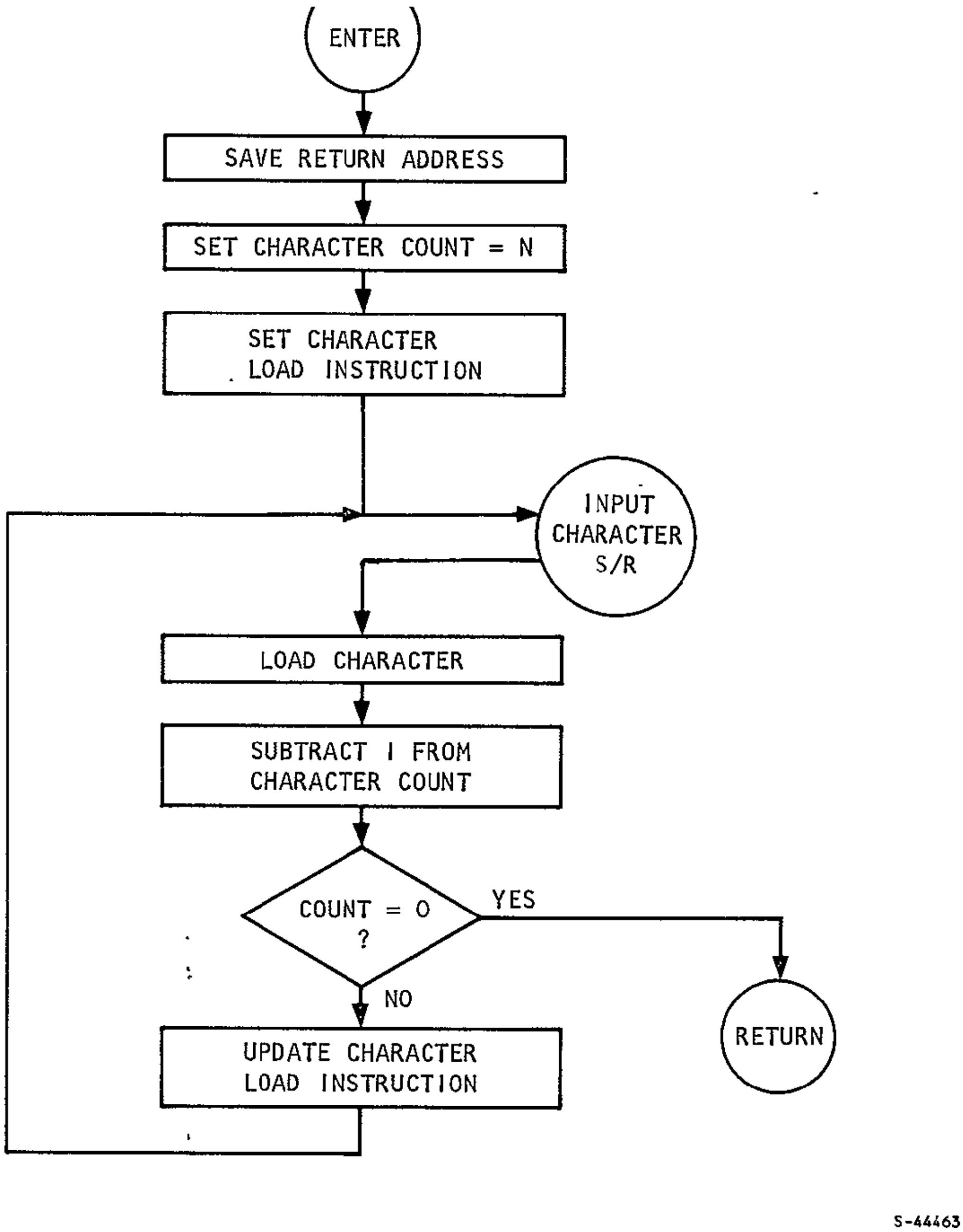

Figure F-8. Tape Format Program - Read N Characters Subroutine

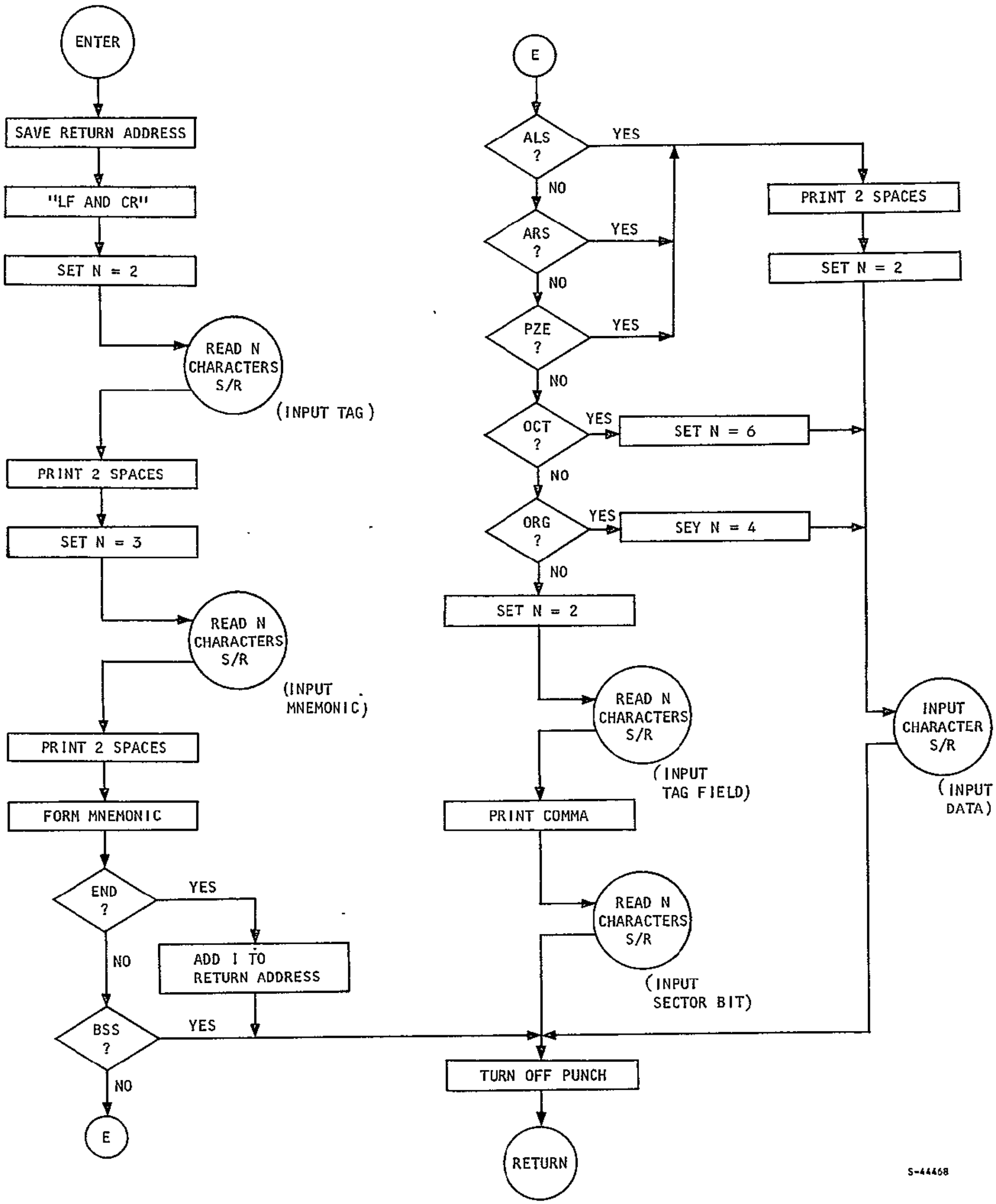

Figure F-9. Tape Format Program - Type Line Subroutine

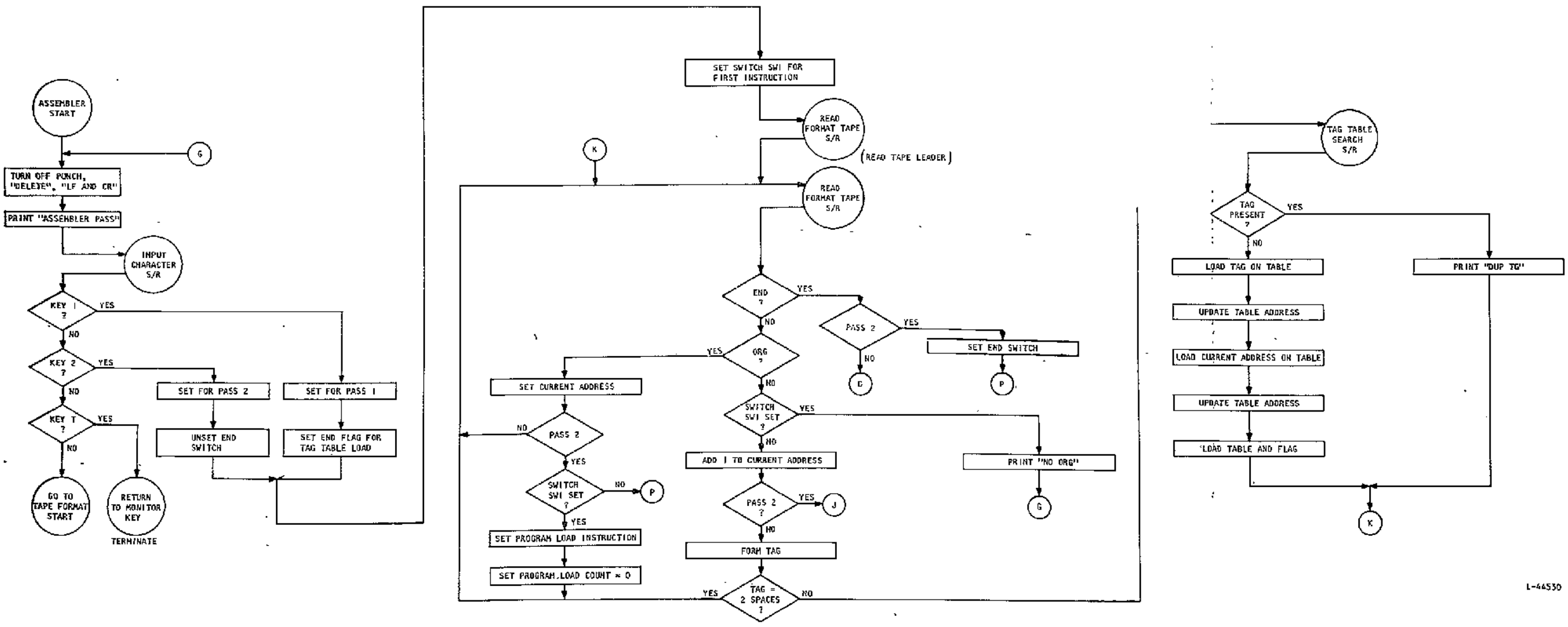

Figure F-10. Assembler Program - Pass I

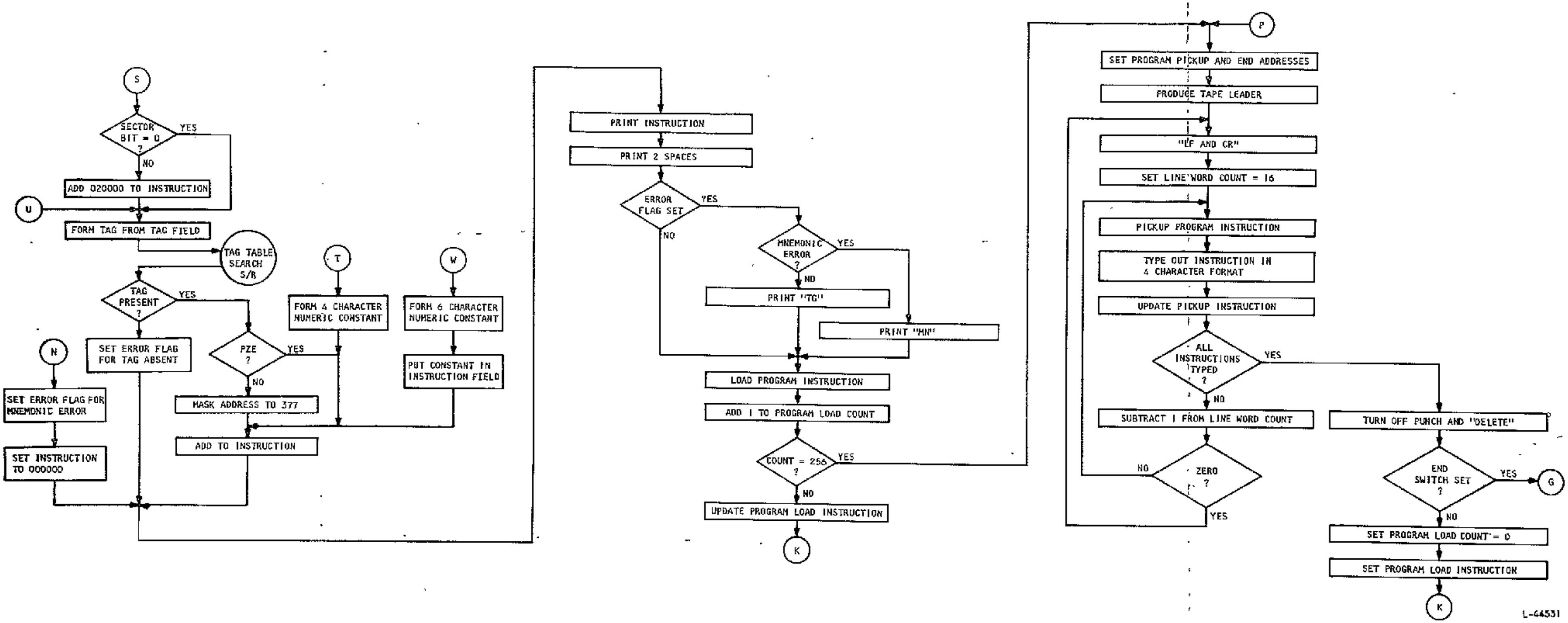

Figure F-11. Assembler Program - Pass 2, Object Coding and Output

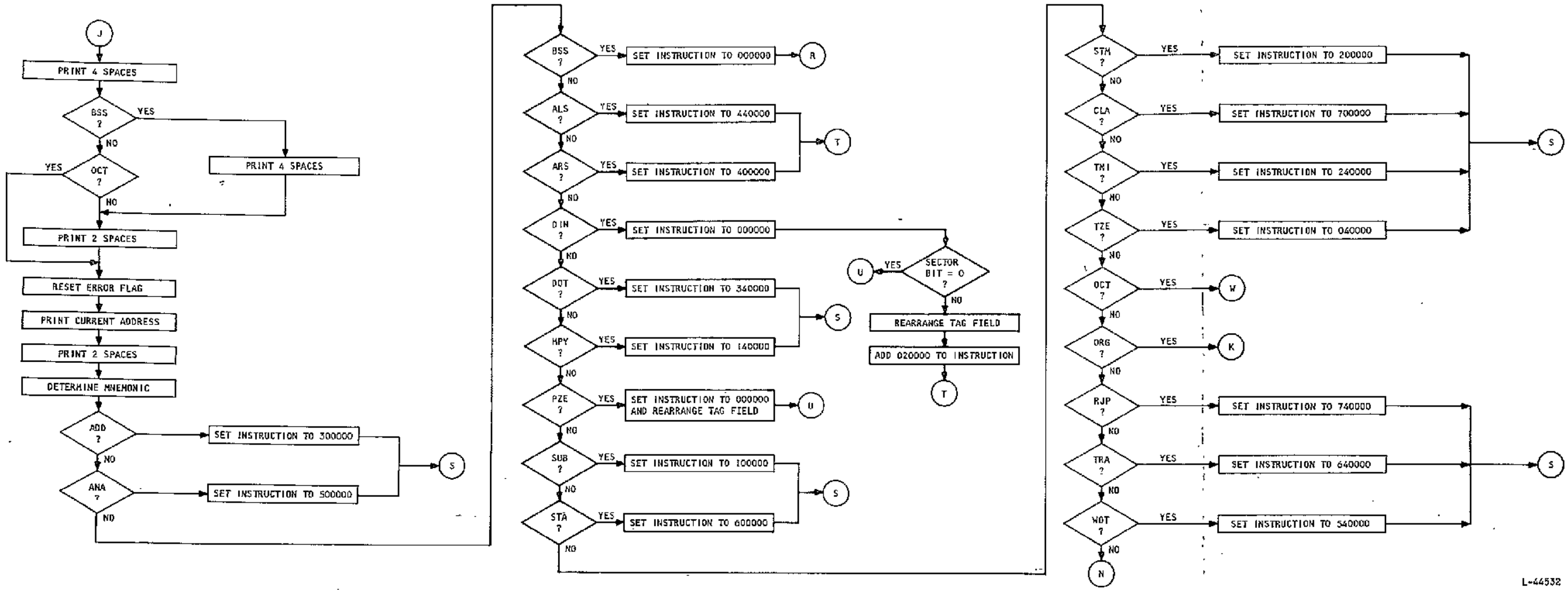

Figure F-12. Assembler Program - Pass 2, Mnemonic Search

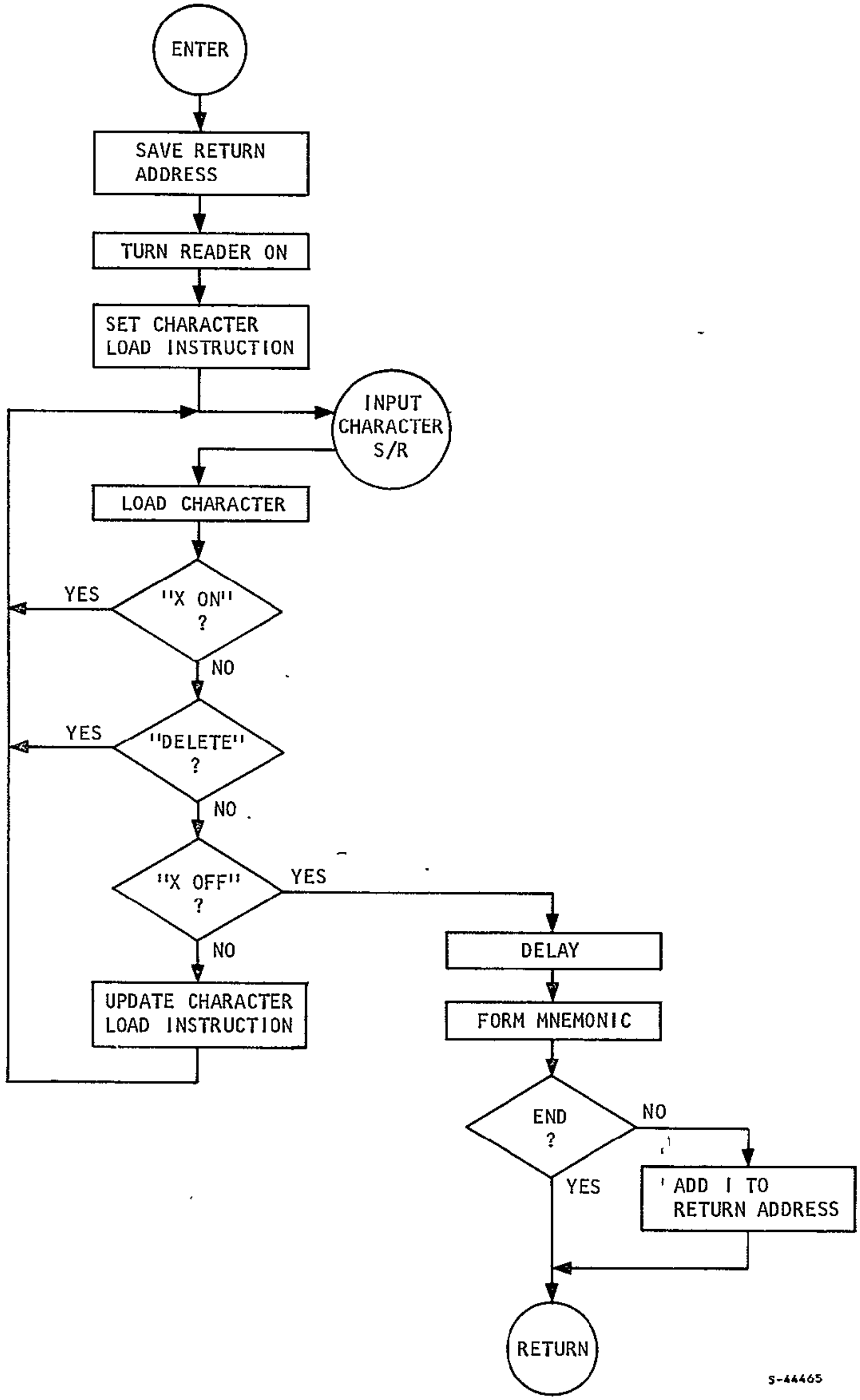

Figure F-13. Assembler Program - Read Format Tape Subroutine

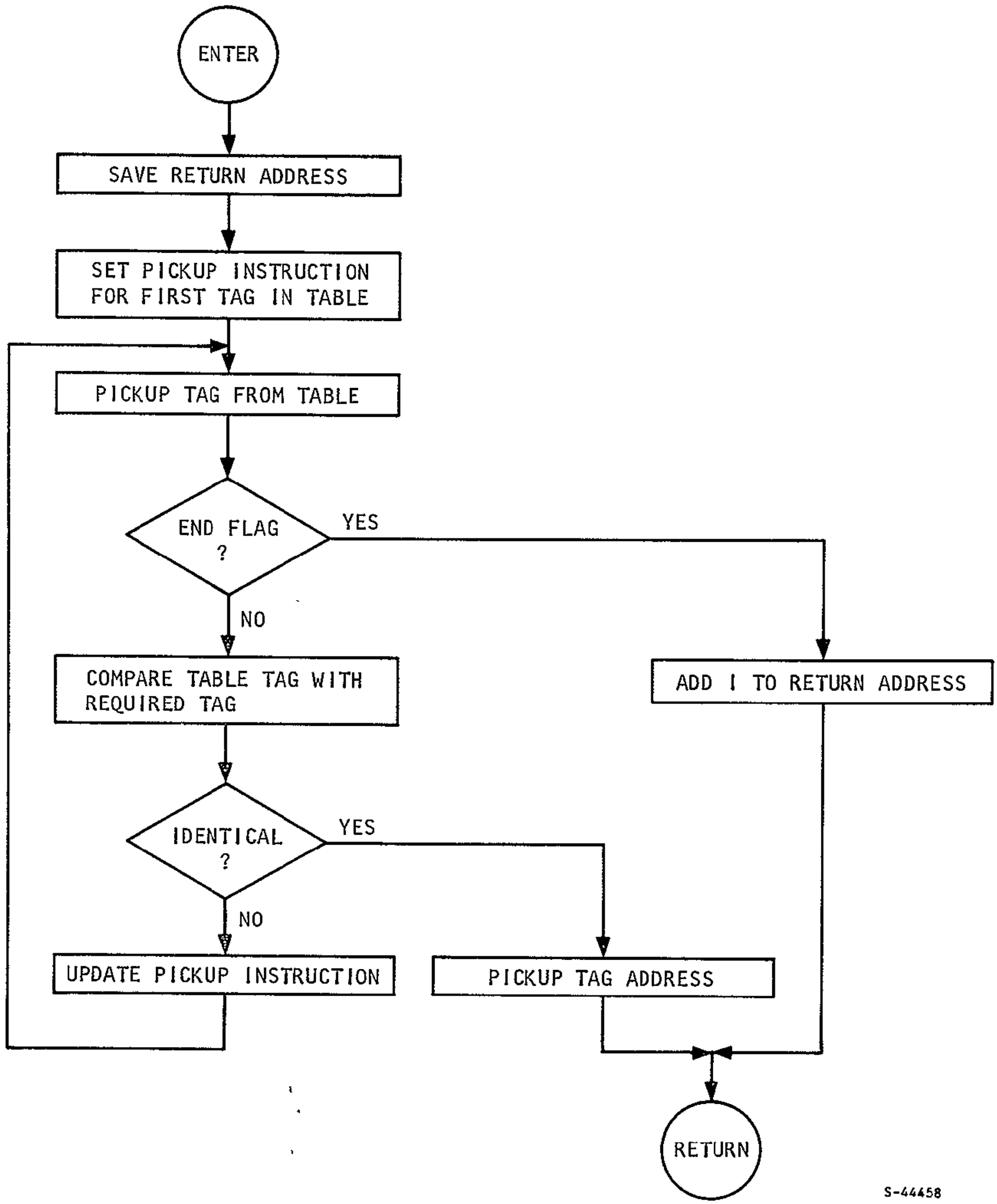

Figure F-14. Assembler Program - Tag Table Search Subroutine

6610	600050	340377	720006	620055	700050	620060	660046	660047
6620	700052	120001	240234	040226	720275	640227	720027	620374
6630	720002	620055	360247	660062	700050	360247	360071	620007
6640	340377	360247	360037	720237	320256	620237	700054	320256
6650	600054	120257	340377	040261	360247	660051	000001	000400
6660	340377	360247	720071	340377	620064	720000	620061	200054
6670	640271	620062	360247	660040	660050	720011	620057	660042
6700	520007	440002	660037	720034	620374	660054	720003	620055
6710	720060	400003	620060	520013	660037	660054	720055	120001
6720	620055	040325	720060	400005	640312	720061	320001	620061
6730	120062	040337	720057	120001	620057	040274	640277	360247
6740	660066	700053	360247	060057	660047	006045	000000	700044
6750	640207	340377	720000	600050	700021	520007	040164	640375
6760	300050	600050	340377	720004	620055	360247	660042	700045
6770	640207	600050	340377	720006	640364	360247	660065	007031
7000	224201	000000	000000	000000	000000	000000	000000	200062
7010	340377	600047	720061	320024	360247	620021	340377	360064
7020	700047	620744	340377	740062	200037	340377	360247	360037
7030	660053	340377	640034	640026	660044	740037	000541	000641
7040	005260	005301	005313	005346	005664	005757	005200	006003
7050	006611	006045	006762	006563	006554	006751	006771	005213
7060	006760	007007	007024	334207	006660	005244	005233	000501
7070	120556	000441	107263	005234	000021	005676	000154	000356

Figure F-15. Assembler Program Coding

MONITOR KEY 1 START 5200 END 7077

5200	200032	340377	020017	240202	720217	360023	020017	240206
5210	720074	360023	740032	340377	720000	600054	720024	360247
5220	360037	620237	660345	200066	340377	720002	620055	720030
5230	620374	660054	660044	740066	200070	120074	060075	120077
5240	060075	320076	340377	740070	340377	700016	600020	700017
5250	600021	720000	600016	600017	720016	440006	360247	660060
5260	200035	340377	020017	240262	720132	360023	720011	620055
5270	720033	620374	660054	720055	120001	620055	040300	640272
5300	740035	200036	340377	720007	620055	720030	620374	660054
5310	660044	740036	700016	200061	340377	720000	600045	360247
5320	360067	720312	620324	340377	700023	520007	300045	600045
5330	720055	120001	620055	040345	700045	440003	600045	720001
5340	360247	360067	320324	620324	640323	740061	200060	340377
5350	720022	620061	660041	660042	720060	120166	040366	720060
5360	100043	040372	720061	320002	620061	640352	700060	320001
5370	600060	640376	720061	320001	620061	660042	740060	000000
5400	720065	620367	360247	660041	720007	620055	720031	620374
5410	360247	660062	660053	120104	040024	120016	120004	040243
5420	120002	060035	360247	660047	360247	660040	360247	660046
5430	640151	640030	640002	600011	640264	640375	720057	120001
5440	620057	040043	640034	360247	660041	720005	620055	720032
5450	620374	360247	660062	660053	600027	120121	040066	700027
5460	120130	040076	700027	120117	040106	640043	720003	620062
5470	620055	720243	620374	360247	660062	640115	720006	620062
5500	620055	720034	620374	360247	660062	640115	720004	620062
5510	620055	720030	620374	360247	660062	720002	640333	700011
5520	520007	440003	600002	700012	520007	300002	640255	720062
5530	120006	040034	020017	240132	720132	360023	720062	120004
5540	040034	640151	640144	640002	720057	120001	620057	040043
5550	640141	200030	660050	720002	640333	660047	720003	640333
5560	660047	360247	640045	360037	700040	120016	040221	640260

Figure F-15. (Continued)

5570	120077	040226	120014	040226	120015	040226	120017	040233
5600	120020	040236	340377	720002	640333	360247	360037	020017
5610	240207	720021	360023	340377	660053	340377	360247	660046
5620	740030	340377	700030	320001	600030	640216	340377	660047
5630	720002	640333	640216	340377	720006	640231	340377	720004
5640	640231	340377	640002	360247	660040	640246	360247	660046
5650	360247	660066	640264	640043	640043	620057	040043	640127
5660	700040	120013	040215	640170	200033	340377	020017	240266
5670	720143	360023	360247	360036	720331	620300	340377	660053
5700	600016	360247	660073	040312	720001	360247	360036	320300
5710	620300	640276	720074	620056	720056	120001	620056	040321
5720	640314	360247	660045	360036	700040	120332	340377	040374
5730	640371	600000	312004	200034	620055	360247	360036	720033
5740	620343	340377	660053	600012	720055	120001	620055	040356
5750	720001	360247	360036	320343	620343	640341	740034	200031
5760	700011	440011	600040	700012	440005	300040	300013	600040
5770	740031	720001	300033	600033	740033	360247	660046	640002
6000	720065	620367	360247	660041	720011	620055	720307	620374
6010	360247	660062	660053	120017	120001	040024	120001	040036
6020	120015	120001	060035	640033	720001	600041	720166	360015
6030	620340	340377	640041	360247	360037	660022	720000	600041
6040	600053	720001	600042	360247	660044	340377	360247	660044
6050	640067	360247	700040	120063	340377	040345	700042	040076
6060	720007	620055	720153	620374	360247	660062	640002	700041
6070	040373	640002	340377	660047	660047	640254	700046	320001
6100	600046	700041	040243	700005	440011	300006	600043	120205
6110	120012	120006	040046	700043	360247	660043	640140	700043
6120	360247	660061	720061	320001	620061	700046	360247	660061
6130	720061	320001	620061	660041	720166	360247	660061	640046
6140	720007	620055	720253	320001	620374	360247	660062	640046
6150	720000	600052	720004	620055	700046	440006	620060	660046
6160	660047	700040	360247	360037	120071	040331	120072	040261
6170	120054	040256	120077	040313	120100	040311	120102	040323

Figure F-15. (Continued)

6200	120103	040263	120104	040265	120101	040320	120105	040267
6210	120106	040271	120107	040273	120110	040275	120111	040277
6220	120112	040301	120113	040326	120114	040045	120131	040303
6230	120132	040305	120133	040307	340377	720001	600052	720000
6240	600050	360247	660050	660047	660047	700040	360247	120072
6250	040072	120000	340377	040150	660047	640150	340377	640237
6260	000000	720135	640332	720140	640332	720141	640332	720142
6270	640332	720143	640332	720144	640332	720145	640332	720146
6300	640332	720147	640332	720150	640332	720151	640332	720152
6310	640332	720137	640314	720136	600050	340377	360247	660052
6320	340377	360247	660054	340377	360247	660055	340377	360247
6330	660056	720134	600050	340377	700021	520007	040343	720016
6340	440006	300050	600050	360247	660053	720004	620055	360247
6350	660042	700045	120001	600046	700041	040361	720000	600042
6360	640046	700042	040375	720024	360247	360037	620237	340377
6370	720000	600054	640356	720001	600053	360247	660064	000000
6400	000115	000116	000324	000107	000240	000116	000317	000240
6410	000317	000322	000107	107263	000300	007562	312004	205457
6420	000523	000254	005641	400017	000240	000104	000125	000120
6430	000240	000324	000107	000240	000101	000123	000123	000305
6440	000115	000102	000314	000305	000322	000240	000120	000101
6450	000123	000123	000240	007771	001262	000240	000053	000240
6460	000104	000104	000240	000305	000314	000305	000324	000305
6470	000240	105304	000475	000113	000311	000120	000240	006440
6500	000300	003654	002333	000506	000645	002335	007737	000014
6510	157364	011250	000634	001457	000523	000306	000317	000322
6520	000115	000101	000324	000240	000115	000317	000104	000305
6530	000240	002411	002361	003063	300000	500000	440000	400000
6540	340000	140000	100000	600000	200000	700000	240000	040000
6550	740000	640000	540000	126005	340377	720000	600050	700020
6560	600016	700021	600017	340377	700016	440011	300017	600043
6570	360247	660043	640176	720002	600052	640212	600044	700040
6600	360247	[illegible]	120153	[illegible]	040247	700044	520071	300050

Figure F-15. (Continued)

FUNCTION TABLE GENERATOR

The 128 point function tables are generated using two programs written in FORTRAN for use on an IBM 1130 computer. The first program determines the coefficients of a polynomial to fit the required function, and the second program uses these coefficients to generate the appropriate points for the stored function.

Curve Fitting Program

This program uses the method of least squares to determine the coefficients of a polynomial to fit the required function. The polynomial has the form:

$$y = A_0 + A_1X + A_2X^2 + A_3X^3 + \ldots\ldots + A_{10}X^{10}$$

where A_0 to A_{10} are the determined coefficients. The polynomial is limited to the tenth order.

The FORTRAN listing for the program is shown in Figure F-16. The program requires the following data cards as input to the program.

Card	Content	Format	
1	Title	19A4	(76 characters)
2	M, N	2I10	

where M is degree of polynomial required

N is the number of X, Y points as input

3-n	X values	8F10	(8 per card)
(n+1)-m	Y values	8F10	(8 per card)

These cards follow after the XEQ card of the source program.

The program printout is shown in Figure F-17 for a sample using 11 data points, with a fifth order polynomial. The printout contains the title, the coefficients A_0 to A_5, the original values of X and Y, the value of Y at that X calculated from the polynomial (Y_C), the absolute error of the Y value (DY), and the percentage error of the Y value (P/E).

Table Generating Program

This program uses the polynomial developed in the first program to generate 129 values of Y for fixed increments of X. The increment of X is chosen so that it may be represented by 2^n (where n is an integer) in the

```
// JOB T
// FOR
*NAMELSQ
*EXTENDED PRECISION
*IOCS(CARD,1132PRINTER)
*LISTALL
      DIMENSION C(11),TITLE(19)
      DIMENSION SUM(21),V(11),A(11),X( 600),Y( 600),B(11,12)
   80 READ(2,65) TITLE
      READ(2,66) M,N
      READ(2,67) (X(I),I=1,N)
      READ(2,67) (Y(I),I=1,N)
   65 FORMAT(19A4)
   66 FORMAT (2I10)
   67 FORMAT (8E10.4)
      LS=2*M+1
      LB=M+2
      LV=M+1
      DO 5 J=2,LS
5     SUM(J)=0.0
      SUM(1)=N
      DO 6 J=1,LV
6     V(J)=0.0
      DO 16 I=1,N
      P=1.0
      V(1)=V(1)+Y(I)
      DO 13 J=2,LV
      P=X(I)*P
      SUM(J)=SUM(J)+P
13    V(J)=V(J)+Y(I)*P
      DO 16 J=LB,LS
      P=X(I)*P
16    SUM(J)=SUM(J)+P
   17 DO 20 I=1,LV
      DO 20 K=1,LV
      J=K+I
20    B(K,I)=SUM(J-1)
      DO 22 K=1,LV
22    B(K,LB)=V(K)
   23 DO 31 L=1,LV
      DIVB=B(L,L)
      DO 26 J=L,LB
26    B(L,J)=B(L,J)/DIVB
      I1=L+1
      IF (I1-LB)28,33,33
   28 DO 31 I=I1,LV
      FMULT =B(I,L)
      DO 31 J=L,LB
31    B(I,J)=B(I,J)-B(L,J)*FMULT
33    A(LV)=B(LV,LB)
      C(LV)=A(LV)
      I=LV
35    SIGMA=0.0
      DO 37 J=I,LV
37    SIGMA=SIGMA+B(I-1,J)*A(J)
      I=I-1
      A(I)=B(I,LB)-SIGMA
      C(I)=A(I)
   40 IF (I-1)43,43,35
   43 WRITE(3,68)TITLE
```

Figure F-16. Curve Fitting Program Listing

```
      WRITE(3,69)(C(I),I=1,LV)
      WRITE(3,71)
      DO 60 J=1,N
      YC=C(1)
      DO 50 I=2,LV
   50 YC=YC+C(I)*X(J)**(I-1)
      DY=Y(J)-YC
      PDE=DY/Y(J)*100.
      WRITE(3,70)J,X(J),Y(J),YC,DY,PDE
   60 CONTINUE
   68 FORMAT(1H1,19A4/17HOCOEFFICIENTS ARE/)
   69 FORMAT(6E20.8)
   70 FORMAT(I4,3X,5E16.8)
   71 FORMAT(79H POINT        X                   Y                   YC
     1      DY                   P/E)
      GO TO 80
      END

VARIABLE ALLOCATIONS
 C     =001E  TITLE=0057  SUM   =0096  V     =00B7  A     =00D8  X     =07E0  Y     =0EE8  B     =1074  P     =1077  DIVB =107A
 FMULT=107D  SIGMA=1080  YC    =1083  DY    =1086  PDE   =1089  M     =108F  N     =1092  I     =1095  LS    =1098  LB    =109B
 LV    =109E  J     =10A1  K     =10A4  L     =10A7  I1    =10AA

UNREFERENCED STATEMENTS
 17       23       40

STATEMENT ALLOCATIONS
 65    =10BC  66    =10BF  67    =10C2  68    =10C5  69    =10D6  70    =10D9  71    =10DE  80    =111B  5     =116D  6     =1189
 13    =11CD  16    =11F0  17    =120B  20    =1219  22    =123F  23    =1259  26    =126C  28    =128D  31    =12A0  33    =12D0
 35    =12EC  37    =12F4  40    =1334  43    =133A  50    =136A  60    =13B5

FEATURES SUPPORTED
 EXTENDED PRECISION
 IOCS

CALLED SUBPROGRAMS
 EADD      EADDX     ESUB      EMPY      EMPYX     EDIV      EDIVX     ELD       ELDX      ESTO      ESTOX     ESBRX     EAXI      FLOAT     SRED
 SWRT      SCOMP     SFIO      SIOAF     SIOFX     SIOF      SIOI      SUBSC     CARDZ     PRNTZ

REAL CONSTANTS
   .000000000E 00=10B0     .100000000E 01=10B3     .100000000E 03=10B6

INTEGER CONSTANTS
     2=10B9       1=10BA       3=10BB

CORE REQUIREMENTS FOR LSQ
 COMMON       0  VARIABLES    4272  PROGRAM     784

END OF COMPILATION
```

Figure F-16. (Continued)

AIRESEARCH MANUFACTURING COMPANY
Los Angeles, California

```
LSQ COEFFICIENTS FOR MACH NO AS A FUNCTION OF PT/PC

COEFFICIENTS ARE

   -0.42045475E 01      0.25125909E 01      -0.38006217E 00      0.31197833E-01      -0.12520838E-02      0.20278485E-04
```

POINT	X	Y	YC	DY	P/E
1	0.77000000E 01	0.30000000E 01	0.29987967E 01	0.12032128E-02	0.40107096E-01
2	0.95800000E 01	0.35000000E 01	0.35051441E 01	-0.51441285E-02	-0.14697510E 00
3	0.11300000E 02	0.40000000E 01	0.39941348E 01	0.58651454E-02	0.14662863E 00
4	0.12880000E 02	0.45000000E 01	0.44980413E 01	0.19586607E-02	0.43525795E-01
5	0.14300000E 02	0.50000000E 01	0.50041218E 01	-0.41217953E-02	-0.82435905E-01
6	0.15560000E 02	0.55000000E 01	0.55047022E 01	-0.47022849E-02	-0.85496089E-01
7	0.16660000E 02	0.60000000E 01	0.59972569E 01	0.27430951E-02	0.45718252E-01
8	0.17630000E 02	0.65000000E 01	0.64952580E 01	0.47419369E-02	0.72952875E-01
9	0.18470000E 02	0.70000000E 01	0.69962252E 01	0.37747621E-02	0.53925173E-01
10	0.19210000E 02	0.75000000E 01	0.75113434E 01	-0.11343479E-01	-0.15124638E 00
11	0.19810000E 02	0.80000000E 01	0.79949765E 01	0.50234198E-02	0.62792748E-01

Figure F-17. Curve Fitting Program Printout computer. This allows interpolation by multiplication and shifting rather than by multiplication and division when in use in the computer programs.

The FORTRAN listing for the program is shown in Figure F-18. The program requires the following data cards as input to the program.

Card	Content	Format
1	Title	20A4 (80 characters)
2	Number of coefficients (n+1)	I10
3	Coefficients A_0 - A_n	5E15.8

3A, 3B as required to up to 11 coefficients

Card	Content	Format
4	X origin, X scale, X offset and Y scale, Y offset	5E15.8
5	Integer increment	F10.0

The cards follow after the XEQ card of the source program.

The program printout is shown in Figure F-19, using the example determined in the first program.

The scaling and offsets must be chosen to provide suitable numbers when in the computer table. For the example shown, X represents P_t/P_c and Y represents M_o. X ranges from 7.5 to 20.0 as Y ranges from 2.9 to 8.2. If we wish X to be represented in the computer by 14 bits of data per word, this will give us the integer range 0 to $(2^{14}-1)$ or 0 to 16383. Scaling X by 1000 and offsetting it by 7.5 (prior to scaling) will give a range of 7.5 to 23.5 to fit within the 14 bits. Corresponding range of Y is 2.9 to 14. This means that not all 129 points are required in the table. We can, therefore, save stroage by using only the range of points required, or increase the accuracy of the stored data by decreasing the scale slightly so that the range of X fits the available table more closely. The scale of Y can also be arranged to provide convenient numbers in the table. The program prints out the octal equivalents of the X and Y values as they will appear in the computer.

```
// JOB T
// FOR
*NAMECON
*LISTALL
      FUNCTION CON(SCAL)
      OCT1=SCAL/32768.0
      IOCT=IFIX(OCT1)
      OCT1=FLOAT(IOCT)
      OCT10=OCT1*32768.0
      OCT2=(SCAL-OCT10)/4096.0
      IOCT=IFIX(OCT2)
      OCT2=FLOAT(IOCT)
      OCT20=OCT2*4096.0
      OCT3=(SCAL-OCT10-OCT20)/512.0
      IOCT=IFIX(OCT3)
      OCT3=FLOAT(IOCT)
      OCT30=OCT3*512.0
      OCT4=(SCAL-OCT10-OCT20-OCT30)/64.0
      IOCT=IFIX(OCT4)
      OCT4=FLOAT(IOCT)
      OCT40=OCT4*64.0
      OCT5=(SCAL-OCT10-OCT20-OCT30-OCT40)/8.0
      IOCT=IFIX(OCT5)
      OCT5=FLOAT(IOCT)
      OCT50=OCT5*8.0
      OCT6= SCAL-OCT10-OCT20-OCT30-OCT40-OCT50
      IOCT=IFIX(OCT6)
      OCT6=FLOAT(IOCT)
      CON=OCT1*100000.0+OCT2*10000.0+OCT3*1000.0+OCT4*100.0+OCT5*10.0+
     1OCT6
      RETURN
      END

VARIABLE ALLOCATIONS
 CON  =0000  OCT1 =0002  OCT10=0004  OCT2 =0006  OCT20=0008  OCT3 =000A  OCT30=000C  OCT4 =000E  OCT40=0010  OCT5 =0012
 OCT50=0014  OCT6 =0016  IOCT =0020

CALLED SUBPROGRAMS
 FADD    FSUB    FMPY    FDIV    FLD     FSTO    IFIX    FLOAT   SUBIN

REAL CONSTANTS
  .327680E 05=0022   .409600E 04=0024   .512000E 03=0026   .640000E 02=0028   .800000E 01=002A   .100000E 06=002C
  .100000E 05=002E   .100000E 04=0030   .100000E 03=0032   .100000E 02=0034

CORE REQUIREMENTS FOR CON
 COMMON      0  VARIABLES     34  PROGRAM    228

END OF COMPILATION
```

Figure F-18. Table Generating Program Listing

```
// FOR
*NAMETAB
*IOCS(CARD,1132PRINTER)
*LISTALL
      DIMENSION C(11),TITLE(20)
      DO 10 I=1,11
   10 C(I)=0.0
      READ(2,15)TITLE
      READ(2,70)N
      READ(2,25)(C(I),I=1,N)
      READ(2,25)ORGX,SCALX,OFX,SCALY,OFY
      READ(2,20)XINC
      WRITE(3,30)TITLE
      WRITE(3,40)(C(I),I=1,N)
      WRITE(3,45)ORGX,SCALX,OFX
      WRITE(3,50)SCALY,OFY
      WRITE(3,55)XINC
      WRITE(3,35)
      XSCAL=((ORGX-OFX)*SCALX)/128.0
      IXS=IFIX(XSCAL)
      XSCAL=FLOAT(IXS)*128.0
      DO 60 I=1,129
      X=XSCAL/SCALX+OFX
      Y=C(1)+C(2)*X+C(3)*X**2+C(4)*X**3+C(5)*X**4+C(6)*X**5+C(7)*X**6
     1+C(8)*X**7+C(9)*X**8+C(10)*X**9+C(11)*X**10
      YSCAL=(Y-OFY)*SCALY
      OCTX=CON(XSCAL)
      OCTY=CON(YSCAL)
      WRITE(3,5)X,OCTX,Y,OCTY
   60 XSCAL=XSCAL+XINC
    5 FORMAT(1X,E15.8,F10.0,E25.8,F10.0)
   15 FORMAT(20A4)
   20 FORMAT(F10.0)
   25 FORMAT(5E15.8)
   30 FORMAT(1H1,20A4/'0COEFFICIENTS USED'/)
   35 FORMAT(8X,'X',7X,'   OCTAL REP',15X,'Y',7X,'   OCTAL REP'/)
   40 FORMAT(6E20.8/)
   45 FORMAT(' X ORIGIN',E16.8,'  X SCALE',E16.8,'  X OFFSET',E16.8/)
   50 FORMAT(' Y SCALE',E16.8,'  Y OFFSET',E16.8/)
   55 FORMAT(' TABULAR INCREMENT',F10.0/)
   70 FORMAT(I10)
      STOP
      END

VARIABLE ALLOCATIONS
 C     =0014  TITLE=003C  ORGX =003E  SCALX=0040  OFX  =0042  SCALY=0044  OFY  =0046  XINC =0048  XSCAL=004A  X    =004C
 Y     =004E  YSCAL=0050  OCTX =0052  OCTY =0054  I    =0068  N    =006A  IXS  =006C

STATEMENT ALLOCATIONS
 5     =008B  15    =0091  20    =0094  25    =0096  30    =0099  35    =00AA  40    =00C2  45    =00C6  50    =00DD  55    =00EC
 70    =00F9  10    =0112  60    =0248

FEATURES SUPPORTED
 IOCS

CALLED SUBPROGRAMS
 CON      FADD     FADDX    FSUB     FMPY     FMPYX    FDIV     FLD      FLDX     FSTO     FSTOX    FAXI     IFIX     FLOAT    SRED
 SWRT     SCOMP    SFIO     SIOAF    SIOFX    SIOF     SIOI     SUBSC    STOP     CARDZ    PRNTZ

REAL CONSTANTS
  .000000E 00=007A    .128000E 03=007C
```

Figure F-18. (Continued)

INTERPOLATION TABLE VALUES FOR MACH NUMBER (Y) AS A FUNCTION OF PT/PC (X)

COEFFICIENTS USED

-0.42045478E 01   0.25125913E 01   -0.38006222E 00   0.31197834E-01   -0.12520838E-02   0.20278486E-04

X ORIGIN 0.75000009E 01 X SCALE 0.10000001E 04 X OFFSET 0.75000009E 01

Y SCALE 0.10000001E 04 Y OFFSET 0.00000000E 00

TABULAR INCREMENT 128.

X	OCTAL REP	Y	OCTAL REP
0.75000009E 01	0.	0.29425191E 01	5576.
0.76280002E 01	200.	0.29786620E 01	5642.
0.77560005E 01	400.	0.30143690E 01	5706.
0.78840007E 01	600.	0.30496993E 01	5751.
0.80120010E 01	1000.	0.30847120E 01	6014.
0.81400013E 01	1200.	0.31194572E 01	6057.
0.82680015E 01	1400.	0.31539840E 01	6121.
0.83960018E 01	1600.	0.31883392E 01	6164.
0.85240001E 01	2000.	0.32225766E 01	6226.
0.86520004E 01	2200.	0.32567234E 01	6270.
0.87800007E 01	2400.	0.32908330E 01	6332.
0.89080009E 01	2600.	0.33249330E 01	6374.
0.90360012E 01	3000.	0.33590607E 01	6437.
0.91640014E 01	3200.	0.33932504E 01	6501.
0.92920017E 01	3400.	0.34275336E 01	6543.
0.94200000E 01	3600.	0.34619350E 01	6605.
0.95480003E 01	4000.	0.34964814E 01	6650.
0.96760006E 01	4200.	0.35312004E 01	6713.
0.98040008E 01	4400.	0.35661091E 01	6756.
0.99320011E 01	4600.	0.36012358E 01	7021.
0.10060001E 02	5000.	0.36365923E 01	7064.
0.10188001E 02	5200.	0.36721987E 01	7130.
0.10316001E 02	5400.	0.37080779E 01	7174.
0.10444000E 02	5600.	0.37442331E 01	7240.
0.10572000E 02	6000.	0.37806811E 01	7304.
0.10700000E 02	6200.	0.38174424E 01	7351.
0.10828001E 02	6400.	0.38545169E 01	7416.
0.10956001E 02	6600.	0.38919229E 01	7463.
0.11084001E 02	7000.	0.39296650E 01	7531.
0.11212001E 02	7200.	0.39677481E 01	7577.
0.11340000E 02	7400.	0.40061836E 01	7646.
0.11468000E 02	7600.	0.40449781E 01	7714.
0.11596000E 02	10000.	0.40841455E 01	7764.
0.11724000E 02	10200.	0.41236648E 01	10033.
0.11852001E 02	10400.	0.41635666E 01	10103.
0.11980001E 02	10600.	0.42038450E 01	10153.
0.12108001E 02	11000.	0.42445097E 01	10224.
0.12236000E 02	11200.	0.42855587E 01	10275.
0.12364000E 02	11400.	0.43269958E 01	10346.
0.12492000E 02	11600.	0.43688211E 01	10420.
0.12620000E 02	12000.	0.44110489E 01	10473.
0.12748001E 02	12200.	0.44536657E 01	10545.
0.12876001E 02	12400.	0.44966964E 01	10620.
0.13004001E 02	12600.	0.45401229E 01	10674.
0.13132001E 02	13000.	0.45839815E 01	10747.
0.13260000E 02	13200.	0.46282434E 01	11024.

Figure F-19. Table Generating Program Printout

0.13388000E 02	13400.	0.46729164E 01	11100.
0.13516000E 02	13600.	0.47180271E 01	11156.
0.13644001E 02	14000.	0.47635879E 01	11233.
0.13772001E 02	14200.	0.48095712E 01	11311.
0.13900001E 02	14400.	0.48560104E 01	11370.
0.14028001E 02	14600.	0.49029111E 01	11446.
0.14156000E 02	15000.	0.49502735E 01	11526.
0.14284000E 02	15200.	0.49981165E 01	11606.
0.14412000E 02	15400.	0.50464525E 01	11666.
0.14540000E 02	15600.	0.50952997E 01	11747.
0.14668001E 02	16000.	0.51446657E 01	12030.
0.14796001E 02	16200.	0.51945610E 01	12112.
0.14924001E 02	16400.	0.52450199E 01	12175.
0.15052000E 02	16600.	0.52960577E 01	12260.
0.15180000E 02	17000.	0.53476886E 01	12343.
0.15308000E 02	17200.	0.53999338E 01	12427.
0.15436000E 02	17400.	0.54528265E 01	12514.
0.15564001E 02	17600.	0.55063905E 01	12602.
0.15692001E 02	20000.	0.55606556E 01	12670.
0.15820001E 02	20200.	0.56156578E 01	12757.
0.15948001E 02	20400.	0.56714143E 01	13047.
0.16076000E 02	20600.	0.57279768E 01	13137.
0.16204002E 02	21000.	0.57853860E 01	13231.
0.16332000E 02	21200.	0.58436641E 01	13323.
0.16460002E 02	21400.	0.59028625E 01	13416.
0.16588001E 02	21600.	0.59630079E 01	13513.
0.16716003E 02	22000.	0.60241565E 01	13610.
0.16844001E 02	22200.	0.60864162E 01	13706.
0.16972000E 02	22400.	0.61497326E 01	14005.
0.17100002E 02	22600.	0.62142715E 01	14106.
0.17228000E 02	23000.	0.62800397E 01	14210.
0.17356002E 02	23200.	0.63470935E 01	14313.
0.17484001E 02	23400.	0.64155016E 01	14417.
0.17612003E 02	23600.	0.64853353E 01	14525.
0.17740001E 02	24000.	0.65566740E 01	14634.
0.17868000E 02	24200.	0.66296148E 01	14745.
0.1~996002E 02	24400.	0.67042226E 01	15060.
0.18124000E 02	24600.	0.67805194E 01	15174.
0.18252002E 02	25000.	0.68586835E 01	15312.
0.18380001E 02	25200.	0.69387388E 01	15432.
0.18508003E 02	25400.	0.70208358E 01	15554.
0.18636001E 02	25600.	0.71050443E 01	15701.
0.18764003E 02	26000.	0.71914501E 01	16027.
0.18892002E 02	26200.	0.72801513E 01	16160.
0.19020000E 02	26400.	0.73713302E 01	16313.
0.19148002E 02	26600.	0.74650564E 01	16451.
0.19276001E 02	27000.	0.75614242E 01	16611.
0.19404003E 02	27200.	0.76605644E 01	16754.
0.19532001E 02	27400.	0.77626457E 01	17122.
0.19660003E 02	27600.	0.78677597E 01	17273.
0.19788002E 02	30000.	0.79760933E 01	17450.
0.19916000E 02	30200.	0.80876865E 01	17627.
0.20044002E 02	30400.	0.82028026E 01	20012.
0.20172000E 02	30600.	0.83215465E 01	20201.
0.20300003E 02	31000.	0.84440441E 01	20374.
0.20428001E 02	31200.	0.85705547E 01	20572.
0.20556003E 02	31400.	0.87011547E 01	20775.
0.20684001E 02	31600.	0.88359832E 01	21203.
0.20812000E 02	32000.	0.89753494E 01	21417.
0.20940002E 02	32200.	0.91193256E 01	21637.

Figure F-19. (Continued)

0.21068000E 02	32400.	0.92681446E 01	22064.
0.21196003E 02	32600.	0.94220237E 01	22316.
0.21324001E 02	33000.	0.95811062E 01	22555.
0.21452003E 02	33200.	0.97456512E 01	23021.
0.21580001E 02	33400.	0.99158287E 01	23273.
0.21708000E 02	33600.	0.10091865E 02	23553.
0.21836002E 02	34000.	0.10274007E 02	24042.
0.21964000E 02	34200.	0.10462484E 02	24336.
0.22092002E 02	34400.	0.10657474E 02	24641.
0.22220001E 02	34600.	0.10859289E 02	25153.
0.22348003E 02	35000.	0.11068193E 02	25474.
0.22476001E 02	35200.	0.11284374E 02	26024.
0.22604000E 02	35400.	0.11508090E 02	26364.
0.22732002E 02	35600.	0.11739740E 02	26733.
0.22860000E 02	36000.	0.11979408E 02	27313.
0.22988002E 02	36200.	0.12227479E 02	27703.
0.23116001E 02	36400.	0.12484270E 02	30304.
0.23244003E 02	36600.	0.12749982E 02	30715.
0.23372001E 02	37000.	0.13024982E 02	31340.
0.23500003E 02	37200.	0.13309579E 02	31775.
0.23628002E 02	37400.	0.13604152E 02	32444.
0.23756000E 02	37600.	0.13908899E 02	33124.
0.23884002E 02	40000.	0.14224218E 02	33620.

Figure F-19. (Continued)

AIRESEARCH MANUFACTURING COMPANY
Los Angeles, California

APPENDIX G

ENGINE CONTROL PROGRAM LISTINGS

APPENDIX G

ENGINE CONTROL PROGRAM LISTINGS

This appendix includes the listings for the engine control programs that have been changed since the previous technical report. The complete set of programs is listed below. Those programs not found in this appendix (*) are shown in Appendix D of the Fifth Control System TDR (AP-68-4129, Data Item No. 55-6.05).

AIR MASS FLOW COMPUTATION - MARK II

```
SUBAMF STM SUBN      SAVE RETURN ADDRESS
       WOT APAVR     SET OPCODE ANALOG IN AIRCRAFT VELOCITY REFERENCE
       ALS 9         DELAY 10 WORD TIMES
       DIN INWORK    INPUT AIRCRAFT VELOCITY REFERENCE
       WOT APAVX     SET OPCODE ANALOG IN AIRCRAFT VELOCITY X
       CLA INWORK
       SUB LOWAVR    SUBTRACT MINIMUM VALUE
       TMI ERROR     UNDER TOLERANCE
       SUB DIFAVR    SUBTRACT MAX-MIN VALUE
       TMI PARA1
       TRA ERROR     OVER TOLERANCE
PARA1  DIN INWORK    INPUT A/C VELOCITY X PARAMETER
       WOT APAVY     SET OPCODE ANALOG IN A/C VELOCITY Y
       CLA INWORK
       ADD OFFAVX    ADD OFFSET FOR A/C VELOCITY X PARAMETER
       ALS 7         SHIFT READY FOR MULTIPLY
       STA PARAM     STORE AS FIRST PARAMETER
       SUB LOWAVX    SUBTRACT MIN VALUE
       TMI ERROR     UNDER LIMIT
       SUB DIFAVX    SUBTRACT MAX-MIN VALUE
       TMI PARA2
       TRA ERROR     OVERLIMIT
PARA2  DIN INWORK    INPUT A/C VELOCITY Y PARAMETER
       WOT APAVZ     SET OPCODE ANALOG IN A/C VELOCITY Z
       CLA INWORK    CHECK LIMITS
       ADD OFFAVY
       ALS 7
       STA PARAM&1   STORE AS SECOND PARAMETER
       SUB LOWAVY
       TMI ERROR     UNDER LIMIT
       SUB DIFAVY
       TMI PARA3
       TRA ERROR     OVER LIMIT
PARA3  DIN INWORK    INPUT A/C VELOCITY Z PARAMETER
       WOT APAATK    SET OPCODE ANALOG IN A/C ANGLE OF ATTACK
       CLA INWORK    CHECK LIMITS
       ADD OFFAVZ
       ALS 7
       STA PARAM&2   STORE AS THIRD PARAMETER
       SUB LOWAVZ
       TMI ERROR     UNDER LIMIT
       SUB DIFAVZ
       TMI PARA4
       TRA ERROR     OVER LIMIT
PARA4  DIN INWORK    INPUT A/C ANGLE OF ATTACK PARAMETER
       WOT APDBET    SET OPCODE ANALOG IN HORZ. DIFF. PRESSURE
       CLA INWORK    CHECK LIMITS
```

```
         ADD OFFATK
         ALS 7
         STA PARAM&3   STORE AS FOURTH PARAMETER
         SUB LOWATK
         TMI ERROR     UNDER LIMIT
         SUB DIFATK
         TMI PARA5
         TRA ERROR     OVER LIMIT
PARA5    DIN INWORK    INPUT HORZ. DIFF. PRESSURE
         WOT APDALP    SET OPCODE ANALOG IN VERT. DIFF. PRESSURE
         CLA INWORK    CHECK LIMITS
         ADD OFFDBE
         ALS 7
         STA PARAM&4   STORE AS FIFTH PARAMETER
         SUB LOWDBE
         TMI ERROR     UNDER LIMIT
         SUB DIFDBE
         TMI PARA6
         TRA ERROR     OVER LIMIT
PARA6    DIN INWORK    INPUT VERT. DIFF. PRESSURE
         WOT APPTLR    SET OPCODE ANALOG IN LOW RANGE SPIKE TOTAL PRESSURE
         CLA INWORK    CHECK LIMITS
         ADD OFFDAL
         ALS 7
         STA PARAM&5   STORE AS SIXTH PARAMETER
         SUB LOWDAL
         TMI ERROR     UNDER LIMIT
         SUB DIFDAL
         TMI PARA7
         TRA ERROR     OVER LIMIT
PARA7    DIN INWORK    INPUT LOW RANGE SPIKE TOTAL PRESSURE
         CLA INWORK
         SUB PTRC      TEST FOR RANGE CHANGE
         TMI PARA8
         WOT APPTHR    SET OPCODE ANALOG IN HIGH RANGE SPIKE TOTAL PRESSURE
         ALS 5         DELAY FOR CONVERSION
         DIN INWORK    INPUT HIGH RANGE SPIKE TOTAL PRESSURE
         CLA INWORK    CHECK LIMITS PT HIGH RANGE
         ADD OFFPTH
         ALS 7
         STA PARAM&6   STORE AS SEVENTH PARAMETER
         SUB LOWPTH
         TMI ERROR     UNDER LIMIT
         SUB DIFPTH
         TMI PARA9
         TRA ERROR     OVER LIMIT
PARA9    CLA PARAM&6
         MPY SCAPTH    SCALE HIGH RANGE SPIKE TOTAL PRESSURE
         STA PTPRIM
         TRA PARSCA
PARA8    CLA INWORK    CHECK LIMITS PT LOW RANGE
```

```
        ADD OFFPTL
        ALS 7
        STA PARAM&6  STORE AS SEVENTH PARAMETER
        SUB LOWPTL
        TMI ERROR    UNDER LIMIT
        SUB DIFPTL
        TMI PARA10
        TRA ERROR    OVER LIMIT
PARA10  CLA PARAM&6
        MPY SCAPTL   SCALE LOW RANGE SPIKE TOTAL PRESSURE
        STA PTPRIM
PARSCA  CLA PARAM
        MPY SCAAVX   SCALE A/C VELOCITY X
        STA AVX
        CLA PARAM&1
        MPY SCAAVY   SCALE A/C VELOCITY Y
        STA AVY
        CLA PARAM&2
        MPY SCAAVZ   SCALE A/C VELOCITY Z
        STA AVZ
        CLA PARAM&3
        MPY SCAATK   SCALE A/C ANGLE OF ATTACK
        STA AATK
        CLA PARAM&4
        MPY SCADBE   SCALE HORZ. DIFF. PRESSURE
        STA DPBETA
        CLA PARAM&5
        MPY SCADAL   SCALE VERT. DIFF. PRESSURE
        STA DPALPH
        CLA AVX      FORM AND STORE SQUARE OF A/C AND WIND VECTOR X
        SUB WVX
        ALS
        STA WGEN
        MPY WGEN
        STA WTAS
        CLA AVY      FORM SQUARE OF A/C AND WIND VECTOR Y AND ADD TO
        SUB WVY      SQUARE OF VECTOR X
        ALS
        STA WGEN
        MPY WGEN
        ADD WTAS
        STA WTAS
        CLA AVZ      FORM SQUARE OF A/C VECTOR Z AND ADD TO VECTORS X&Y
        ALS
        STA WGEN
        MPY WGEN
        ADD WTAS
        ARS
        DOT SUBSRT   FORM SQUARE ROOT OF VELOCITY COMPONENTS
        TRA SUBINT
        STA ATAS     STORE AIRCRAFT TAS
```

```
ALS
MPY AMCON     FORM AND STORE AIRCRAFT MACH NUMBER
STA AMACH
CLA AATK      FORM B X ALPHA
ALS
STA WGEN&1
MPY CONB
ARS
STA WGEN
CLA ONE       FORM (1-B X ALPHA) X AIRCRAFT MACH NO.
SUB WGEN
ALS
MPY AMACH
ARS
STA·WGEN
CLA WGEN&1    FORM CALCULATED MACH NO. MOC
MPY CONC
ARS
ADD WGEN
STA MOC
CLA PTPRIM
DOT SUBREC    FORM RECIPROCAL OF P'T
TRA SUBINT
ALS
STA WGEN      SAVE 1/P'T
CLA MOC
DOT SUBANG    FORM FUNCTION OF MOC FOR ENGINE ANGLE OF ATTACK
TRA SUBINT
ALS
STA WGEN&1    SAVE FUNCTION OF MOC
CLA DPALPH    FORM ALPHA LOCAL
ALS
MPY WGEN
ALS
MPY WGEN&1
ARS
STA ALPHAL    STORE ALHA LOCAL
CLA DPBETA    FORM BETA LOCAL
ALS
MPY WGEN
ALS
MPY WGEN&1
ARS
STA BETAL     STORE BETA LOCAL
CLA MOC
DOT SUBMAN    FORM FUNCTION OF MACH ALPHA MIN.
TRA SUBINT
STA WGEN      STORE MINIMUM VALUE
DOT SUBMAX    FORM FUNCTION OF MACH ALPHA MAX.
TRA SUBINS
SUB WGEN
```

```
ALS
STA WGEN&1    STORE INCREMENT
CLA ALPHAL    FORM INTERPOLATION  1-(ALPHA LOCAL/ALPHA MAX)SQUARED
ALS
STA WGEN&2
MPY WGEN&2
MPY RECALF
ARS
STA WGEN&2
CLA ONE
SUB WGEN&2
ALS
MPY WGEN&1    MULTIPLY BY INCREMENT
ARS
ADD WGEN      FORM FUNCTION OF MOC AND ALPHA LOCAL
STA FMOAFL
CLA BETAL     FORM INTERPOLATION  1-(BETA LOCAL/ALPHA MAX)SQUARED
ALS
STA WGEN&2
MPY WGEN&2
MPY RECALF
ARS
STA WGEN&2
CLA ONE
SUB WGEN&2
ALS
MPY WGEN&1    MULTIPLY BY INCREMENT
ARS
ADD WGEN      FORM FUNCTION OF MOC AND BETA LOCAL
STA FMOBTL
ADD FMOAFL
ALS
STA WGEN      STORE F(MOC,ALPHA LOCAL) & F(MOC,BETA LOCAL)
CLA ATAS
DOT SUBREC    FORM RECIPROCAL OF AIRCRAFT VELOCITY
TRA SUBINT
ALS
MPY WGEN      FORM(F(MOC,ALPHA LOCAL)&F(MOC,BETA LOCAL) X 1/TAS
ALS
STA WGEN
CLA PTPRIM
ALS
MPY WGEN      FORM AIR MASS FLOW EQUAL TO
MPY COND       BXP'TX(F(MOC,ALPHA LOCAL)&F(MOC,BETA LOCAL))X1/TAS
ARS
STA AMFC      STORE CALCULATED AIRMASS FLOW
CLA AMACH     FORM FUNCTION OF AIRCRAFT MACH NUMBER
DOT SUBMAC
TRA SUBINT
ALS
MPY RTOTSD    MULTIPLY BY SQUARE ROOT OF TO/TSTD
```

```
        ALS 8
        STA RTTOTS     SAVE FOR COMBUSTOR LIMIT ROUTINE
        RJP SUBN

                       CONSTANTS AND WORKING LOCATIONS

CONB    DEC            CONSTANTS B AND C FOR MACH NUMBER MO CALCULATION
CONC    DEC
COND    DEC            CONSTANT D FOR THE AIR MASS FLOW
ONE     DEC 1          CONSTANT ONE
PTRC    OCT            CONSTANT SPIKE TOTAL PRESSURE FOR RANGE CHANGE
RECALF  DEC            RECIPROCAL OF MAXIMUM ALPHA VALUE SQUARED
SUBANG  OCT            WORD TO SET SR FOR F(MOC) FOR ANGLE OF ATTACK
SUBMAC  OCT            WORD TO SET SR FOR FUNCTION OF AIRCRAFT MACH NUMBER
SUBMAN  OCT            WORD TO SET SR FOR F(MOC) ALPHA MINIMUM
SUBMAX  OCT            WORD TO SET SR FOR F(MOC) ALPHA MAXIMUM
SUBREC  OCT            WORD TO SET SR FOR RECIPROCAL ROUTINF
SUBSRT  OCT            WORD TO SET SR FOR SQUARE ROOT ROUTINE
RTOTSD  BSS 1          SQUARE ROOT OF TO/TSTD (SHIFTED FOR MULTIPLY)
                          - A PREFLIGHT INPUT
TFCON   DEC            CONSTANT PROPORTIONAL TO 1/(K X T INF.)
WVX     BSS 1          WIND VELOCITY - X - CONSTANT FOR FLIGHT
WVY     BSS 1          WIND VELOCITY - Y - CONSTANT FOR FLIGHT
ALPHAL  BSS 1          ALPHA LOCAL - ANGLE OF ATTACK
AMACH   BSS 1          AIRCRAFT MACH NUMBER
AMFC    BSS 1          CALCULATED AIR MASS FLOW
ATAS    BSS 1          AIRCRAFT TRUE AIRSPEED
BETAL   BSS 1          BETA LOCAL - ANGLE OF YAW
FMOAFL  BSS 1          FUNCTION OF MOC AND ALPHA LOCAL
FMOBTL  BSS 1          FUNCTION OF MOC AND BETA LOCAL
RTTOTS  BSS 1          CALCULATED VALUE SQUARE ROOT OF TTO/TSTD (SHIFTED)
SUBN    BSS 1          RETURN ADDRESS
WGEN    BSS 3          GENERAL WORKING STORAGE
WTAS    BSS 1          WORKING LOCATION TAS

AVX     BSS 1          AIRCRAFT VELOCITY - X
AVY     BSS 1          AIRCRAFT VELOCITY - Y
AVZ     BSS 1          AIRCRAFT VELOCITY - Z
AATK    BSS 1          AIRCRAFT ANGLE OF ATTACK
DPALPH  BSS 1          PRESSURE DIFFERENTIAL FOR ANGLE OF ATTACK
DPBETA  BSS 1          PRESSURE DIFFERENTIAL FOR ANGLE OF YAW
PTPRIM  BSS 1          SPIKE TOTAL PRESSURE

APAVR   OCT            OPCODE FOR ANALOG IN AIRCRAFT VELOCITY REFERENCE
APAVX   OCT            OPCODE FOR ANALOG INPUT AIRCRAFT VELOCITY X
APAVY   OCT            OPCODE FOR ANALOG INPUT AIRCRAFT VELOCITY Y
APAVZ   OCT            OPCODE FOR ANALOG INPUT AIRCRAFT VELOCITY Z
APAATK  OCT            OPCODE FOR ANALOG INPUT AIRCRAFT ANGLE OF ATTACK
APDALP  OCT            OPCODE FOR ANALOG INPUT VERT. DIFFERENTIAL PRESSURE
APDBET  OCT            OPCODE FOR ANALOG INPUT HORZ. DIFFERENTIAL PRESSURE
APPTLR  OCT            OPCODE FOR ANALOG INPUT LOW RANGE SPIKE TOTAL PRESS
```

```
APPTHR OCT          OPCODE FOR ANALOG INPUT HIGH RANGE SPIKE TOTAL PRESS
LOWAVR OCT          MINIMUM VALUE FOR AIRCRAFT VELOCITY REFERENCE
LOWAVX OCT          MINIMUM VALUE FOR A/C VELOCITY X
LOWAVY OCT          MINIMUM VALUE FOR A/C VELOCITY Y
LOWAVZ OCT          MINIMUM VALUE FOR A/C VELOCITY Z
LOWATK OCT          MINIMUM VALUE FOR A/C ANGLE OF ATTACK
LOWDAL OCT          MINIMUM VALUE FOR VERT. DIFFERENTIAL PRESSURE
LOWDBE OCT          MINIMUM VALUE FOR HORZ. DIFFERENTIAL PRESSURE
LOWPTL OCT          MINIMUM VALUE FOR LOW RANGE SPIKE TOTAL PRESSURE
LOWPTH OCT          MINIMUM VALUE FOR HIGH RANGE SPIKE TOTAL PRESSURE
DIFAVR OCT          MAX-MIN VALUE FOR AIRCRAFT VELOCITY REFERENCE
DIFAVX OCT          MAX-MIN VALUE FOR A/C VELOCITY X
DIFAVY OCT          MAX-MIN VALUE FOR A/C VELOCITY Y
DIFAVZ OCT          MAX-MIN VALUE FOR A/C VELOCITY Z
DIFATK OCT          MAX-MIN VALUE FOR A/C ANGLE OF ATTACK
DIFDAL OCT          MAX-MIN VALUE FOR VERT. DIFFERENTIAL PRESSURE
DIFDBE OCT          MAX-MIN VALUE FOR HORZ. DIFFERENTIAL PRESSURE
DIFPTL OCT          MAX-MIN VALUE FOR LOW RANGE SPIKE TOTAL PRESSURE
DIFPTH OCT          MAX-MIN VALUE FOR HIGH RANGE SPIKE TOTAL PRESSURE
OFFAVX OCT          OFFSET FOR A/C VELOCITY X
OFFAVY OCT          OFFSET FOR A/C VELOCITY Y
OFFAVZ OCT          OFFSET FOR A/C VELOCITY Z
OFFATK OCT          OFFSET FOR A/C ANGLE OF ATTACK
OFFDAL OCT          OFFSET FOR VERT. DIFFERENTIAL PRESSURE
OFFDBE OCT          OFFSET FOR HORZ. DIFFERENTIAL PRESSURE
OFFPTL OCT          OFFSET FOR LOW RANGE SPIKE TOTAL PRESSURE
OFFPTH OCT          OFFSET FOR HIGH RANGE SPIKE TOTAL PRESSURE
SCAAVX OCT          SCALE FACTOR FOR A/C VELOCITY X
SCAAVY OCT          SCALE FACTOR FOR A/C VELOCITY Y
SCAAVZ OCT          SCALE FACTOR FOR A/C VELOCITY Z
SCAATK OCT          SCALE FACTOR FOR A/C ANGLE OF ATTACK
SCADAL OCT          SCALE FACTOR FOR VERT. DIFFERENTIAL PRESSURE
SCADBE OCT          SCALE FACTOR FOR HORZ. DIFFERENTIAL PRESSURE
SCAPTL OCT          SCALE FOR LOW RANGE SPIKE TOTAL PRESSURE
SCAPTL OCT          SCALE FOR HIGH RANGE SPIKE TOTAL PRESSURE

INWORK BSS 1        WORKING LOCATION FOR PARAMETER INPUT
PARAM  BSS 7        WORKING LOCATIONS FOR INPUT PARAMETERS

                    TABLES TO BE IN SEPERATE SECTORS

TABANG BSS 128      TABLE FOR FUNCTION OF MOC FOR ANGLE OF ATTACK

TABMAC BSS 128      TABLE FOR FUNCTION OF AIRCRAFT MACH NUMBER

TABMAN BSS 128      TABLE FOR FUNCTION OF MOC ALPHA MINIMUM

TABMAX BSS 128      TABLE FOR FUNCTION OF MOC ALPHA MAXIMUM

TABREC BSS 128      TABLE FOR RECIPROCAL FUNCTION

TABSRT BSS 128      TABLE FOR SQUARE ROOT FUNCTION
```

FUEL MASS FLOW DISTRIBUTION - SUBSONIC COMBUSTION

```
FFSCI   STM SUBN      SAVE RETURN ADDRESS - START OPERATION
        CLA ZERO
        STA REG1      SET COMBUSTORS 1,2 AND 3 OUTPUT REGISTERS EQUAL TO
        STA REG2         ZERO
        STA REG3
        WOT ANAOP1    SET OPCODE ANALOG OUTPUT CHANNEL 1
        WOT REG1      OUTPUT CONTENTS OF REGISTER 1
        WOT ANAOP3    SET OPCODE ANALOG OUTPUT CHANNEL 3
        WOT REG3      OUTPUT CONTENTS OF REGISTER 3
        TRA FSD2
FFSC    STM SUBN      SAVE RETURN ADDRESS - NORMAL OPERATION
        DOT SRMAN2    SET SR FOR MANIFOLD 2 PARAMETERS
        TRA SUBFFS    GO TO MANIFOLD FUEL FLOW SUBROUTINE
FSD2    STA FFCOM2    STORE FUEL FLOW FOR COMBUSTOR 2
        CLA CALTTF    FORM FUEL FLOW ERROR FOR COMBUSTOR 2
        SUB FFCOM2    EQUALS TOTAL REQUIRED - ACTUAL FOR COMBUSTOR 2
        ALS 8
        MPY KDF2      FORM INCREMENT
        ADD REG2      ADD TO PREVIOUS OUTPUT
        STA REG2
        SUB REGMAX    TRUNCATE TO 9 BITS
        TMI FSD3
        CLA REGMAX
        STA REG2
FSD3    WOT ANAOP2    SET OPCODE ANALOG OUTPUT CHANNEL 2
        WOT REG2      OUTPUT CONTENTS OF REGISTER 2
        RJP SUBN      RETURN
```

FUEL MASS FLOW DISTRIBUTION - SUPERSONIC COMBUSTION

```
FFSSCI  STM SUBN      SAVE RETURN ADDRESS - START OPERATION
        CLA ZERO      SET COMBUSTORS 1,2 AND 3 OUTPUT REGISTERS EQUAL TO
        STA REG1         ZERO
        STA REG2
        STA REG3
        CLA MAXERR    SET EXISTING PRESSURE RATIO ERROR FOR COMBUSTOR 1
        STA EITL1        EQUAL TO A MAXIMUM VALUE
        CLA CALTTF    SET FUEL FLOW ERROR FOR MANIFOLD 1 EQUAL TO TOTAL
        ALS 8         FUEL FLOW REQUIRED
        STA EITF1
        TRA FFSSCB
FFSSC   STM SUBN      SAVE RETURN ADDRESS - NORMAL OPERATION
        CLA EITF1     SAVE PREVIOUS ERRORS FOR COMBUSTOR 1
        STA EITTF1
        CLA EITL1
        STA EITTL1
```

```
        CLA SRCOM1   SET SR CONSTANT FOR COMBUSTOR 1 LIMIT PARAMETERS
        STA SRREQ
        CLA SRCOM2
        STA SRREQ&1
        TRA SUBCL1   GO TO COMBUSTOR LIMIT SUBROUTINE - COMBUSTOR 1 ENTRY
        ALS 8
        STA EITL1    SAVE PRESSURE RATIO ERROR
        TMI FDA      PRESSURE RATIO ERROR IS NEGATIVE
        DOT SRMN1A   SET SR FOR MANIFOLD 1A PARAMETERS
        TRA SUBFFS   GO TO MANIFOLD FUEL FLOW SUBROUTINE
        STA FFCOM1   STORE FUEL FLOW FOR MANIFOLD 1A
        DOT SRMN1B   SET SR FOR MANIFOLD 1B PARAMETERS
        TRA SUBFFS   GO TO MANIFOLD FUEL FLOW SUBROUTINE
        ADD FFCOM1   FORM TOTAL FUEL FLOW FOR COMBUSTOR 1 EQUALS 1A&1B
        CLA CALTTF   FORM FUEL FLOW ERROR FOR COMBUSTOR 1
        SUB FFCOM1   EQUALS TOTAL REQUIRED - ACTUAL FOR COMBUSTOR 1
        ALS 8
        STA EITF1
        TMI FDB      FUEL FLOW ERROR IS NEGATIVE
        MPY EITTL1
        STA PROD1    FORM EI(T)F1 X EI(T-T)L1
        CLA EITTF1
        MPY EITL1    FORM EI(T-T)F1 X EI(T)L1
        SUB PROD1
        TMI FD2
        CLA EITF1
FDB     MPY KDF1     FORM OUTPUT INCREMENT
        STA INC
        CLA ONE
        STA SWOP1    SET SWOP1 ONE
        TRA FD3
FD2     CLA EITL1
FDA     MPY KDL1     FORM OUTPUT INCREMENT
        STA INC
        CLA ZERO
        STA SWOP1    SET SWOP1 EQUAL ZERO
FD3     CLA REG1     ADD INCREMENT TO OUTPUT
        ADD INC
        STA REG1
        SUB REGMAX   TRUNCATE TO 9 BITS
        TMI FD4
        CLA REGMAX
        STA REG1
FD4     WOT ANAOP1   SET OPCODE ANALOG OUTPUT CHANNEL 1
        WOT REG1     OUTPUT CONTENTS OF REGISTER 1
        CLA EITF1
        TMI FD5      FUEL FLOW ERROR FOR COMBUSTOR 1 NEGATIVE
        CLA SWOP1
        TZE FD7      FUEL FLOW GOVERNING
FD5     CLA ZERO
        STA SWOP2A   SET SWOP2A EQUAL ZERO
```

```
        STA REG2      SET OUTPUTS TO F.C.V.S 2 AND 3 EQUAL ZERO
        STA REG3
        WOT ANAOP2    OUTPUT CONTENTS OF REGISTERS 2 AND 3
        WOT REG2
        WOT ANAOP3
        WOT REG3
        CLA MAXERR    SET PRESSURE RATIO ERROR FOR COMBUSTOR 2 TO MAXIMUM
        STA EITL2
        RJP SUBN      RETURN
FD6     CLA ONE       SET SWOP2A EQUAL ONE
        STA SWOP2A
        CLA EITF1     SET COMBUSTOR 2 FUEL FLOW ERROR = COMBUSTOR 1 ERROR
        STA EITF2
        TRA FDC
FD7     CLA SWOP2A
        TZE FD6
        CLA EITF2     SAVE PREVIOUS ERRORS FOR COMBUSTOR 2
        STA EITTF2
        CLA EITL2
        STA EITTL2
        CLA SRCOM2    SET SR CONSTANT FOR COMBUSTOR 2 LIMIT PARAMETERS
        STA SRREQ
        CLA SRCOM3
        STA SRREQ&1
        TRA SUBCL2    GO TO COMBUSTOR LIMIT SUBROUTINE - COMBUSTOR 2 ENTRY
        ALS 8
        STA EITL2     SAVE PRESSURE RATIO ERROR
        TMI FD9       PRESSURE RATIO ERROR IS NEGATIVE
        DOT SRMAN2    SET SR FOR MANIFOLD 2 PARAMETERS
        TRA SUBFFS    GO TO MANIFOLD FUEL FLOW SUBROUTINE
        STA FFCOM2    STORE FUEL FLOW FOR COMBUSTOR 2
        ALS 8         SHIFT FOR MULTIPLY
        STA INWORK    TEMPORARY STORE
        CLA EITF1     FORM FUEL FLOW ERROR FOR COMBUSTOR 2
        SUB INWORK     EQUALS REQUIRED - ACTUAL FOR COMBUSTOR 2
        STA EITF2
        TMI FDC       FUEL FLOW ERROR IS NEGATIVE
        MPY EITTL2
        STA PROD1     FORM EI(T)F2 X EI(T-T)L2
        CLA EITTF2
        MPY EITL2     FORM EI(T-T)F2 X EI(T)L2
        SUB PROD1
        TMI FD8
        CLA EITF2
FDC     MPY KDF2      FORM OUTPUT INCREMENT
        STA INC
        CLA ONE
        STA SWOP2B    SET SWOP2B EQUAL ONE
        TRA FD10
FD8     CLA EITL2
FD9     MPY KDL2      FORM OUTPUT INCREMENT
```

```
         STA INC
         CLA ZERO
         STA SWOP2B   SET SWOP2B EQUAL ZERO
FD10     CLA REG2     ADD INCREMENT TO OUTPUT
         ADD INC
         STA REG2
         SUB REGMAX   TRUNCATE TO 9 BITS
         TMI FD11
         CLA REGMAX
         STA REGMAX
FD11     WOT ANAOP2   SET OPCODE ANALOG OUTPUT CHANNEL 2
         WOT REG2     OUTPUT CONTENTS OF REGISTER 2
         CLA EITF2
         TMI FD12     FUEL FLOW ERROR FOR COMBUSTOR 2 NEGATIVE
         CLA SWOP2B
         TZE FD14     FUEL FLOW GOVERNING
FD12     CLA ZERO
         STA SWOP3    SET SWOP3 EQUAL ZERO
         STA REG3     SET OUTPUT TO F.C.V. 3 EQUAL ZERO
         WOT ANAOP3   OUTPUT CONTENTS OF REGISTER 3
         WOT REG3
         RJP SUBN     RETURN
FD13     CLA ONE      SET SWOP3 EQUAL ONE
         STA SWOP3
         CLA EITF2    SET COMBUSTOR 3 FUEL FLOW ERROR = COMBUSTOR 2 ERROR
         TRA FD15
FD14     CLA SWOP3
         TZE FD13
         OUT SRMAN3   SET SR FOR MANIFOLD 3 PARAMETERS
         TRA SUBFFS   GO TO MANIFOLD FUEL FLOW SUBROUTINE
         STA FFCOM3   STORE FUEL FLOW FOR COMBUSTOR 3
         ALS 8        SHIFT FOR MULTIPLY
         STA INWORK   TEMPORARY STORE
         CLA EITF2
         SUB INWORK
FD15     MPY KDF3     FORM OUTPUT INCREMENT
         ADD REG3
         STA REG3     ADD INCREMENT TO OUTPUT
         SUB REGMAX   TRUNCATE TO 9 BITS
         TMI FD16
         CLA REGMAX
         STA REG3
FD16     WOT ANAOP3   SET OPCODE ANALOG OUTPUT CHANNEL 3
         WOT REG3     OUTPUT CONTENTS OF REGISTER 3
         RJP SUBN     RETURN

                      CONSTANTS AND WORKING LOCATIONS

ANAOP1 OCT            OPCODE TO SET ANALOG OUTPUT CHANNEL 1
ANAOP2 OCT            OPCODE TO SET ANALOG OUTPUT CHANNEL 2
ANAOP3 OCT            OPCODE TO SET ANALOG OUTPUT CHANNEL 3
```

```
CALTTF BSS 1          CALCULATED TOTAL FUEL FLOW REQUIRED
KDF1   OCT            SCALING CONSTANT FOR FUEL FLOW OUTPUT 1 -RDY FOR MPY
KDF2   OCT            SCALING CONSTANT FOR FUEL FLOW OUTPUT 2 -RDY FOR MPY
KDF3   OCT            SCALING CONSTANT FOR FUEL FLOW OUTPUT 3 -RDY FOR MPY
KDL1   OCT            SCALING CONSTANT FOR PRESS RAT OUTPUT 1 -RDY FOR MPY
KDL2   OCT            SCALING CONSTANT FOR PRESS RAT OUTPUT 2 -RDY FOR MPY
MAXERR DEC            MAXIMUM PRESSURE RATIO ERROR
REGMAX OCT 000777     MAXIMUM VALUE FOR REGISTER OUTPUT
SRCOM1 OCT            CONSTANT SET SR TO COMBUSTOR 1 INPUTS
SRCOM2 OCT            CONSTANT SET SR TO COMBUSTOR 2 INPUTS
SRCOM3 OCT            CONSTANT SET SR TO COMBUSTOR 3 INPUTS
SRMN1A OCT            CONSTANT TO SET SR FOR MANIFOLD 1A PARAMETERS
SRMN1B OCT            CONSTANT TO SET SR FOR MANIFOLD 1B PARAMETERS
SRMAN2 OCT            CONSTANT TO SET SR FOR MANIFOLD 2 PARAMETERS
SRMAN3 OCT            CONSTANT TO SET SR FOR MANIFOLD 3 PARAMETERS

EITF1  BSS 1          EXISTING FUEL FLOW ERROR FOR COMBUSTOR 1
EITF2  BSS 1          EXISTING FUEL FLOW ERROR FOR COMBUSTOR 2
EITTF1 BSS 1          PREVIOUS FUEL FLOW ERROR FOR COMBUSTOR 1
EITTF2 BSS 1          PREVIOUS FUEL FLOW ERROR FOR COMBUSTOR 2
EITL1  BSS 1          EXISTING PRESSURE RATIO ERROR FOR COMBUSTOR 1
EITL2  BSS 1          EXISTING PRESSURE RATIO ERROR FOR COMBUSTOR 2
EITTL1 BSS 1          PREVIOUS PRESSURE RATIO ERROR FOR COMBUSTOR 1
EITTL2 BSS 1          PREVIOUS PRESSURE RATIO ERROP FOR COMBUSTOR 2
FFCOM1 BSS 1          FUEL FLOW FOR COMBUSTOR 1
FFCOM2 BSS 2          FUEL FLOW FOR COMBUSTOR 2
FFCOM3 BSS 3          FUEL FLOW FOR COMBUSTOR 3
INC    BSS 1          REQUIRED OUTPUT INCREMENT
PROD1  BSS 1          WORKING LOCATION FOR EI(T)F X EI(T-T)L
REG1   BSS 1          OUTPUT TO F.C.V. NUMBER 1
REG2   BSS 1          OUTPUT TO F.C.V. NUMBER 2
REG3   BSS 1          OUTPUT TO F.C.V. NUMBER 3
SRREQ  BSS 2          WORKING LOCATIONS FOR REQUIRED SR CONSTANTS
SUBN   BSS 3          RETURN ADDRESS WORKING LOCATIONS
SWOP1  BSS 1          SWITCH FOR COMBUSTOR 1 DISTRIBUTION
SWOP2A BSS 1          SWITCH FOR COMBUSTOR 2 DISTRIBUTION
SWOP2B BSS 1          SWITCH FOR COMBUSTOR 2 DISTRIBUTION
SWOP3  BSS 1          SWITCH FOR COMBUSTOR 3 DISTRIBUTION
```

MANIFOLD FUEL FLOW SUBROUTINE

THIS SUBROUTINE CALCULATES THE FUEL FLOW IN THE MANIFOLD FROM PRESSURE AND TEMPERATURE MEASUREMENTS TAKEN ON A VENTURI INSTALLED IN THE FUEL LINE. PRIOR TO ENTRY THE SECTOR REGISTER IS SET FOR INPUTTING THE APPROPRIATE PARAMETERS. THE FUEL FLOW QUANTITY IS SET IN THE ACCUMULATOR ON RETURN

```
SUBFFS STM SUBRET    SAVE RETURN ADDRESS
       WOT ANAPT1,1 SET OPCODE ANALOG IN FUEL TOTAL PRESSURE
       ALS 9         DELAY 10 WORD TIMES
       DIN INWORK    INPUT FUEL TOTAL PRESSURE
       WOT ANATT1,1 SET OPCODE ANALOG IN FUEL TOTAL TEMPERATURE
       CLA INWORK
       ADD OFFPT1,1 ADD OFFSET
       ALS 7         SHIFT FOR SCALING
       STA PAR       SAVE PARAMETER
       SUB LOWPT1,1 SUBTRACT MINIMUM VALUE
       TMI ERROR     UNDER LIMIT
       SUB DIFPT1,1 SUBTRACT MAX-MIN VALUE
       TMI FF4
       TRA ERROR     OVER LIMIT
FF4    DIN INWORK    INPUT FUEL TOTAL TEMPERATURE
       WOT ANAPD1,1 SET OPCODE ANALOG IN FUEL DIFFERENTIAL PRESSURE
       CLA INWORK
       ADD OFFTT1,1 ADD OFFSET
       ALS 7
       STA PAR&1
       SUB LOWTT1,1
       TMI ERROR     UNDER LIMIT
       SUB DIFTT1,1
       TMI FF5
       TRA ERROR     OVER LIMIT
FF5    DIN INWORK    INPUT FUEL DIFFERENTIAL PRESSURE
       DIN8100       SAMPLE SECTOR REGISTER
       SUB MAN3TS    TEST FOR MANIFOLD 3
       TZE FF8
FF10   CLA INWORK
       ADD OFFPD1,1 ADD OFFSET
       ALS 7
       STA PAR&2
       SUB LOWPD1,1
       TMI ERROR     UNDER LIMIT
       SUB DIFPD1,1
       TMI FF6
       TRA ERROR     OVER LIMIT
FF6    CLA PAR&2
       MPY SCAPD1,1 SCALE
       STA MFPD      STORE MANIFOLD DIFFERENTIAL PRESSURE
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FF7     CLA PAR
        MPY SCAPT1,1 SCALE
        STA MFPT      STORE MANIFOLD FUEL TOTAL PRESSURE
        CLA PAR&1
        MPY SCATT1,1 SCALE
        STA MFTT      STORE MANIFOLD FUEL TOTAL TEMPERATURE
        DOT SRRSQT    SET SR FOR RECIPROCAL SQUARE ROOT TABLE
        TRA SUBINT    GO TO INTERPOLATION SUBROUTINE
        MPY MFPT      FORM AND SAVE FPT/SQ.RT.FTT
        ALS 8
        STA WGEN
        CLA MFPS
        DOT SRREC     SET SR FOR RECIPROCAL TABLE
        TRA SUBINT    GO TO INTERPOLATION SUBROUTINE
        MPY MFPT      FORM FPT/FPS
        DOT SRFFF     SET SR FOR FUEL FLOW FUNCTION TABLE
        TRA SUBINT    GO TO INTERPOLATION SUBROUTINE
        ALS 8
        MPY WGEN      FORM WF = FPT X F(FPT/FPS)/SQ.RT.FTT
        RJP SUBRET    RETURN
FF8     WOT ANAPDH,1 SET OPCODE ANALOG IN FUEL DIFFERENTIAL PRESSURE HR
        CLA INWORK
        SUB MAN3RC    TEST FOR HIGH RANGE INPUT
        TMI FF10
        ALS 6         YES,DELAY FOR CONVERSION
        DIN INWORK    INPUT FUEL DIFFERENTIAL PRESSURE - HIGH RANGE
        CLA INWORK
        ADD OFFPDH,1 ADD OFFSET
        ALS 7
        STA PAR&3
        SUB LOWPDH,1
        TMI ERROR     UNDER LIMIT
        SUB DIFPDH,1
        TMI FF9
        TRA ERROR     OVER LIMIT
FF9     CLA PAR&3
        MPY SCAPDH,1 SCALE
        STA MFPD      STORE MANIFOLD FUEL DIFFERENTIAL PRESSURE
        TRA FF7

                      CONSTANTS AND WORKING LOCATIONS

MAN3RC OCT            MAXIMUM VALUE OF DIFF. PRESS. INPUT FOR RANGE CHANGE
MAN3TS OCT            CONTENTS OF SECTOR REGISTER FOR MANIFOLD 3
SRFFF  OCT            CONSTANT TO SET SR TO FUEL FLOW FUNCTION TABLE
SRREC  OCT            CONSTANT TO SET SR TO RECIPROCAL TABLE
SRRSQT OCT            CONSTANT TO SET SR TO RECIPROCAL SQUARE ROOT TABLE

INWORK BSS 1          WORKING LOCATION FOR PARAMETER INPUT
MFPT   BSS 1          MANIFOLD FUEL TOTAL PRESSURE
MPPD   BSS 1          MANIFOLD FUEL DIFFERENTIAL PRESSURE
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MFTT    BSS 1         MANIFOLD FUEL TOTAL TEMPERATURE
PAR     BSS 4         WORKING LOCATIONS FOR PARAMETER INPUT
SUBRET  BSS 1         WORKING LOCATION FOR RETURN ADDRESS
WGEN    BSS 1         WORKING LOCATION.

        THE FOLLOWING GROUPS TO BE IN FOUR SEPERATE SECTORS

ANAPT1  OCT           OPCODE SET ANALOG IN MANIFOLD 1A FUEL TOTAL PRESSURE
ANAPD1  OCT           OPCODE SET ANALOG IN MANIFOLD 1A FUEL DIFF. PRESSURE
ANATT1  OCT           OPCODE SET ANALOG IN MANIFOLD 1A FUEL TOTAL TEMP.
LOWPT1  OCT           MINIMUM VALUE FOR MANIFOLD 1A FUEL TOTAL PRESSURE
LOWPD1  OCT           MINIMUM VALUE FOR MANIFOLD 1A FUEL DIFF. PRESSURE
LOWTT1  OCT           MINIMUM VALUE FOR MANIFOLD 1A FUEL TOTAL TEMPERATURE
DIFPT1  OCT           MAX-MIN VALUE FOR MANIFOLD 1A FUEL TOTAL PRESSURE
DIFPD1  OCT           MAX-MIN VALUE FOR MANIFOLD 1A FUEL DIFF. PRESSURE
DIFTT1  OCT           MAX-MIN VALUE FOR MANIFOLD 1A FUEL TOTAL TEMPERATURE
OFFPT1  OCT           OFFSET FOR MANIFOLD 1A FUEL TOTAL PRESSURE
OFFPD1  OCT           OFFSET FOR MANIFOLD 1A FUEL DIFF. PRESSURE
OFFTT1  OCT           OFFSET FOR MANIFOLD 1A FUEL TOTAL TEMP.
SCAPT1  OCT           SCALE FOR MANIFOLD 1A FUEL TOTAL PRESSURE
SCAPD1  OCT           SCALE FOR MANIFOLD 1A FUEL DIFF. PRESSURE
SCATT1  OCT           SCALE FOR MANIFOLD 1A FUEL TOTAL TEMPERATURE

        OCT           OPCODE SET ANALOG IN MANIFOLD 1B FUEL TOTAL PRESSURE
        OCT           OPCODE SET ANALOG IN MANIFOLD 1B FUEL DIFF. PRESSURE
        OCT           OPCODE SET ANALOG IN MANIFOLD 1B FUEL TOTAL TEMP.
        OCT           MINIMUM VALUE FOR MANIFOLD 1B FUEL TOTAL PRESSURE
        OCT           MINIMUM VALUE FOR MANIFOLD 1B FUEL DIFF. PRESSURE
        OCT           MINIMUM VALUE FOR MANIFOLD 1B FUEL TOTAL TEMPERATURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 1B FUEL TOTAL PRESSURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 1B FUEL DIFF. PRESSURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 1B FUEL TOTAL TEMPERATURE
        OCT           OFFSET FOR MANIFOLD 1B FUEL TOTAL PRESSURE
        OCT           OFFSET FOR MANIFOLD 1B FUEL DIFF. PRESSURE
        OCT           OFFSET FOR MANIFOLD 1B FUEL TOTAL TEMP.
        OCT           SCALE FOR MANIFOLD 1B FUEL TOTAL PRESSURE
        OCT           SCALE FOR MANIFOLD 1B FUEL DIFF. PRESSURE
        OCT           SCALE FOR MANIFOLD 1B FUEL TOTAL TEMPERATURE

        OCT           OPCODE SET ANALOG IN MANIFOLD 2 FUEL TOTAL PRESSURE
        OCT           OPCODE SET ANALOG IN MANIFOLD 2 FUEL DIFF. PRESSURE
        OCT           OPCODE SET ANALOG IN MANIFOLD 2 FUEL TOTAL TEMP.
        OCT           MINIMUM VALUE FOR MANIFOLD 2 FUEL TOTAL PRESSURE
        OCT           MINIMUM VALUE FOR MANIFOLD 2 FUEL DIFF. PRESSURE
        OCT           MINIMUM VALUE FOR MANIFOLD 2 FUEL TOTAL TEMPERATURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 2 FUEL TOTAL PRESSURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 2 FUEL DIFF. PRESSURE
        OCT           MAX-MIN VALUE FOR MANIFOLD 2 FUEL TOTAL TEMPERATURE
        OCT           OFFSET FOR MANIFOLD 2 FUEL TOTAL PRESSURE
        OCT           OFFSET FOR MANIFOLD 2 FUEL DIFF. PRESSURE
        OCT           OFFSET FOR MANIFOLD 2 FUEL TOTAL TEMPERATURE
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```
       OCT          SCALE FOR MANIFOLD 2 FUEL TOTAL PRESSURE
       OCT          SCALE FOR MANIFOLD 2 FUEL DIFF. PRESSURE
       OCT          SCALE FOR MANIFOLD 2 FUEL TOTAL TEMPERATURE

       OCT          OPCODE SET ANALOG IN MANIFOLD 3 FUEL TOTAL PRESSURE
       OCT          OPCODE SET ANALOG IN MANIFOLD 3 FUEL DIFF. PRESS. LR
       OCT          OPCODE SET ANALOG IN MANIFOLD 3 FUEL TOTAL TEMP.
       OCT          MINIMUM VALUE FOR MANIFOLD 3 FUEL TOTAL PRESSURE
       OCT          MINIMUM VALUE FOR MANIFOLD 3 FUEL DIFF. PRESSURE LR
       OCT          MINIMUM VALUE FOR MANIFOLD 3 FUEL TOTAL TEMPERATURE
       OCT          MAX-MIN VALUE FOR MANIFOLD 3 FUEL TOTAL PRESSURE
       OCT          MAX-MIN VALUE FOR MANIFOLD 3 FUEL DIFF. PRESSURE LR
       OCT          MAX-MIN VALUE FOR MANIFOLD 3 FUEL TOTAL TEMPERATURE
       OCT          OFFSET FOR MANIFOLD 3 FUEL TOTAL PRESSURE
       OCT          OFFSET FOR MANIFOLD 3 FUEL DIFF. PRESSURE LR
       OCT          OFFSET FOR MANIFOLD 3 FUEL TOTAL TEMPERATURE
       OCT          SCALE FOR MANIFOLD 3 FUEL TOTAL PRESSURE
       OCT          SCALE FOR MANIFOLD 3 FUEL DIFF. PRESSURE  LR
       OCT          SCALE FOR MANIFOLD 3 FUEL TOTAL TEMPERATURE
ANAPDH OCT          OPCODE SET ANALOG IN MANIFOLD 3 FUEL DIFF. PRESS. HR
LOWPDH OCT          MINIMUM VALUE FOR MANIFOLD 3 FUEL DIFF. PRESSURE HR
DIFPDH OCT          MAX-MIN VALUE FOR MANIFOLD 3 FUEL DIFF. PRESSURE HR
OFFPDH OCT          OFFSET FOR MANIFOLD 3 FUEL DIFF. PRESSURE HR
SCAPDH OCT          SCALE FOR MANIFOLD 3 FUEL DIFF. PRESSURE  HR

                    TABLES TO BE IN SEPERATE SECTORS

TABFF  BSS 128      TABLE FOR FUEL FLOW FUNCTION

TABREC BSS 128      TABLE FOR RECIPROCAL

TABRSQ BSS 128      TABLE FOR RECIPROCAL SQUARE ROOT
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COMBUSTOR LIMIT SUBROUTINE MK II

THE LIMIT ERROR IS DETERMINED AS THE DIFFERENCE BETWEEN A COMPUTED PRESSURE RATIO AS A FUNCTION OF MACH AND A MEASURED PRESSURE RATIO. PRIOR TO ENTRY THE SECTOR REGISTER IS SET FOR INPUTTING THE APPROPRIATE PARAMETERS. THE LIMIT ERROR IS SET IN THE ACCUMULATOR ON RETURN

```
SUBCL1 STM SUBRET    SAVE RETURN ADDRESS FOR FIRST ENTRY
       CLA MOC       DETERMINE MAX AND MIN VALUES OF MACH FUNCTION
       DOT SRFCLN    SET SR FOR TABLE FOR F(MO) FOR COMBUSTOR LIMIT MIN.
       TRA SUBTLF    GO TO TABLE LOOK-UP SUBROUTINE - FIRST ENTRY
       STA FNMIN     STORE MINIMUM VALUE
       DOT SRFCLX    SET SR FOR TABLE FOR F(MO) FOR COMBUSTOR LIMIT MAX.
       TRA SUBTLS    GO TO TABLE LOOK-UP SUBROUTINE - SECOND ENTRY
       SUB FNMIN     FORM AND SAVE INCREMENT
       ALS 7
       STA FNINC
       TRA CL1
SUBCL2 STM SUBRET    SAVE RETURN ADDRESS FOR SECOND ENTRY
CL1    DOT SRREQ     SET SR FOR REQUIRED COMBUSTOR
       WOT APPB11,1  SET OPCODE ANALOG IN COMBUSTOR PRESSURE AT PORT 1
       ALS 9         DELAY
       DIN INWORK    INPUT COMBUSTOR PRESSURE AT PORT 1
       WOT APPB12,1  SET OPCODE ANALOG IN COMBUSTOR PRESSURE AT PORT 2
       CLA INWORK
       ADD OFFP11,1  ADD OFFSET
       ALS 7         SHIFT FOR SCALING
       STA PAR       SAVE PARAMETER
       SUB LOWP11,1  SUBTRACT MINIMUM VALUE
       TMI ERROR     UNDER LIMIT
       SUB DIFP11,1  SUBTRACT MAX-MIN VALUE
       TMI CL2
       TRA ERROR     OVER LIMIT
CL2    DIN INWORK    INPUT COMBUSTOR PRESSURE AT PORT 2
       WOT APPB13,1  SET OPCODE ANALOG IN COMBUSTOR PRESSURE AT PORT 3
       CLA INWORK
       ADD OFFP12,1
       ALS 7
       STA PARE1
       SUB LOWP12,1
       TMI ERROR     UNDER LIMIT
       SUB DIFP12,1
       TMI CL3
       TRA ERROR     OVER LIMIT
CL3    DIN INWORK    INPUT COMBUSTOR PRESSURE AT PORT 3
       WOT APPB14,1  SET OPCODE ANALOG IN COMBUSTOR PRESSURE AT PORT 4
       CLA INWORK
       ADD OFFP13,1
```

```
        ALS 7
        STA PAR&2
        SUB LOWP13,1
        TMI ERROR     UNDER LIMIT
        SUB DIFP13,1
        TMI CL4
        TRA ERROR     OVER LIMIT
CL4     DIN INWORK    INPUT COMBUSTOR PRESSURE AT PORT 4
        CLA INWORK
        ADD OFFP14,1
        ALS 7
        STA PAR&3
        SUB LOWP14,1
        TMI ERROR     UNDER LIMIT
        SUB DIFP14,1
        TMI CL5
        TRA ERROR     OVER LIMIT
CL5     CLA PAR
        MPY SCAP11,1 SCALE COMBUSTOR PRESSURE AT PORT 1
        STA PB11,1    SAVE COMBUSTOR PRESSURE AT PORT 1
        STA LOWPAR    SET PRESSURE AT PORT 1 TO BE LOWEST PRESSURE
        CLA ZERO      SET MODIFIER FOR PORT 1
        STA MODIFY
        CLA PAR&1
        MPY SCAP12,1 SCALE
        STA PB12,1    SAVE COMBUSTOR PRESSURE AT PORT 2
        SUB LOWPAR
        TMI CL8       LOWPAR LOWEST PRESSURE
CL6     CLA PAR&2     YES
        MPY SCAP13,1 SCALE
        STA PB13,1    SAVE COMBUSTOR PRESSURE AT PORT 3
        SUB LOWPAR
        TMI CL9       LOWPAR LOWEST PRESSURE
CL7     CLA PAR&3     YES
        MPY SCAP14,1 SCALE
        STA PB14,1    SAVE COMBUSTOR PRESSURE AT PORT 4
        SUB LOWPAR
        TMI CL10      LOWPAR LOWEST PRESSURE
        TRA CL11      YES
CL8     CLA PB12,1    SET PRESSURE AT PORT 2 TO BE LOWEST PRESSURE
        STA LOWPAR
        CLA ONE       SET MODIFIER FOR PORT 2
        STA MODIFY
        TRA CL6
CL9     CLA PB13,1    SET PRESSURE AT PORT 3 TO BE LOWEST PRESSURE
        STA LOWPAR
        CLA TWO       SET MODIFIER FOR PORT 3
        STA MODIFY
        TRA CL7
CL10    CLA PB14,1    SET PRESSURE AT PORT 4 TO BE LOWEST PRESSURE
        STA LOWPAR
```

```
       CLA THREE    SET MODIFIER FOR PORT 4
       STA MODIFY
CL11   CLA INST     SET APPROPRIATE OPCODE ANALOG IN
       ADD MODIFY
       STA CL12
       CLA INST&1   SET APPROPRIATE OFFSET
       ADD MODIFY
       STA CL13
       CLA INST&2   SET APPROPRIATE MINIMUM VALUE
       ADD MODIFY
       STA CL14
       CLA INST&3   SET APPROPRIATE MAX-MIN VALUE
       ADD MODIFY
       STA CL15
       CLA INST&4   SET APPROPRIATE SCALE
       ADD MODIFY
       STA CL17
       DOT SRREQ&1  SET SR FOR REQUIRED COMBUSTOR
CL12   WOT APPB11,1 SET OPCODE ANALOG IN REQUIRED PRESSURE
       CLA LOWPAR   FORM PB/PSTD
       ALS 7
       MPY RPSTD
       DIN INWORK   INPUT REQUIRED PRESSURE
       SUB PRSTMN   FORM PB/PSTD - PB/PSTD(MIN)
       ALS 7
       STA WGEN
       MPY WGEN     FORM 1-((X-XMIN)/(XMAX-XMIN)SQUARED,WHERE X=PB/PSTD
       ALS 7
       MPY RECPBS
       STA WGEN
       CLA ONE
       SUB WGEN
       ALS 7
       MPY FNINC
       ADD FNMIN
       STA WGEN     STORE FORMED FUNCTION OF MACH AND PB
       CLA INWORK   REQUIRED PRESSURE TO ACCUMULATOR
CL13   ADD OFFP11,1 ADD OFFSET
       ALS 7
       STA PAR      SAVE PARAMETER
CL14   SUB LOWP11,1 SUBTRACT MINIMUM VALUE
       TMI ERROR    UNDER LIMIT
CL15   SUB DIFP11,1 SUBTRACT MAX-MIN VALUE
       TMI CL16
       TRA ERROR    OVER LIMIT
CL16   CLA PAR
CL17   MPY SCAP11,1 SCALE
       ALS 7
       STA PAR      SAVE VALUE OF PRESSURE
       CLA LOWPAR   FORM RECIPROCAL OF LOWEST PRESSURE
       DOT SRREC    SET SR TO RECIPROCAL TABLE
```

```
        TRA SUBINT   GO TO INTERPOLATION SUBROUTINE
        ALS 8
        MPY PAR      FORM PB(2)/PB(1)
        ALS 8
        MPY RTTOTS   FORM PB(2)/PB(1) X(SQ.RT. TTO/TSTD)
        STA PAR      STORE
        CLA WGEN     FORM COMBUSTOR LIMIT ERROR
        SUB PAR
        RJP SUBRET   RETURN

                     CONSTANTS AND WORKING LOCATIONS

INST    WOT APPB11,1 INITIAL VALUE OF OPCODE ANALOG IN
        ADD OFFP11,1 INITIAL VALUE OF OFFSET
        SUB LOWP11,1 INITIAL VALUE OF MINIMUM VALUE
        SUB DIFP11,1 INITIAL VALUE OF MAX-MIN VALUE
        MPY SCAP11,1 INITIAL VALUE OF SCALE
PRSTMN  OCT          MINIMUM VALUE OF PB/PSTD
RECPBS  OCT          RECIPROCAL OF PB/PSTD(MAX-MIN)SQUARED(SHIFTED FOR M)
RPSTD   OCT          RECIPROCAL OF STANDARD PRESSURE (SHIFTED FOR MULT.)
RTTOTS  BSS 1        SQ.RT. OF TTO/TSTD COMPUTED IN AIR MASS FLOW ROUTINE
SRFCLN  OCT          CONSTANT TO SET SR FOR F(MO) TABLE  COMB. LIMIT MIN.
SRFCLX  OCT          CONSTANT TO SET SR FOR F(MO) TABLE  COMB. LIMIT MAX.
SRREC   OCT          CONSTANT TO SET SR TO RECIPROCAL TABLE
ZERO    DEC 0        CONSTANT ZERO
ONE     DEC 1        CONSTANT ONE
TWO     DEC 2        CONSTANT TWO
THREE   DEC 3        CONSTANT THREE

FNINC   BSS 1        WORKING LOCATION FOR INCREMENT OF FUNCTION
FNMIN   BSS 1        WORKING LOCATION FOR MINIMUM VALUE OF FUNCTION
INWORK  BSS 1        WORKING LOCATION FOR PARAMETER INPUT
LOWPAR  BSS 1        WORKING LOCATION FOR LOWEST PRESSURE
MODIFY  BSS 1        MODIFIER FOR REQUIRED PRESSURE PORT
PAR     BSS 4        WORKING LOCATION FOR PARAMETER INPUT
WGEN    BSS 1        GENERAL WORKING LOCATION

                     TABLES TO BE IN SEPERATE SECTORS

TABREC  BSS 128      TABLE FOR RECIPROCAL FUNCTION

TABCLN  BSS 128      TABLE FOR F(MO) FOR COMBUSTER LIMIT PB(MIN)/PSTD

TABCLX  BSS 128      TABLE FOR F(MO) FOR COMBUSTER LIMIT PB(MAX)/PSTD
                NOTE A SHALLOW CURVE MAY PERMIT SUFFICIENT ACCURACY WITH
                     ONLY 64 POINTS OR LESS

           THE FOLLOWING GROUPS TO BE IN THREE SEPERATE SECTORS

PB11    BSS 1        COMBUSTOR 1 PRESSURE AT PORT 1
PB12    BSS 1        COMBUSTOR 1 PRESSURE AT PORT 2
```

```
PB13    BSS 1       COMBUSTOR 1 PRESSURE AT PORT 3
PB14    BSS 1       COMBUSTOR 1 PRESSURE AT PORT 4
APPB11 OCT          OPCODE SET ANALOG IN FOR COMBUSTOR 1 PRESSURE PORT 1
APPB12 OCT          OPCODE SET ANALOG IN FOR COMBUSTOR 1 PRESSURE PORT 2
APPB13 OCT          OPCODE SET ANALOG IN FOR COMBUSTOR 1 PRESSURE PORT 3
APPB14 OCT          OPCODE SET ANALOG IN FOR COMBUSTOR 1 PRESSURE PORT 4
DIFP11 OCT          MAX-MIN VALUE FOR COMBUSTOR 1 PRESSURE PORT 1
DIFP12 OCT          MAX-MIN VALUE FOR COMBUSTOR 1 PRESSURE PORT 2
DIFP13 OCT          MAX-MIN VALUE FOR COMBUSTOR 1 PRESSURE PORT 3
DIFP14 OCT          MAX-MIN VALUE FOR COMBUSTOR 1 PRESSURE PORT 4
LOWP11 OCT          MINIMUM VALUE FOR COMBUSTOR 1 PRESSURE PORT 1
LOWP12 OCT          MINIMUM VALUE FOR COMBUSTOR 1 PRESSURE PORT 2
LOWP13 OCT          MINIMUM VALUE FOR COMBUSTOR 1 PRESSURE PORT 3
LOWP14 OCT          MINIMUM VALUE FOR COMBUSTOR 1 PRESSURE PORT 4
OFFP11 OCT          OFFSET FOR COMBUSTOR 1 PRESSURE PORT 1
OFFP12 OCT          OFFSET FOR COMBUSTOR 1 PRESSURE PORT 2
OFFP13 OCT          OFFSET FOR COMBUSTOR 1 PRESSURE PORT 3
OFFP14 OCT          OFFSET FOR COMBUSTOR 1 PRESSURE PORT 4
SCAP11 OCT          SCALE FOR COMBUSTOR 1 PRESSURE PORT 1
SCAP12 OCT          SCALE FOR COMBUSTOR 1 PRESSURE PORT 2
SCAP13 OCT          SCALE FOR COMBUSTOR 1 PRESSURE PORT 3
SCAP14 OCT          SCALE FOR COMBUSTOR 1 PRESSURE PORT 4

        BSS 1       COMBUSTOR 2 PRESSURE AT PORT 1
        BSS 1       COMBUSTOR 2 PRESSURE AT PORT 2
        BSS 1       COMBUSTOR 2 PRESSURE AT PORT 3
        BSS 1       COMBUSTOR 2 PRESSURE AT PORT 4
        OCT         OPCODE SET ANALOG IN FOR COMBUSTOR 2 PRESSURE PORT 1
        OCT         OPCODE SET ANALOG IN FOR COMBUSTOR 2 PRESSURE PORT 2
        OCT         OPCODE SET ANALOG IN FOR COMBUSTOR 2 PRESSURE PORT 3
        OCT         OPCODE SET ANALOG IN FOR COMBUSTOR 2 PRESSURE PORT 4
        OCT         MAX-MIN VALUE FOR COMBUSTOR 2 PRESSURE PORT 1
        OCT         MAX-MIN VALUE FOR COMBUSTOR 2 PRESSURE PORT 2
        OCT         MAX-MIN VALUE FOR COMBUSTOR 2 PRESSURE PORT 3
        OCT         MAX-MIN VALUE FOR COMBUSTOR 2 PRESSURE PORT 4
        OCT         MINIMUM VALUE FOR COMBUSTOR 2 PRESSURE PORT 1
        OCT         MINIMUM VALUE FOR COMBUSTOR 2 PRESSURE PORT 2
        OCT         MINIMUM VALUE FOR COMBUSTOR 2 PRESSURE PORT 3
        OCT         MINIMUM VALUE FOR COMBUSTOR 2 PRESSURE PORT 4
        OCT         OFFSET FOR COMBUSTOR 2 PRESSURE PORT 1
        OCT         OFFSET FOR COMBUSTOR 2 PRESSURE PORT 2
        OCT         OFFSET FOR COMBUSTER 2 PRESSURE PORT 3
        OCT         OFFSET FOR COMBUSTOR 2 PRESSURE PORT 4
        OCT         SCALE FOR COMBUSTOR 2 PRESSURE PORT 1
        OCT         SCALE FOR COMBUSTOR 2 PRESSURE PORT 2
        OCT         SCALE FOR COMBUSTOR 2 PRESSURE PORT 3
        OCT         SCALE FOR COMBUSTOR 2 PRESSURE PORT 4

        BSS 1       COMBUSTOR 3 PRESSURE AT PORT 1
        BSS 1       COMBUSTOR 3 PRESSURE AT PORT 2
        BSS 1       COMBUSTOR 3 PRESSURE AT PORT 3
```

```
BSS 1          COMBUSTOR 3 PRESSURE AT PORT 4
OCT            OPCODE SET ANALOG IN FOR COMBUSTOR 3 PRESSURE PORT 1
OCT            OPCODE SET ANALOG IN FOR COMBUSTOR 3 PRESSURE PORT 2
OCT            OPCODE SET ANALOG IN FOR COMBUSTOR 3 PRESSURE PORT 3
OCT            OPCODE SET ANALOG IN FOR COMBUSTOR 3 PRESSURE PORT 4
OCT            MAX-MIN VALUE FOR COMBUSTOR 3 PRESSURE PORT 1
OCT            MAX-MIN VALUE FOR COMBUSTOR 3 PRESSURE PORT 2
OCT            MAX-MIN VALUE FOR COMBUSTOR 3 PRESSURE PORT 3
OCT            MAX-MIN VALUE FOR COMBUSTOR 3 PRESSURE PORT 4
OCT            MINIMUM VALUE FOR COMBUSTOR 3 PRESSURE PORT 1
OCT            MINIMUM VALUE FOR COMBUSTOR 3 PRESSURE PORT 2
OCT            MINIMUM VALUE FOR COMBUSTOR 3 PRESSURE PORT 3
OCT            MINIMUM VALUE FOR COMBUSTOR 3 PRESSURE PORT 4
OCT            OFFSET FOR COMBUSTOR 3 PRESSURE PORT 1
OCT            OFFSET FOR COMBUSTOR 3 PRESSURE PORT 2
OCT            OFFSET FOR COMBUSTOR 3 PRESSURE PORT 3
OCT            OFFSET FOR COMBUSTOR 3 PRESSURE PORT 4
OCT            SCALE FOR COMBUSTOR 3 PRESSURE PORT 1
OCT            SCALE FOR COMBUSTOR 3 PRESSURE PORT 2
OCT            SCALE FOR COMBUSTOR 3 PRESSURE PORT 3
OCT            SCALE FOR COMBUSTOR 3 PRESSURE PORT 4
```

APPENDIX H

POWER SUPPLY STATUS

APPENDIX H

POWER SUPPLY STATUS

SUPPLIES USING 28-VDC AIRCRAFT POWER (+15-V, -15-V, AND +25-V SUPPLIES)

The initial breadboard was functionally and environmentally tested with satisfactory test results. Then the final breadboard was constructed, and passed through functional testing with excellent results. However, no environmental testing was completed.

The final breadboard unit is shown in Figure H-1 and Figure H-2.

SUPPLIES USING 115-VAC SINGLE-PHASE AIRCRAFT POWER (REFERENCE SUPPLIES)

The final breadboard was built in a box of the same size as assigned for the proposed engine layout. The functional testing and the environmental tests were satisfactorily completed.

Figure H-3 shows an internal picture of the final breadboard unit.

Figure H-4 shows the final breadboard of the reference supplies closed up and in final configuration.

SUPPLY USING 115-VAC THREE-PHASE AIRCRAFT POWER (+5-V LOGIC SUPPLY)

Figure H-5 shows the initial breadboard, which was functionally and environmentally tested with acceptable results.

The final breadboard, shown in Figure H-6 and Figure H-7 passed the functional test specifications, but environmental testing was never initiated.

SUPPLY MONITORING, LEVEL DETECTION, AND TURN ON/OFF SEQUENCING

For this portion the initial breadboard of the interrupt level detector, the output failure monitoring, and the sequencing timing board were completed and tested. The final breadboards of the interrupt level detector and the output failure monitoring were built and functionally tested. None of the other circuits were started.

TEST RACK ASSEMBLY

In this area the power supply case was constructed for the final breadboard console. The 5-v logic supply and the +15-v, -15-v, and +25-v supply were mounted in the case. A picture of the case is shown in Figure H-8 with some units in place. The construction shown here was adopted to provide adequate EMI shielding and heat sinking.

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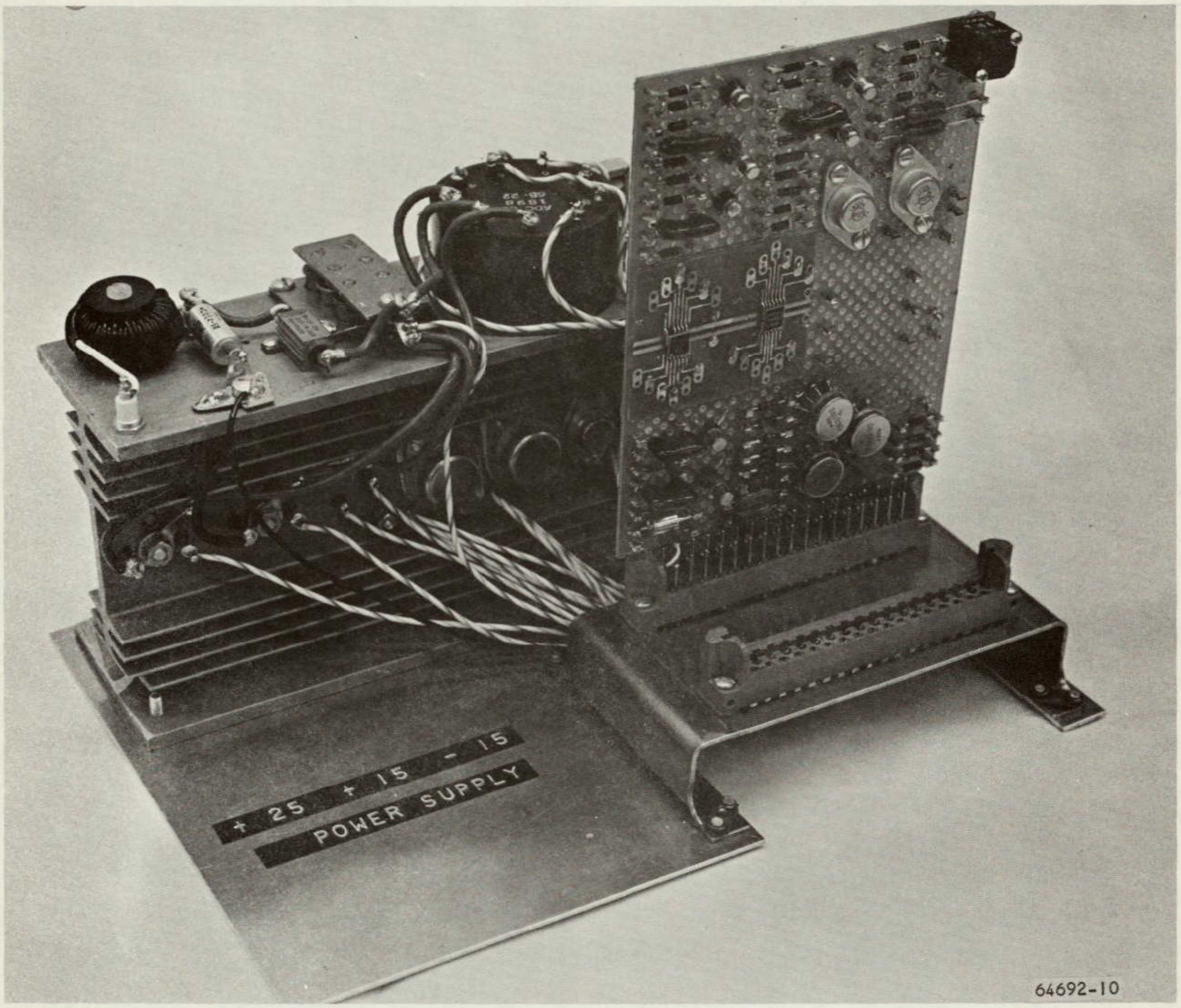

Figure H-1. Supplies Using 28-vdc Aircraft Power. +15-v, -15-v, and +25-v Supplies Final Breadboard Unit (Front View)

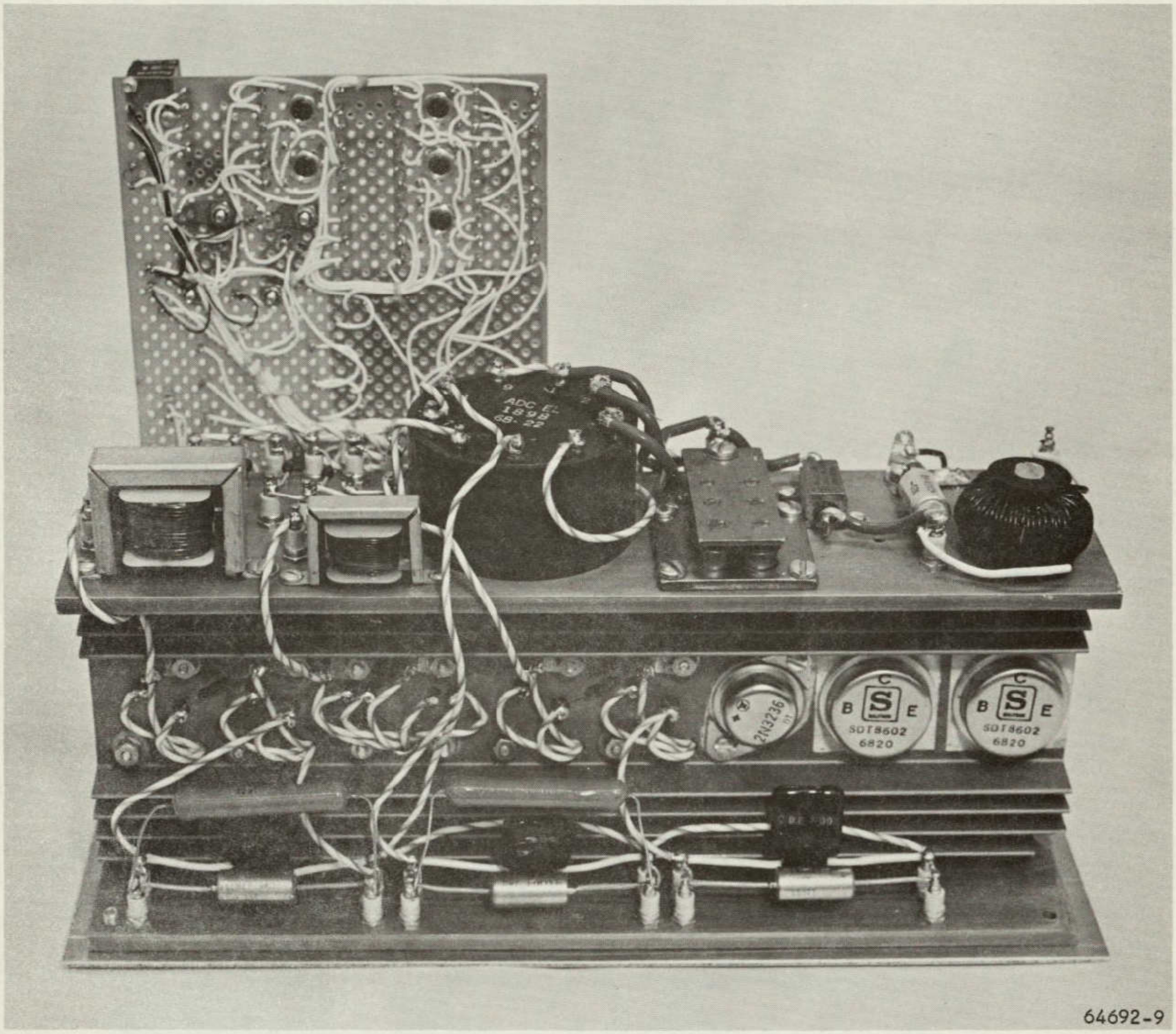

Figure H-2. Supplies Using 28-vdc Aircraft Power. +15-v, -15-v, and +25-v Supplies Final Breadboard Unit (Rear View)

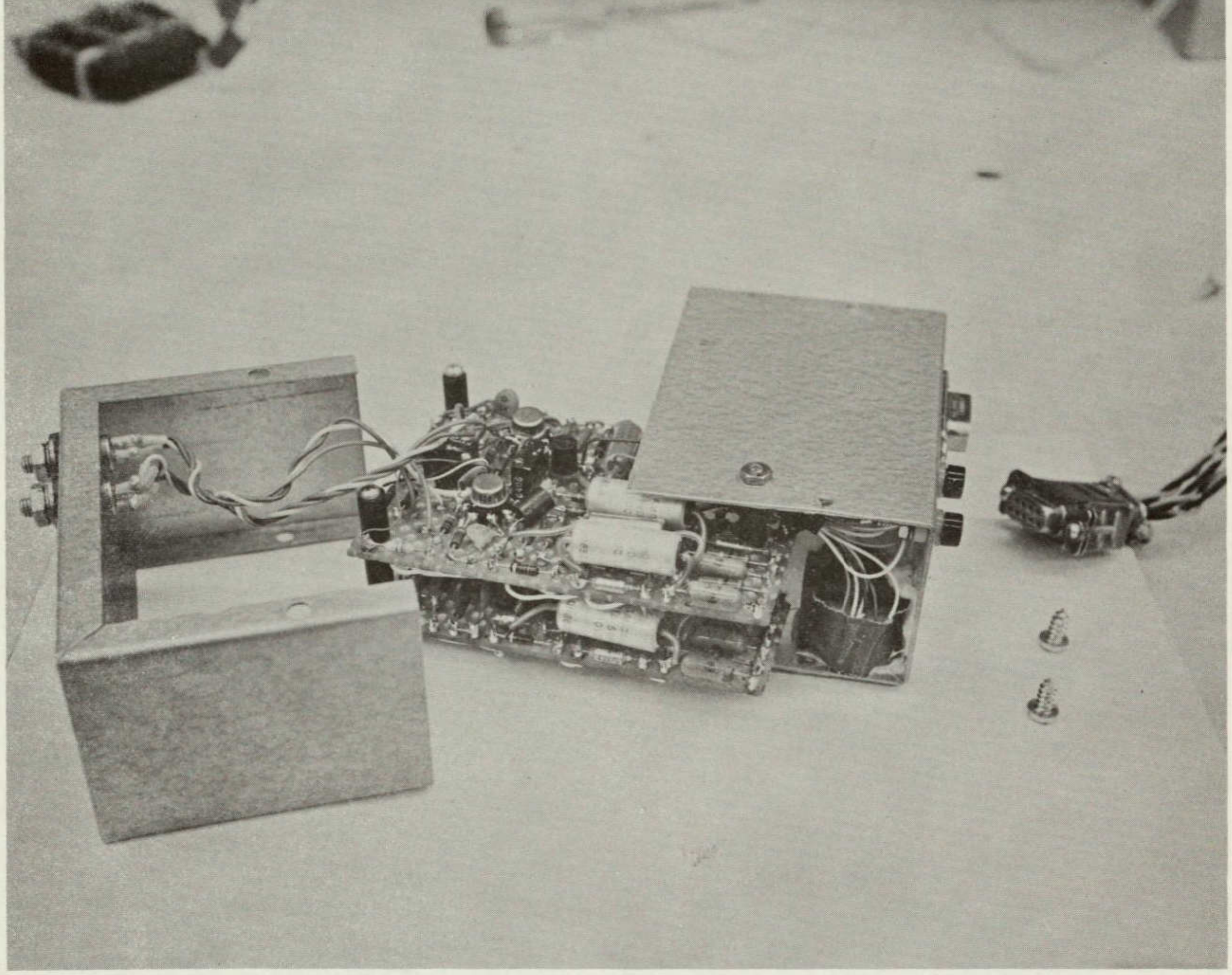

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Figure H-3. HRE Reference Supplies Final Breadboard Box

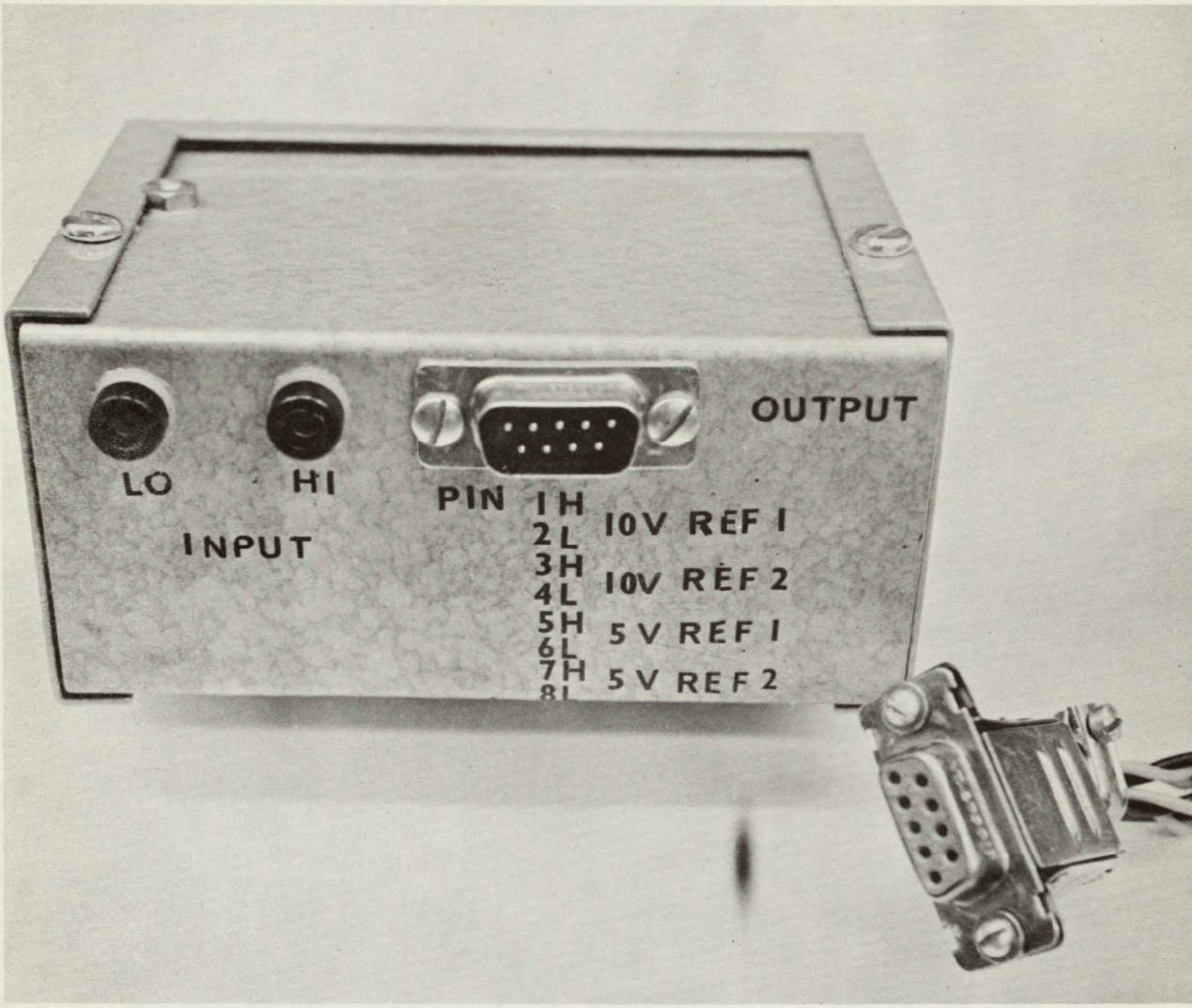

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Figure H-4. HRE Reference Supplies Final Breadboard Box

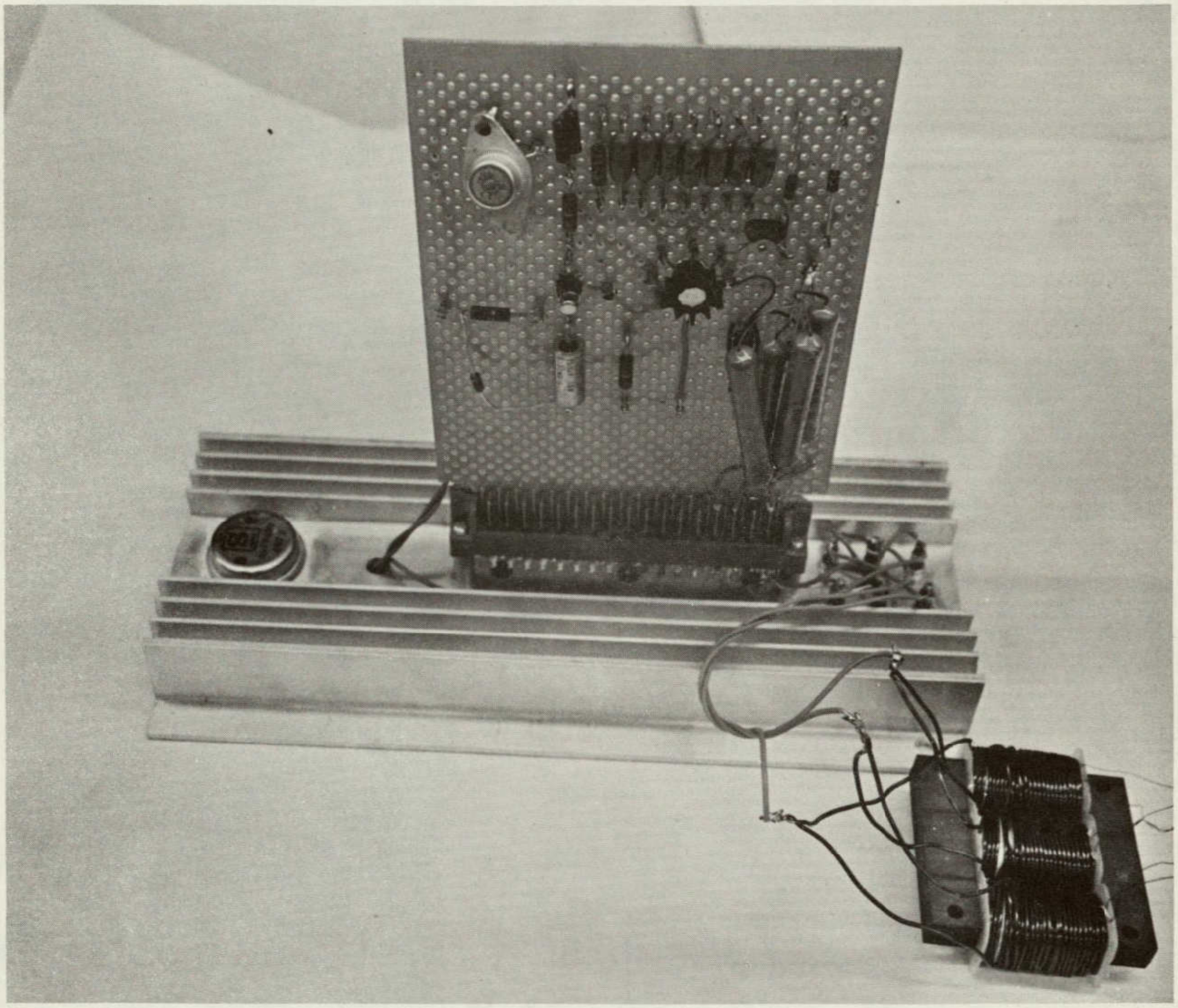

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Figure H-5. 5-V Logic Supply Initial Breadboard

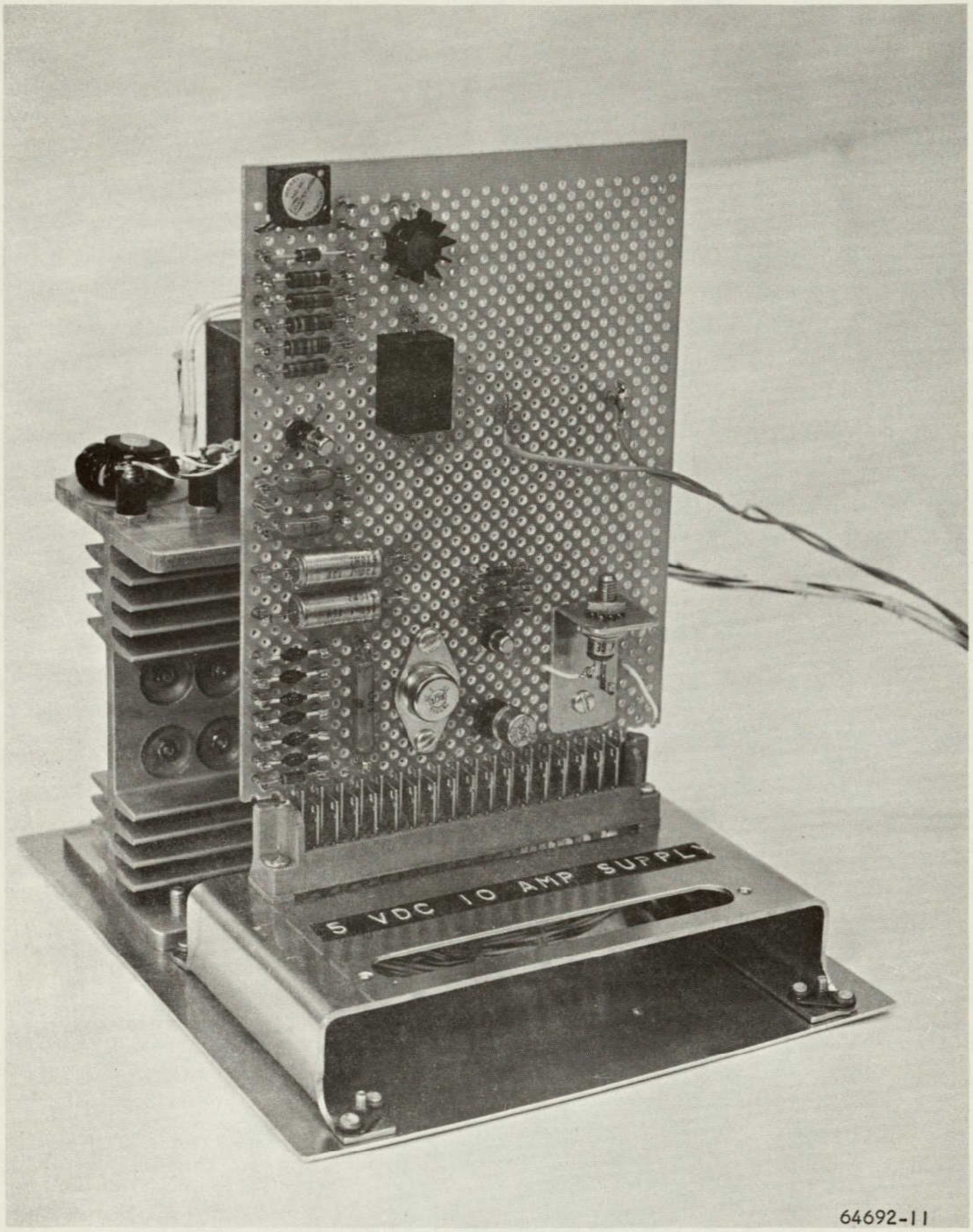


Figure H-6. 5-V Logic Supply Final Breadboard

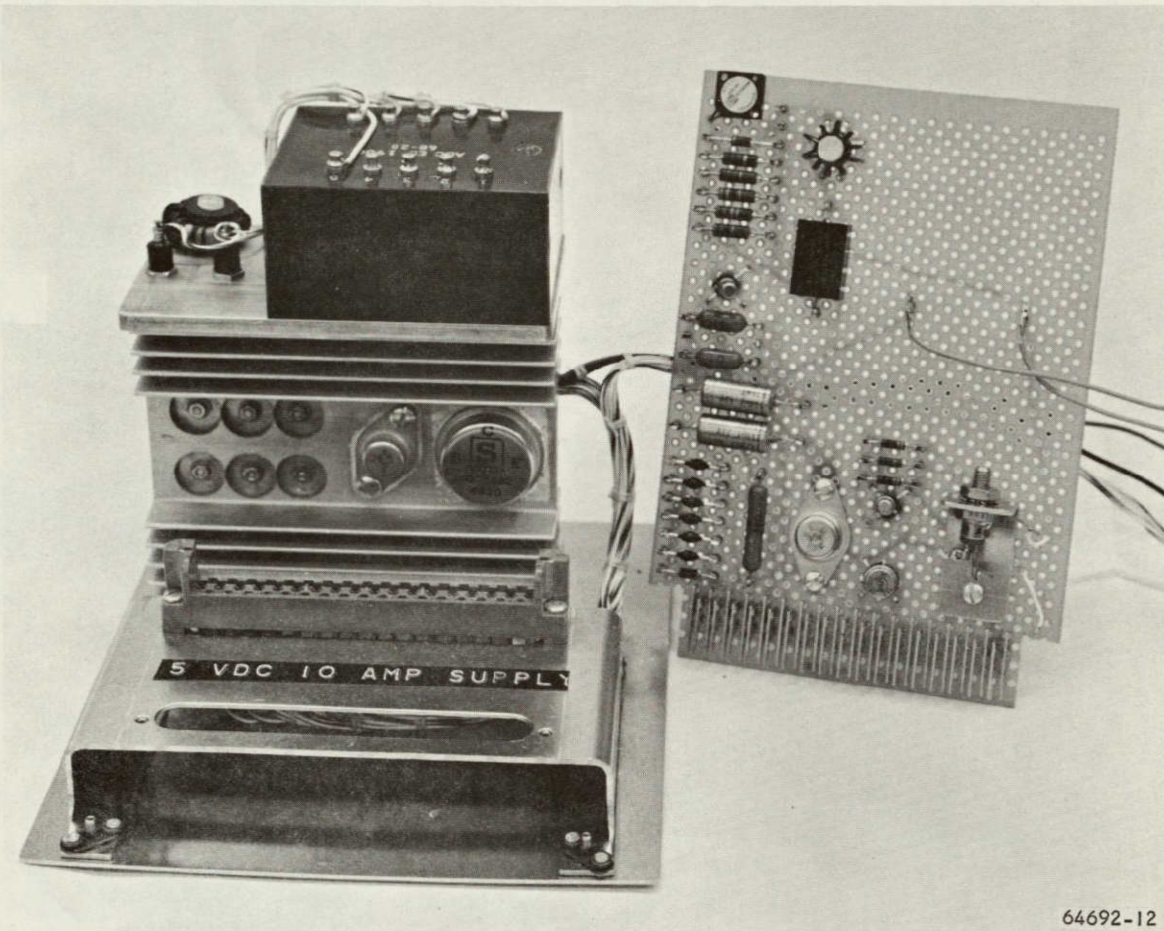


Figure H-7. 5-V Logic Supply Final Breadboard

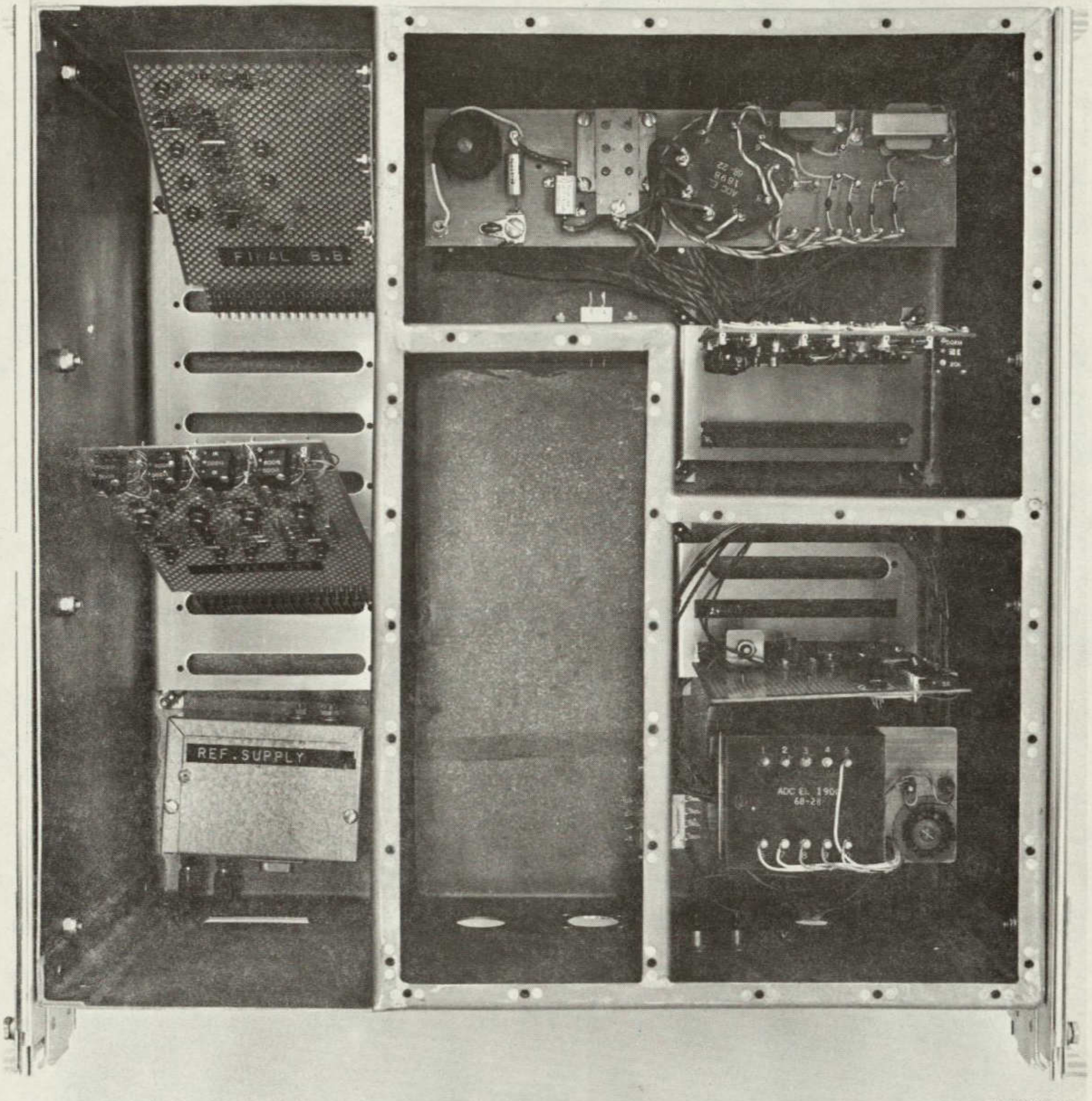


Figure H-8. HRE Final Test Panel Power Supply Case

CONCLUSIONS

All main supplies and parts of the monitoring section were finished. About 80 percent of the overall effort was completed at termination of the program.

APPENDIX I

CIU ELECTRONICS STATUS

APPENDIX I

CIU ELECTRONICS STATUS

SYSTEM BREADBOARD STATUS

System breadboards 5, 6, and 7 are at the following status.

Breadboard No. 5

This has all the electronics associated with the spike loop electronics. The board has been completely fabricated and has the correct parts, except some lower-accuracy components (which are to be trimmed) have been substituted for the various high-accuracy scaling resistors required in the final article. As yet the board has not had power applied to it. Most of the circuitry has been functional on other preliminary breadboards, but no temperature testing was performed at that time.

Breadboard No. 6

This board performs the signal conditioning necessary for low-level signals originating in pressure transducers and thermocouples. It provides the required low-level multiplexing at the inputs to the various amplifiers, the output multiplexing for entry into the ADC. The writing has been completely fabricated but the semiconductor transistors amd amplifiers have not been inserted. No power has been applied and no temperature testing performed.

Previously, a two channel pressure conditioning amplifier was tested functionally at room temperature on a preliminary breadboard. For the system breadboard, low-tolerance scaling resistors have been substituted temporarily for the high accuracy ones required in the pressure amplifiers, and the thermocouple amplifier.

Breadboard No. 7

This breadboard is in two sections, and due to recent system concept changes, fabrication is not complete. The first board has been completed, and contains the reference supply, ADC, high-level multiplexer, multiplexed DAC output multiplexer, the fuel valve drive circuits, and the remote input buffer with its associated multiplex switch. As yet, the attenuator for the remote inputs has not been added. About 80 percent of this circuitry has been functional and has shown satisfactory operation at room temperature.

The second board, which has not been fabricated, will contain the following:

(a) Four individual DACs with output buffer amplifier

(b) Two output hold circuits

(c) Submultiplexer for monitoring the four main DC supply voltages (scaled)

(d) Two-channel, two-pole multiplexer for the monitoring of the 10 v excitation supplies for the pressure transducers

SENSORS AND LOADS

The sensors and loads interfacing with the fuel control loop are as follows:

(a) LVDT

(b) Pressure transducers

(c) Thermocouples and cold junction compensator

(d) Fuel control values

(e) Spike value (hydraulic valve)

The above items require a specification and adequate characteristization to assure compatible performance with the fuel control loop electronics. Status on these items is as follows:

LVDT

This sensor has been adequately specified (AiResearch Source Control Drawing No. 981156). The specification reflects compatible performance with the electronics. As yet, no characterization testing has been performed on a unit although some vendor data is available.

Pressure Transducer

Only the electrical parameter portion of the specification has been written in preliminary form, and indicates compatible performance with the electronics.

Thermocouple and Cold Junction Compensation

A preliminary specification has been written, but is not as yet in source control drawing format. Some characterization has been performed (on a similar device used in the temperature control loop) and this has indicated satisfactory operation for the tests thus far performed.

Fuel Control Valve

Characterization and formal specification of this item is pending information and a sample valve unit from AiResearch, Phoenix.

Spike Valve

A preliminary specification in source control drawing format (AiResearch drawing No. 981160)exists. The specification is to be finalized pending completion of characterization with proper hydraulic loading.

APPENDIX J

THERMOCOUPLE SIGNAL CONDITIONING AMPLIFIER

APPENDIX J

THERMOCOUPLE SIGNAL CONDITIONING AMPLIFIER

GENERAL REQUIREMENTS

1. Eight thermocouples are required to be conditioned

	Normal Operate Range	Reduced Temp
4 thermocouples	340° to 1250 $^\circ$F	-65° to $+200^\circ$F

Approx. 10°F max error satisfactory on these channels in normal operate mode. 20°F for reduced temperature these channels are assigned to the manifolds.

	Normal Operate Range	Reduced Temp
4 thermocouples	200° to 400°F	-65° to $+200^\circ$F

Approx. 15°F max error satisfactory on these channels. For normal operate mode 20°F for reduced temp. These channels presently unassigned. Above errors include the thermocouple, cold junction compensator, multiplexer, and conditioning amplifier, and A-D converter

2. Cold junction compensator will operate from a +5-v isolated supply - accuracy 0.2 percent.

3. Hot junctions for thermocuples are chromel-constantan in all cases.

4. Offsetting of thermocouple signal, and scaling can be performed by computer. However, the necessity for scaling correction by computer should be avoided if possible.

5. Thermocouple and cold junction compensators have the following specifications.

   a. Impedance + to - outputs : 50Ω $\pm 5\Omega$

   b. Nominal output of compensator and cold and hot junctions combination at 32°F on hot junction to be zero volts (temperature of cold junctions and compensator bridge -55°C to $+125^\circ$C)

   c. Output accuracy - cold junctions and compensator temp range -55°C to $+125^\circ$C, hot junction -65°F to 1250°F, error 2.5 $^\circ$F This error is tracking error of compensator of cold junction.

d. Bridge excitation, 5 v isolated

e. Bridge dissipation 5 mw max with 5 v excitation

From Figure J-1.

$$V_o = V_1 + \left[V_1 - V_4 \frac{R9}{R8 + R9}\right] \frac{(R8 + R9)}{R8R9} \quad R2$$

$$V_4 = - V_2 \left[1 + R4/R5 \right] \frac{R6}{R3} - V_{REF} \frac{R6}{R_X}$$

$$\therefore V_o = V_1 \left[1 + R2 \frac{(R8 + R9)}{R8R9} \right]$$

$$+ \frac{R2}{R8} \left[V_2 \left(1 + R4/R5 \right) \frac{R6}{R3} + V_{REF} \frac{R6}{R_X} \right]$$

$$= V_1 \left[1 + \frac{R2}{\frac{R8R9}{R8 + R9}} \right] + \frac{R2}{R8} \left[V_2 \left(1 + \frac{R4}{R5} \right) . \frac{R6}{R3} + V_{REF} \frac{R6}{R_X} \right]$$

Let $V_1 = V_s + V_{T2}$

where V_s = total signal generated by hot junction

V_{T2} = signal due to cold junction

$$\therefore V_o = (V_s + V_{T2}) \left[1 + \frac{R2}{\frac{R8R9}{R8 + R9}} \right]$$

$$+ V_2 \left(1 + \frac{R4}{R5} \right) \left(\frac{R6}{R3} \right) \left(\frac{R2}{R8} \right) + V_{REF} \frac{R6}{R_X} \cdot \frac{R2}{R8}$$

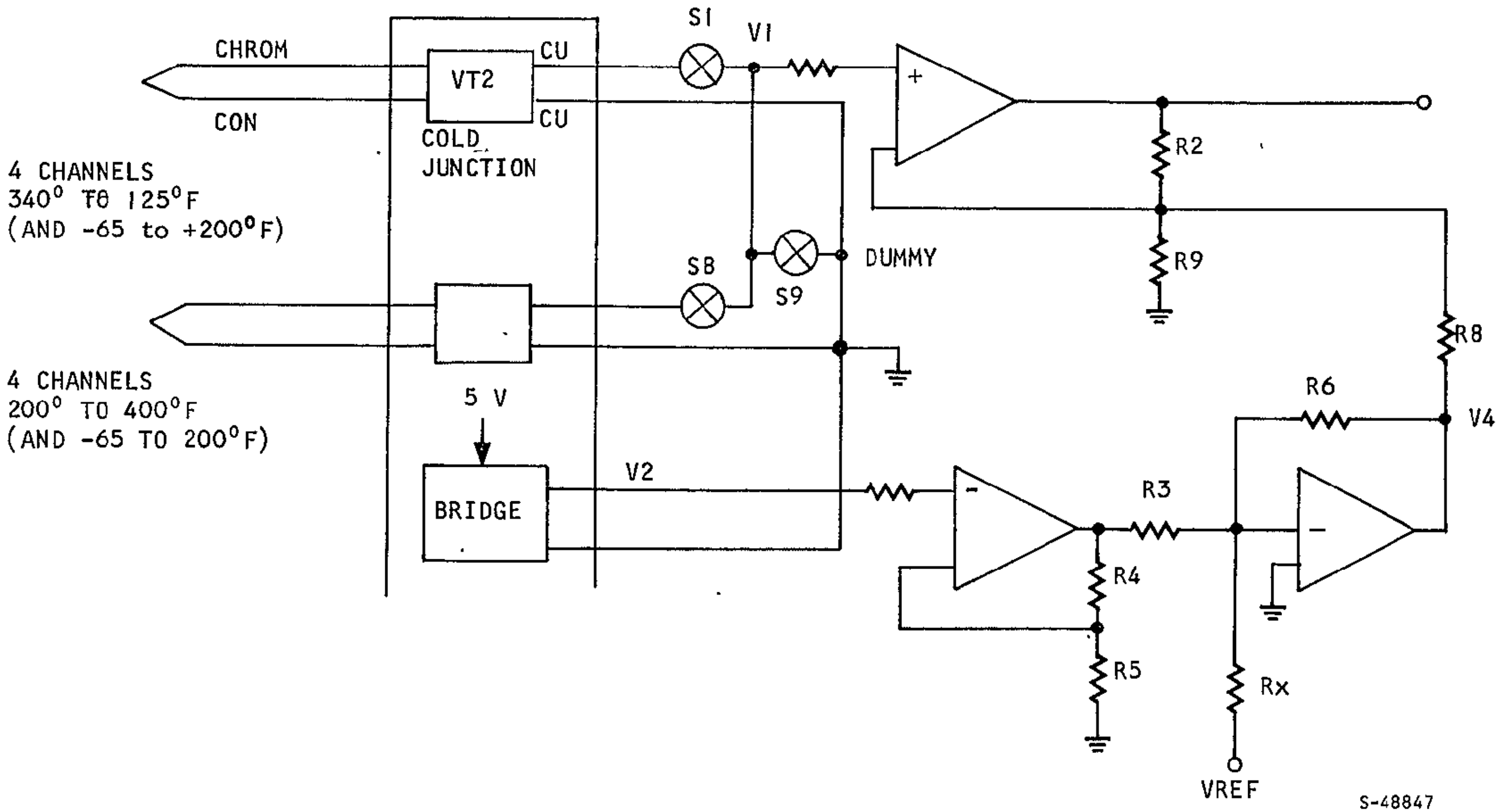


Figure J-1. Thermocouple and Cold Junction Compensator

TRADEOFFS (FOUR MECHANIZATIONS CONSIDERED)

1. Offset not performed by computer. For this configuration, offsetting is performed in an analog manner, and switches must be provided for an offset for normal operation and for reduced temperature operation.

   It also requires generation of a negative reference.

2. Temperature ranges for both cases to be separated (in each range, and its corresponding offset to be full range to ADC).

   For this configuration the computer requires to offset, and analog offset switching will be required for lower temperature range. Advantage is that low temperature range is more accurate than Method 4.

3. Use a fixed bias in system to assure input to ADC always positive. Computer does no offsetting, and a single scale factor use over entire temperature range encompassing low and high ranges.

   For this case, the nonlinearity error of thermocouple becomes unacceptable (about 15°F to 18°F for this along).

4. Fix bias in system for assurance of positive voltage to ADC. Let computer perform conversion of entire temperature range. Computer then will subtract out system bias and perform scaling, depending on which temperature range the signal occurs. Note ranges are distinguished by a test mode signal.

Method 4 is the one selected for mechanization. Estimated error is

for	340°F to 1250°F	Error $<$12°F
	-65°F to 200°F	Error $<$15°F

SCALING SELECTION

since

$$V_o = \left(V_s \qquad +V_{T_2}\right) \left[\quad + \frac{R2}{\frac{R8R4}{R8+R4}} \right]$$

$$+ V_2 \left(1 + R4/R5\right) \frac{R6}{R3} \frac{R2}{R8} + V_{REF} \frac{R6}{R_X} \frac{R2}{R8}$$

let R2 = R8, & R6 = R3, & 1 + R4/R5 = K (Figure J-1)

$$\therefore V_o = \left(V_s \qquad +V_{T_2}\right) \left[K\right] \quad +V_2 K \quad +V_{REF} \frac{R6}{R_X}$$

Since the cold junction (V_{T_2}) is compensated by the compensation bridge (V_2) then $V_{T_2} = -V_2$

and $V_o = V_s K \qquad +V_{REF} \frac{R6}{R_X}$

Let $V_s = \left|V_s^+\right| + \left|V_s^-\right|$

where V_s^+ = positive signal range of signal

V_s^- = negative signal range of signal

$$- V_o = V_s^+ K + V_s^- K + V_{REF} \frac{R6}{R_X}$$

for $-65^0F \quad V_s^- = -3.026$ mv

$+1250^0F \quad V_s^+ = 51.27$ mv

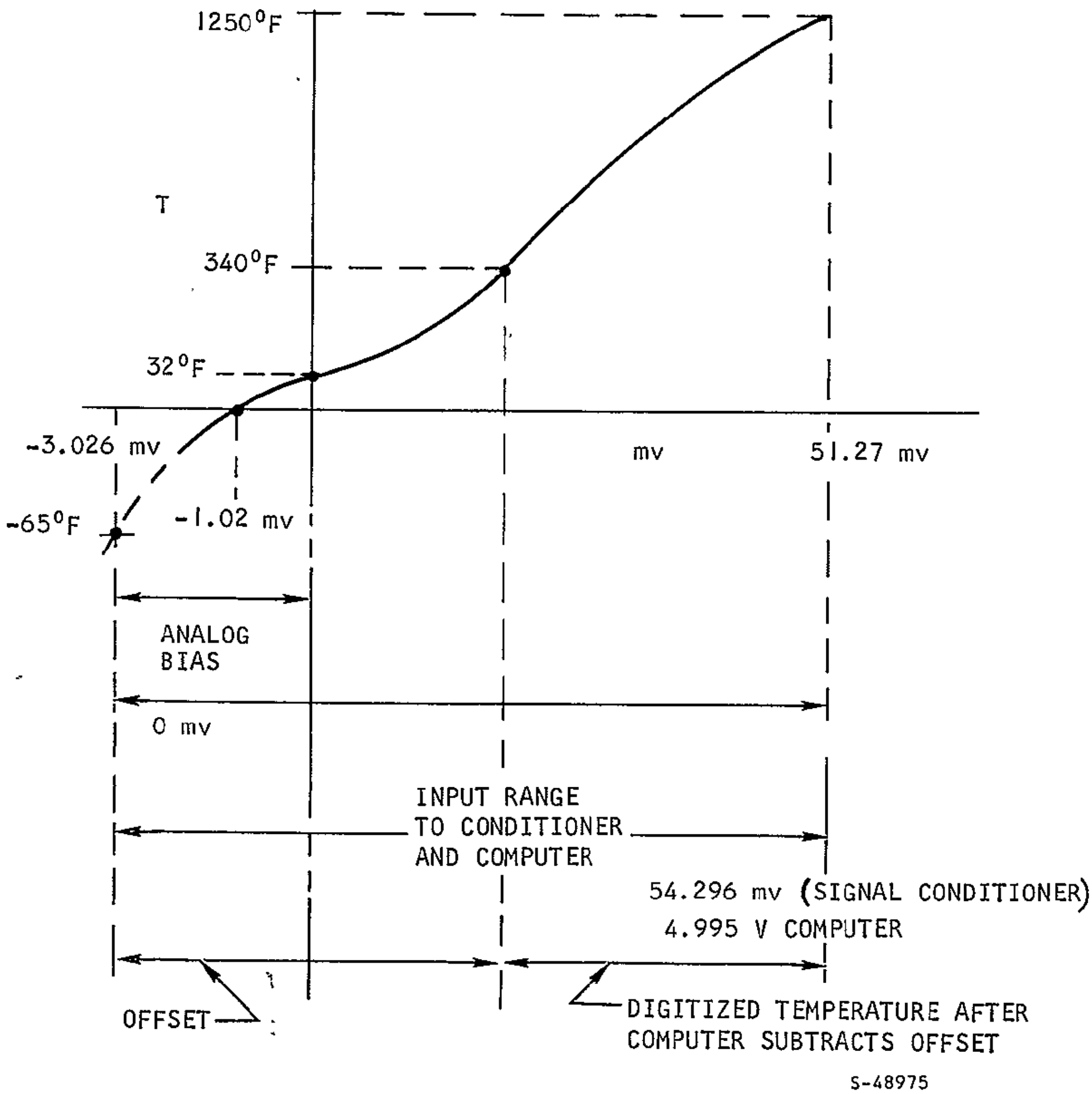
when $V_s^+ = 0$, $V_s^- = 3.026$ mv V_o is to be 0

$$\therefore \quad 0 = -3.026\ K + V_{REF} \frac{R6}{R_X}$$

$$\frac{R6}{R_X} = \frac{3.026\ K}{V_{REF}}$$

$$R_X = R6 \frac{V_{REF}}{3.026\ K} \qquad V_{REF} \text{ in mv}$$

For the fourth method, the functions of circuitry and computer are shown graphically.



With an amplifier gain, K, of 91 (resistor ratio = 90), the computer ADC will accommodate an input range of $\frac{4.995}{91} \times 1000$ mv = 54.890 mv to the signal conditioner.

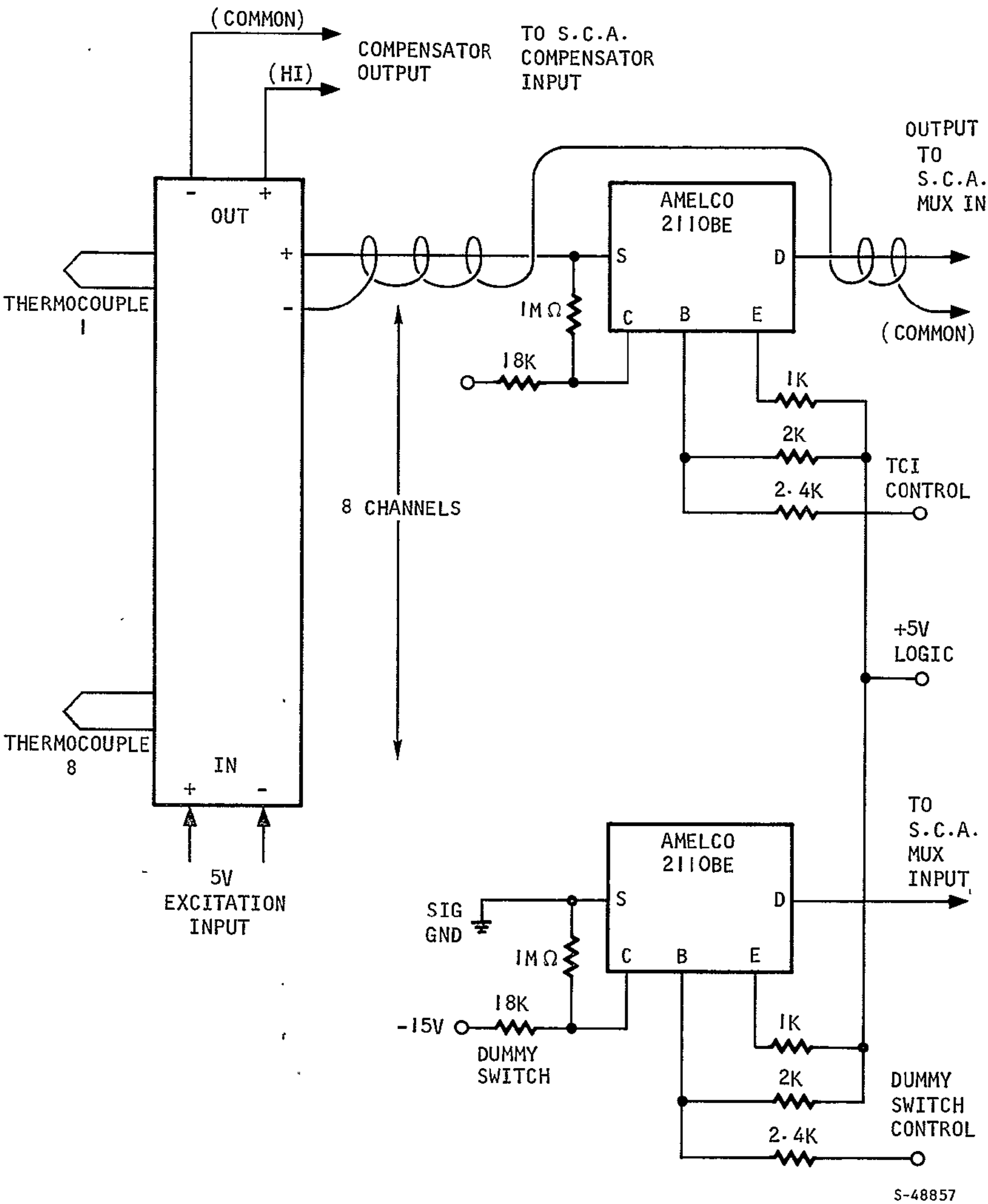


Figure J-2. Thermocouple Low-Level Multiplexer

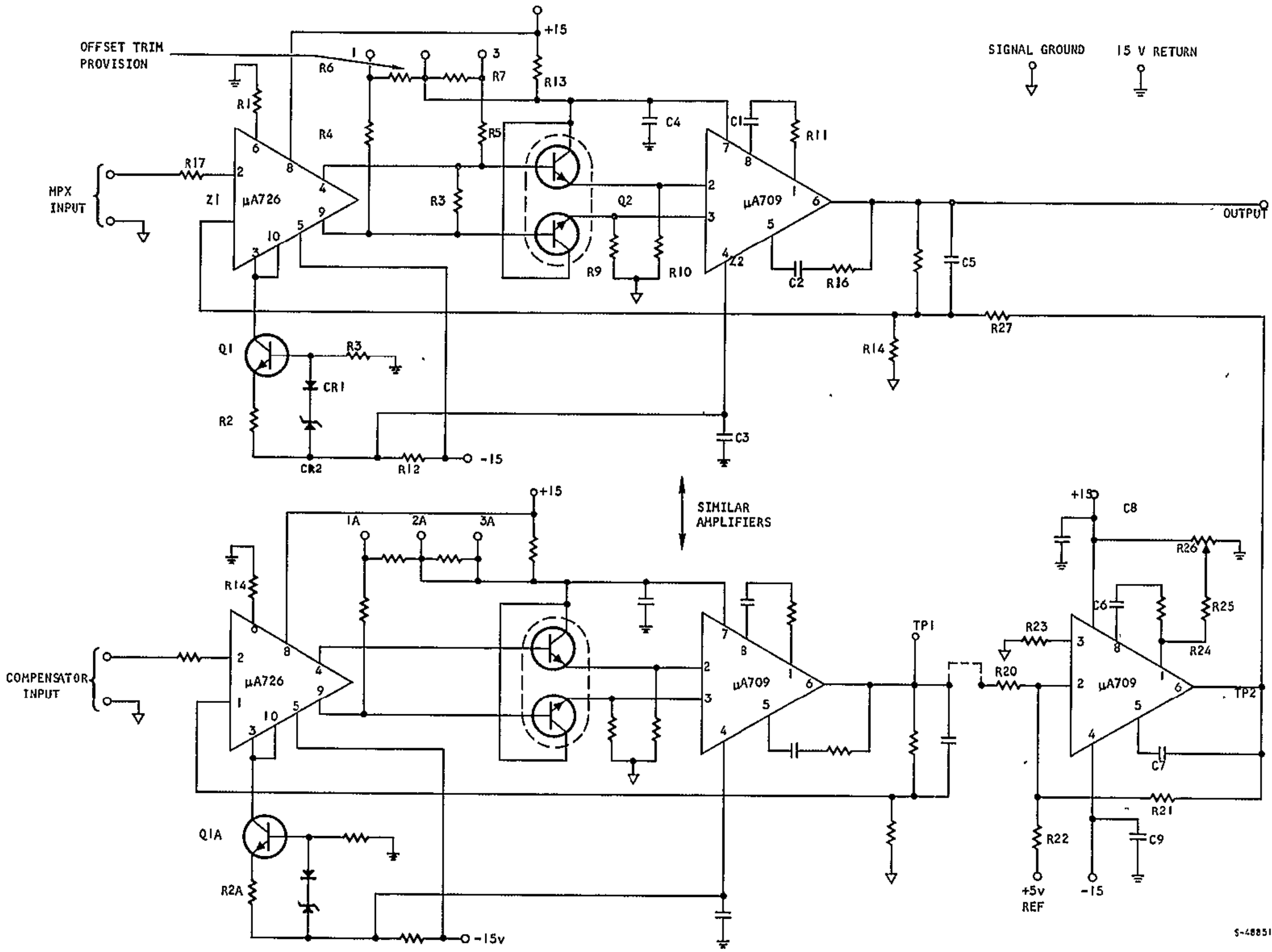


Figure J-3. Thermocouple Signal Conditioning Amplifier

PARTS LIST FOR THERMOCOUPLE SIGNAL CONDITIONING AMPLIFIER

R1, R1A	62 K 1%	
R2, R2A	200 K .1%	
R3, R3A	7.5 K 1%	
R4, R5, R4A, R5A	590 K 1%	
R6, R6A, R7, R7A	100 K 1%	
R8, R8A	200 K 1%	
R9, R10, R9A, R10A	200 K 1%	
R11, R11A	1.5 K 1%	
R12, R13, R12A, R13A	100 Ω 5%	
R15	9 K 1%	Ratio $\frac{R15}{R14}$ = 90 ±0.02% TC Match ±8 ppm/°C
R14	100 Ω 1%	
R15A, R27	9 K 1%	Ratio $\frac{R15A}{R14A}$, $\frac{R27}{R14A}$ = 89 ±0.02% TC Match ±8 ppm/°C
R14A	100 Ω 1%	
R16, R16A	1 K 5%	
R17, R17A	47 Ω 5%	
R20, R21	9 K 1%	Ratio 0.02% TC Match ±8 ppm/°C
R22	163.4 K 1% Matched to R_{20}	Ratio 18.55 ±0.2% TC ±10 ppm/°C
R23	4.7 K 5% 1/4 w	
R24	1.5 K 5%	
R25	200 K 1%	
R26	Trimmed Value	
Q1, Q1A	2N3717	
Q2, Q2A	2N4044	

CR1,CR1A	1N914
CR2,CR2A	1N4572A
Z1,Z1A	μA726
Z2,Z2A,Z3	μA709
C1,C1A	1000 pf
C2,C2A	100 pf
C6	2700 pf
C7	100 pf
C3,C4,C3A,C4A,C8,C9	1 μf
C5,C5A	300 pf MICA

APPENDIX K

ERROR BUDGETS

APPENDIX K

ERROR BUDGETS

ADC-DAC ERROR BUDGET

ADC Error Budget (From Hi Level Mux Input)

	Percent
Reference Supply	0.1
Comparator (initially zeroed)	0.1
Ladder 10 Bit	0.05
Ladder Switch	0.03
High Level Mux	0.02 - (up to 30 channels using G118F)
RSS =	0.15 percent
Quantizing Error	0.1 percent
Total Error =	0.25 percent

DAC Error Budget (up to Buffer Amp Output)

	Percent
Reference Supply	0.1
Ladder	0.05
Ladder Switch	0.03
Buffer Amplifier (initially zeroed)	0.1
RSS =	0.15 percent

Pressure Sensor Channels Budget - Excluding Sensor

		Percent
1.	Bridge Excitation	0.2
2.	Low Level Mux	0.2
3.	Amplifier	0.3
4.	ADC	0.25
	RSS ≃	0.5 percent
5.	Transducer Error (estimate with Δ Temp 120°F)	0.85 percent
	Total Error RSS ≃	1 percent

Thermocouple Channel Error Budget - Normal Operate Range

Compensator Excitation (0.2 percent accurate) 0.07 percent

Amplifier	1	0.3	
	2	0.3	
	3	0.1	
	Bias	0.03	
RSS ≃		0.45 percent	0.45 percent
ADC ≃			0.25 percent
		RSS ≃	0.75 percent ≃6.5°F of 1300°F

Thermocouple Curve Nonlinearity (Bias Selection) . . . . 5°F
(This is a single straight line approximation.)

Other Thermocouple Errors

Cold Junction (fixed channel) 2°F

Cold Junction Channel to Channel 1°F

Hot Junction Mux

(100°C operation

8 channel Amelco 2108B or 2118B) - 0.15 percent - 1.5°F

RSS Random Error = $\sqrt{6.5^2+2^2+1^2+1.5^2}$ = 7°F

Total Error = Random + fixed nonlinearity

= 7° + 5°

≈ 12°F

This is 2°F higher than originally budgeted (can be reduced by selecting a curve fit to thermocouple by 2 lines instead of 1).

Error for reduced temperature operation will be higher (budget breakdown not available at this time).

SPIKE LOOP ELECTRONIC ERROR BUDGET

Percentages are referred to full travel of spike (approximately 5.5 inch).

Circuit	(May 22) Initial Budget, Percent RSS	Design Result, Percent RSS
LVDT Buffer Amp	0.1	0.06
LVDT Demodulator	0.2	0.15
LVDT Filter	0.1	0.1
	0.25	0.2
Spike Hold Amp (100 pps minimum)	0.2	0.1
Invert Amp	0.1	0.1
Sum Amp	0.1	0.1
A/D Conversion	0.25	0.25
	0.33	0.27
Oscillator (Amp 0.5 percent)	0.25	0.25
(Distortion 1 percent 3rd, 0.5 percent 5th)	0.2	0.05
	0.33	0.26

LVDT Linearity	0.4	0.4
*Scale Factor $\Delta T = 20^{0}F$	0.1	0.16
(Δf = 2 percent) Frequency Change (attenuation)	0.1	0.1
Hysteresis	0.05	None
Loading (input & output)	0.1	0.1
Phase Error	--	included in demod calc
Harmonic Distortion	0.1	0.03
*Null Shift $\Delta T = 20^{0}F$	0.1	0.16
	0.46	0.49
Total Error percent RSS ≃	0.7 percent	≃ 0.7 percent

*Computer Compensation Included

APPENDIX L

TEMPERATURE CONTROL BREADBOARD STATUS

APPENDIX L

TEMPERATURE CONTROL BREADBOARD STATUS

This appendix documents the present status of the final breadboard circuitry for the temperature control. Included are

(a) A chart showing the status of each plug-in board (Figure L-1)

(b) A diagram showing the function of each board (Figure L-2)

(c) Diagrams of the breadboard interconnections (these have not been checked) (Figures L-3, L-4, and L-5)

(d) Final wiring diagrams for all breadboard (Note: These diagrams represent the finished wiring scheme, and not necessarily the present status of the breadboard circuitry.) (Figures L-6 through L-14)

(e) Photographs of all breadboards (Figures L-15 through L-18)

Board Designation (As Marked on Final Breadboards)	Modification Status	Circuitry Schematic Complete to Date	Layout Drawing Complete	Pins Installed in Board	Wiring Complete	Components Installed	Functional Testing Completed	Additional Comments
J1	up to date	Yes	Yes	Yes	Yes	Yes	Yes	Empty sockets on J1 thru J8 are provided for possible increase in thermocouple inputs.
J2	"	Yes	Yes	Yes	Yes	Yes	Yes	
J3	"	Yes	Yes	Yes	Yes	Yes	Yes	
J4	"	Yes	Yes	Yes	No	No	No	
J5	"	Yes	Yes	Yes	No	No	No	
J6	"	Yes	Yes	Yes	No	No	No	
J7	"	Yes	Yes	Yes	No	No	No	
J8	"	Yes	Yes	Yes	No	No	No	
J9	"	Yes	Yes	Yes	Yes	No	No	
J10	"	Yes	Yes	Yes	Yes	No	No	
J11	"	Yes	Yes	Yes	Yes	No	No	
J12	"	Yes	Yes	Yes	Yes	No	No	
J13	"	Yes	Yes	Yes	No	No	No	
J14	"	Yes	Yes	Yes	No	No	No	
J15	"	Yes	Yes	Yes	No	No	No	
J16	"	Yes	Yes	Yes	No	No	No	
J17	"	Yes	Yes	Yes	No	No	No	
J18	"	Yes	Yes	Yes	Yes	Yes	Yes	
J19	"	Yes	Yes	Yes	Yes	No	No	
J20	not used							
J21	"	Yes	Yes	Yes	Yes	No	No	
J22	not used							
J23	"	Yes	Yes	Yes	Yes	No	No	
J24	"	Yes	No	Yes	Yes	No	No	
J25	"	Yes	Yes	Yes	Yes	No	No	
J26	"	Yes	Yes	Yes	Yes	No	No	
J27	"	Yes	Yes	Yes	Yes	Yes	Yes	

Figure L-1. HRE Temperature Control Final Breadboard Status (Nov. 6, 1968)

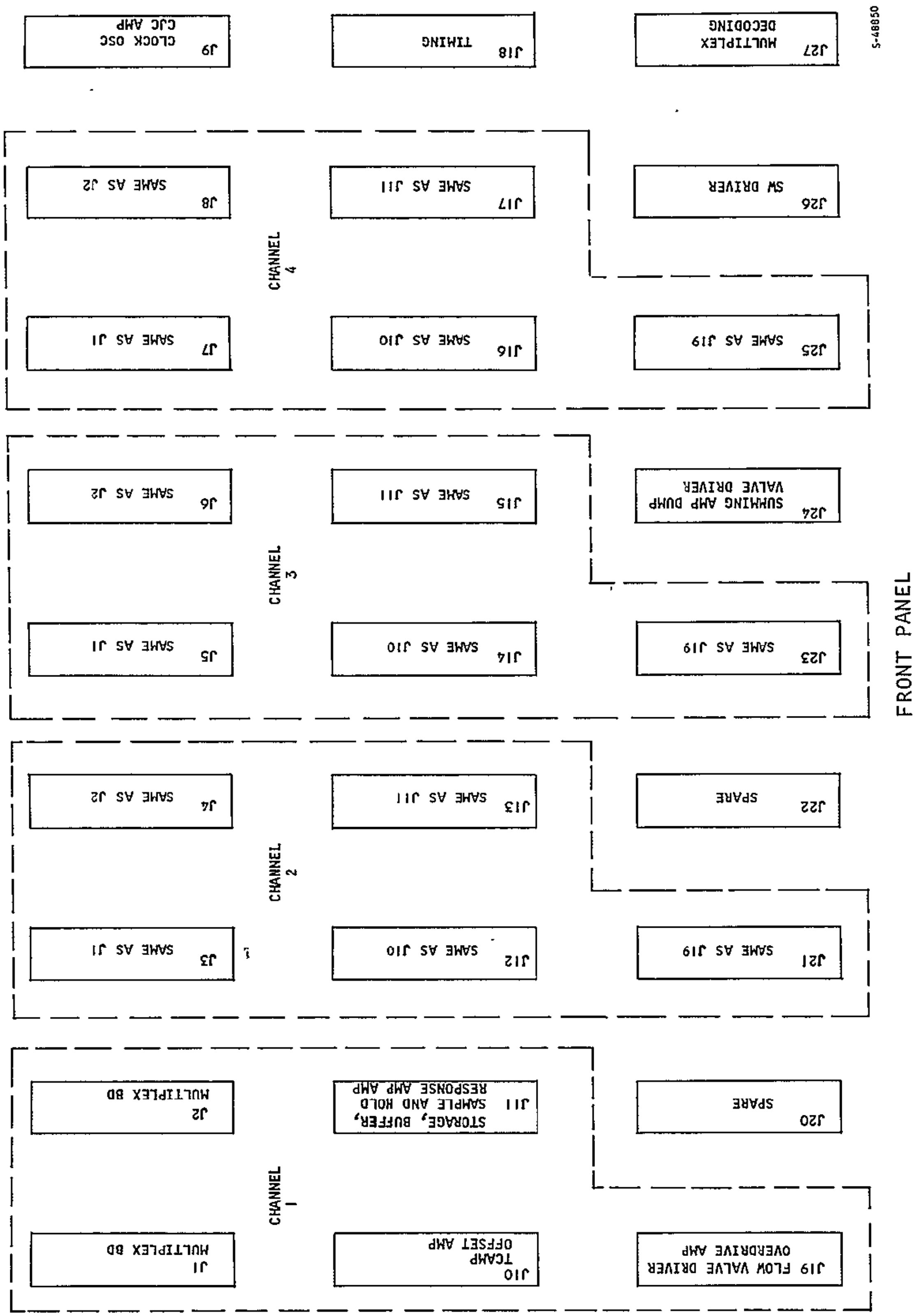


Figure L-2. Temperature Control (Final Breadboard) Chassis Layout (Top View)

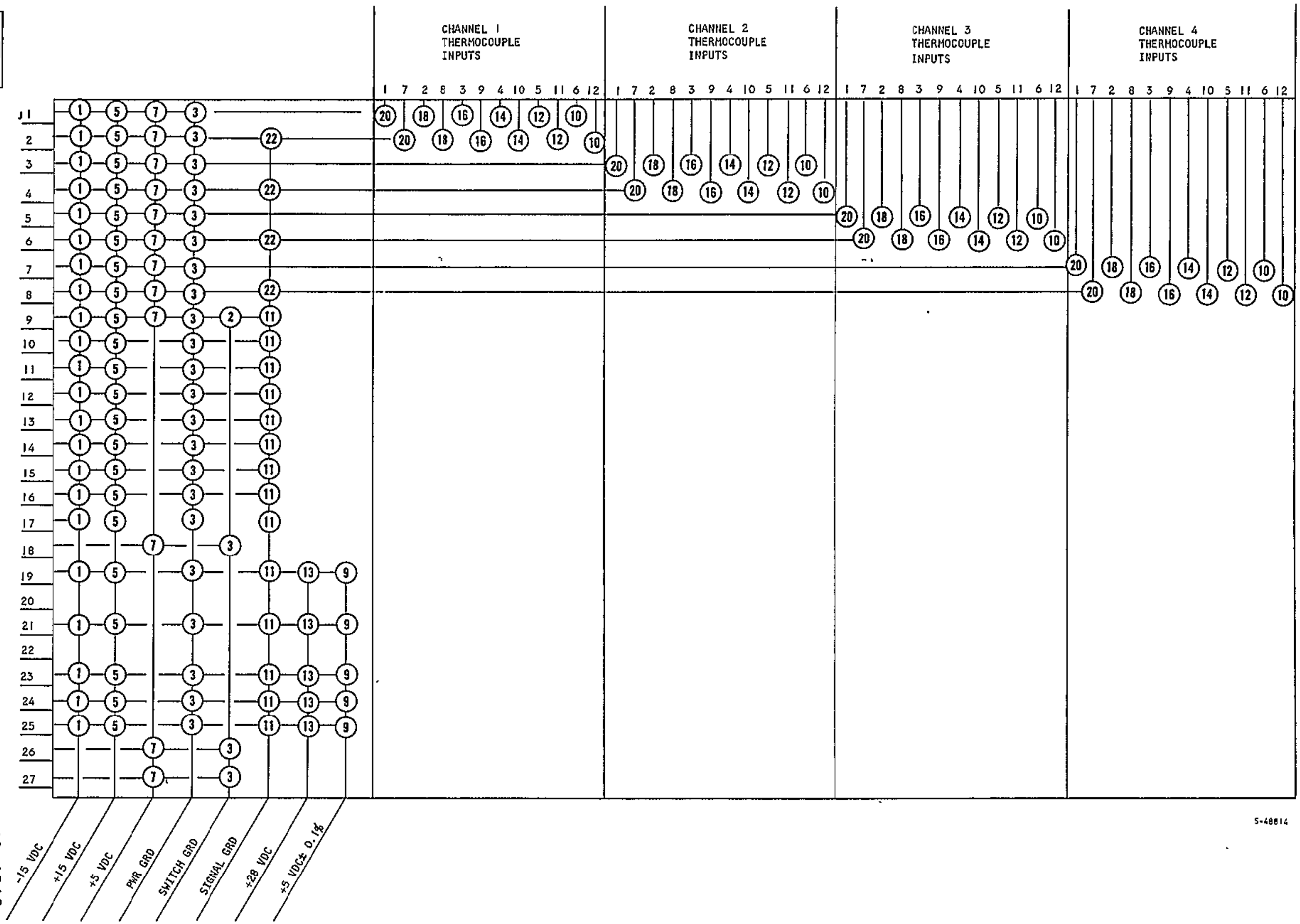


Figure L-3. Breadboard Interconnections

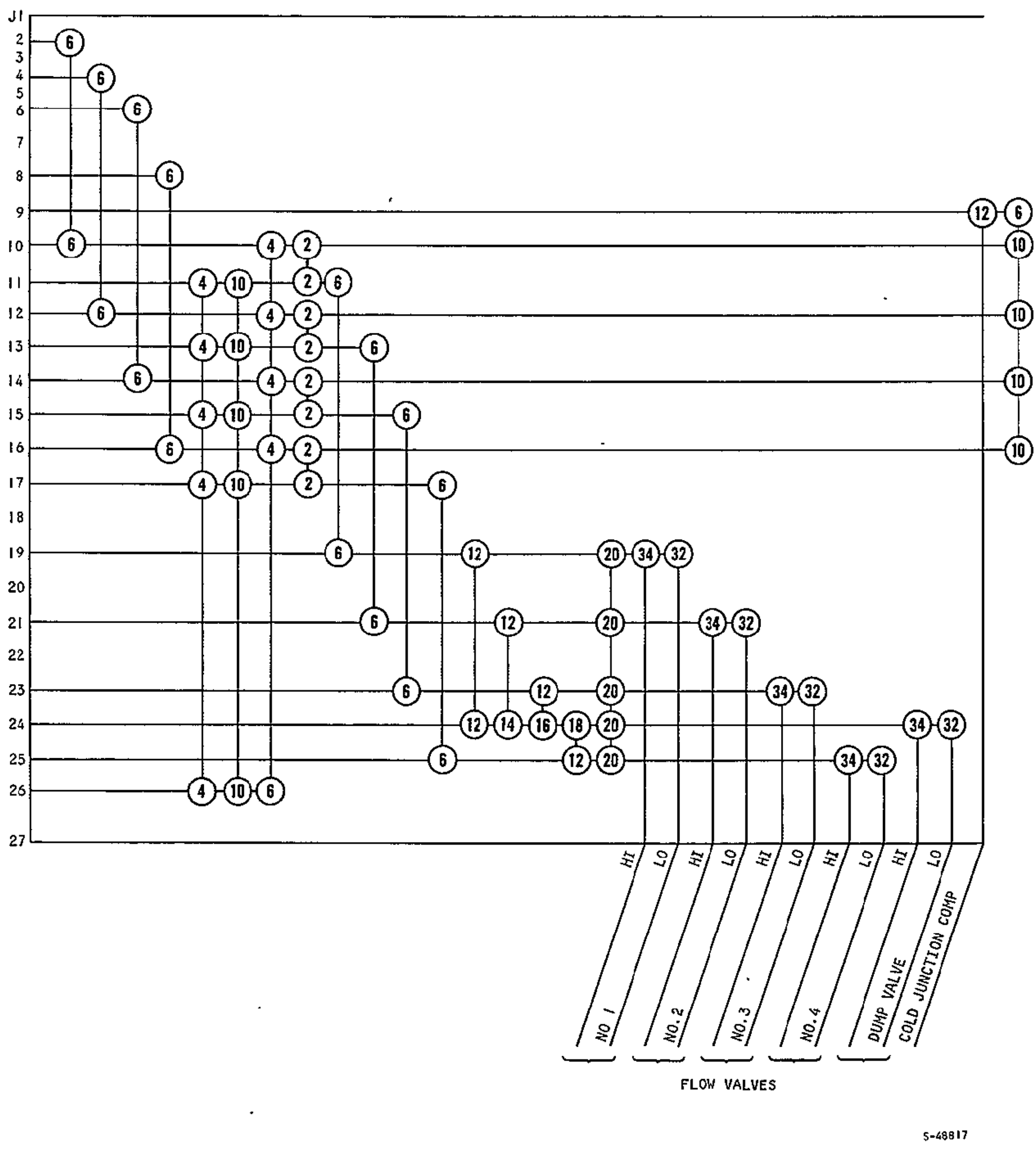


Figure L-4. Breadboard Interconnections

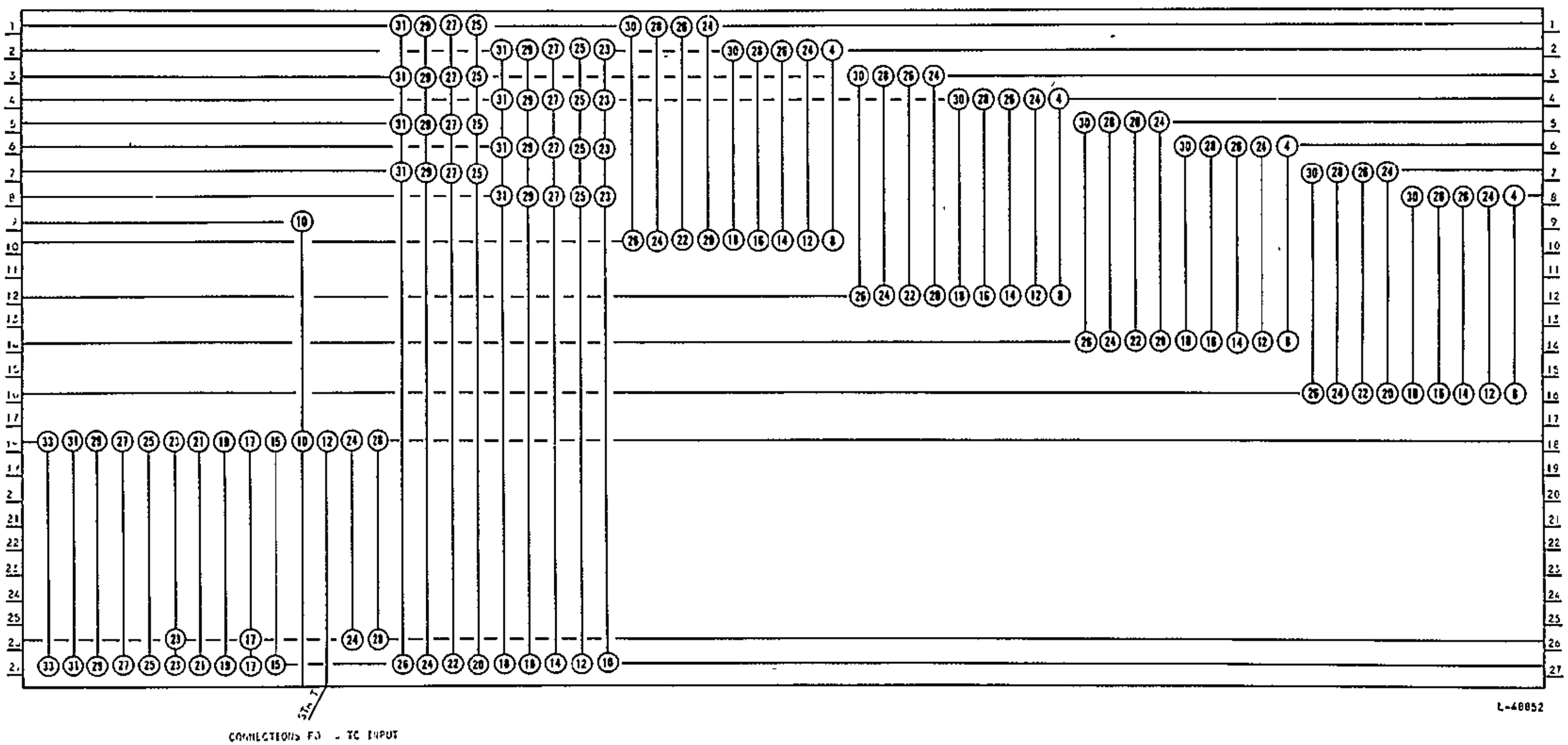
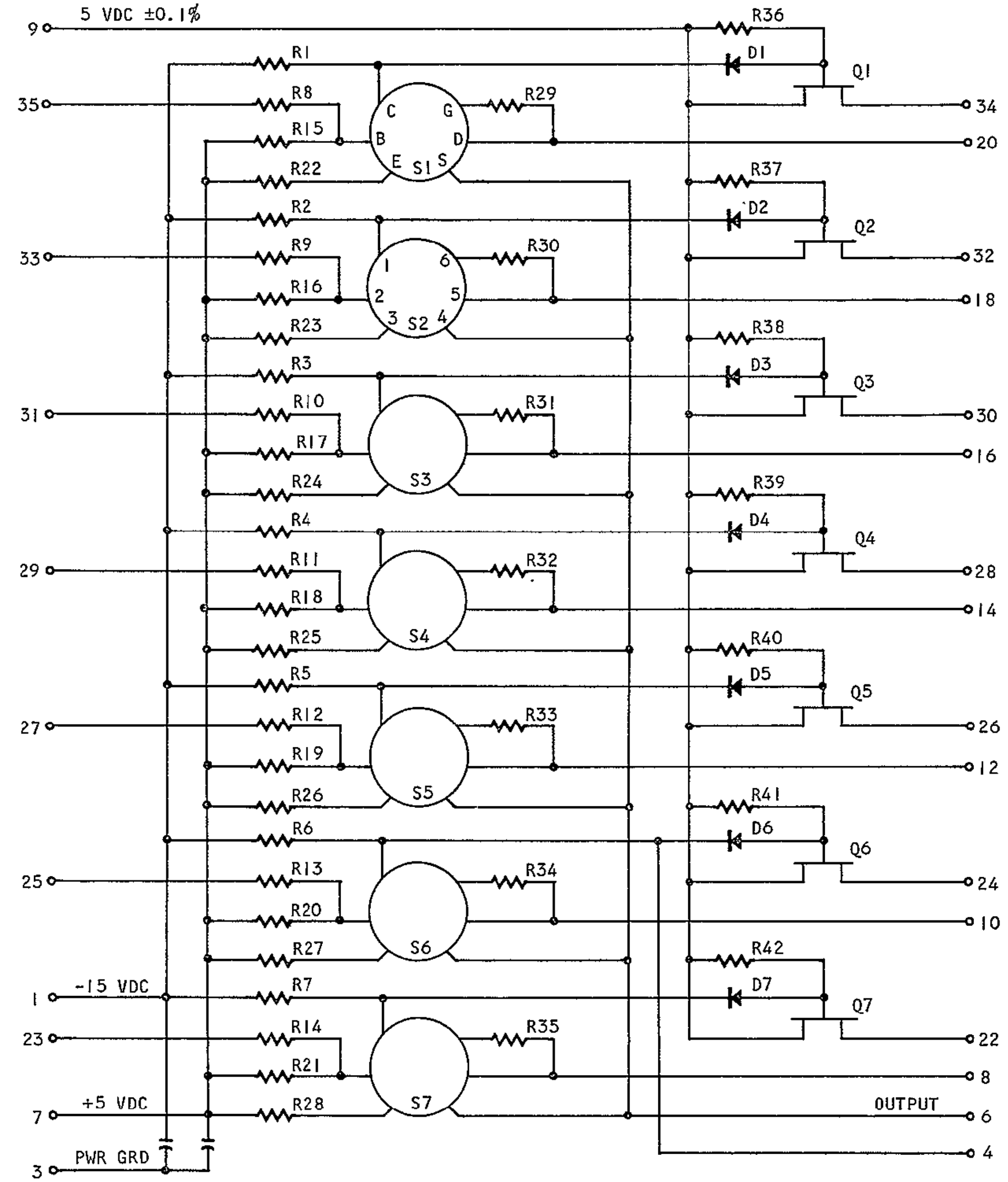


Figure L-5. Breadboard Interconnections



R1 THRU R7	18 K RC07	S1 THRU S7	2108 BE	J1, J2, J3, J4, J5, J6, J7, J8
R8 THRU R14	2.4 K RC07			
R15 THRU R21	2 K RC07	Q1 THRU Q7	2N4392	
R22 THRU R28	1 K RC07			
R29 THRU R42	1 MEG RC07	D1 THRU D7	1N4761	

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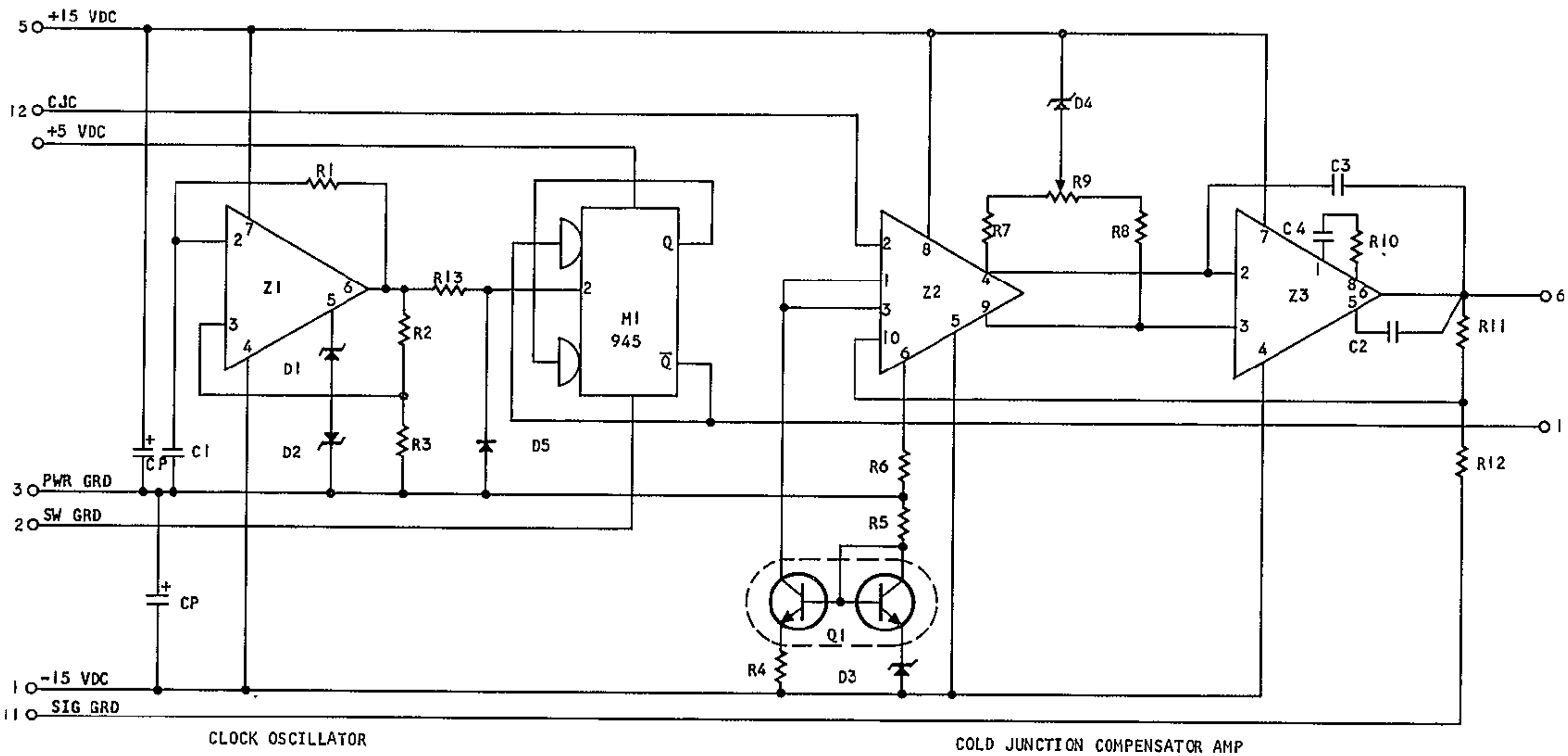
Figure L-6. Wiring Diagram



R1		C1	
R2		C2	20 pf/50v
R3		C3	82 pf/50v
R4	28K ±1% 20 ppm/°C	C4	500 pf/50v
R5	9.1K RC07 ±5%	Cp	0.02 uf/35v
R6	62K 1%	Z1	LM101
R7	20K 1%	Z2	μ726
R8	20K 1%	Z3	μ709
R9	50K TRIMPOT ±50 ppm/°C	M1	945
R10	1.5K RC07	Q1	2N2453
R11	45K ±0.1% 10 ppm/°C	D2	
R12	337 Ω ±0.1% 10 ppm/°C	D3	1N3512
R13		D4	1N3516
D1		J9	

S-48861

Figure L-7. Clock Oscillator and Cold Junction Compensation Amp

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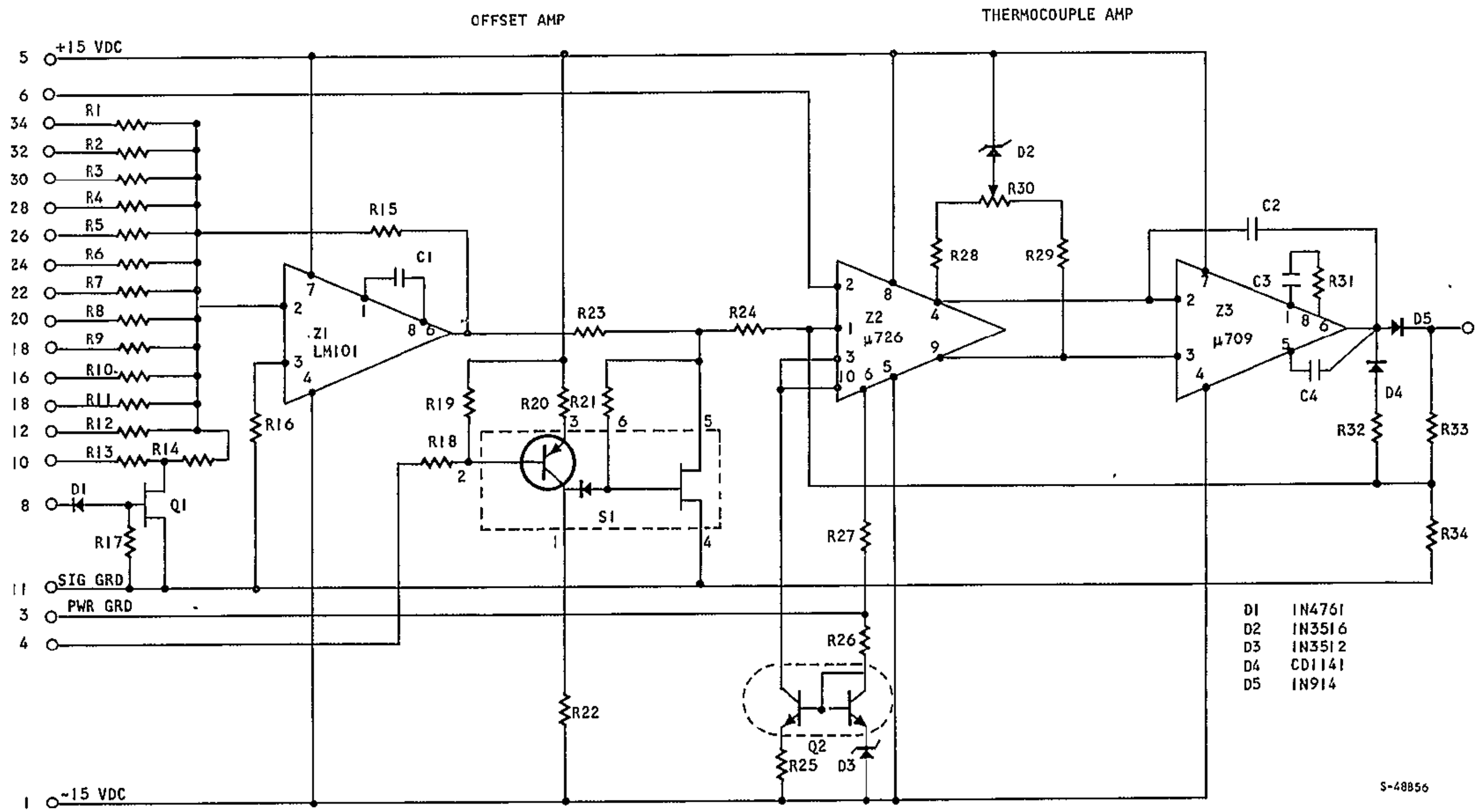
AIRESEARCH MANUFACTURING COMPANY
Los Angeles, California

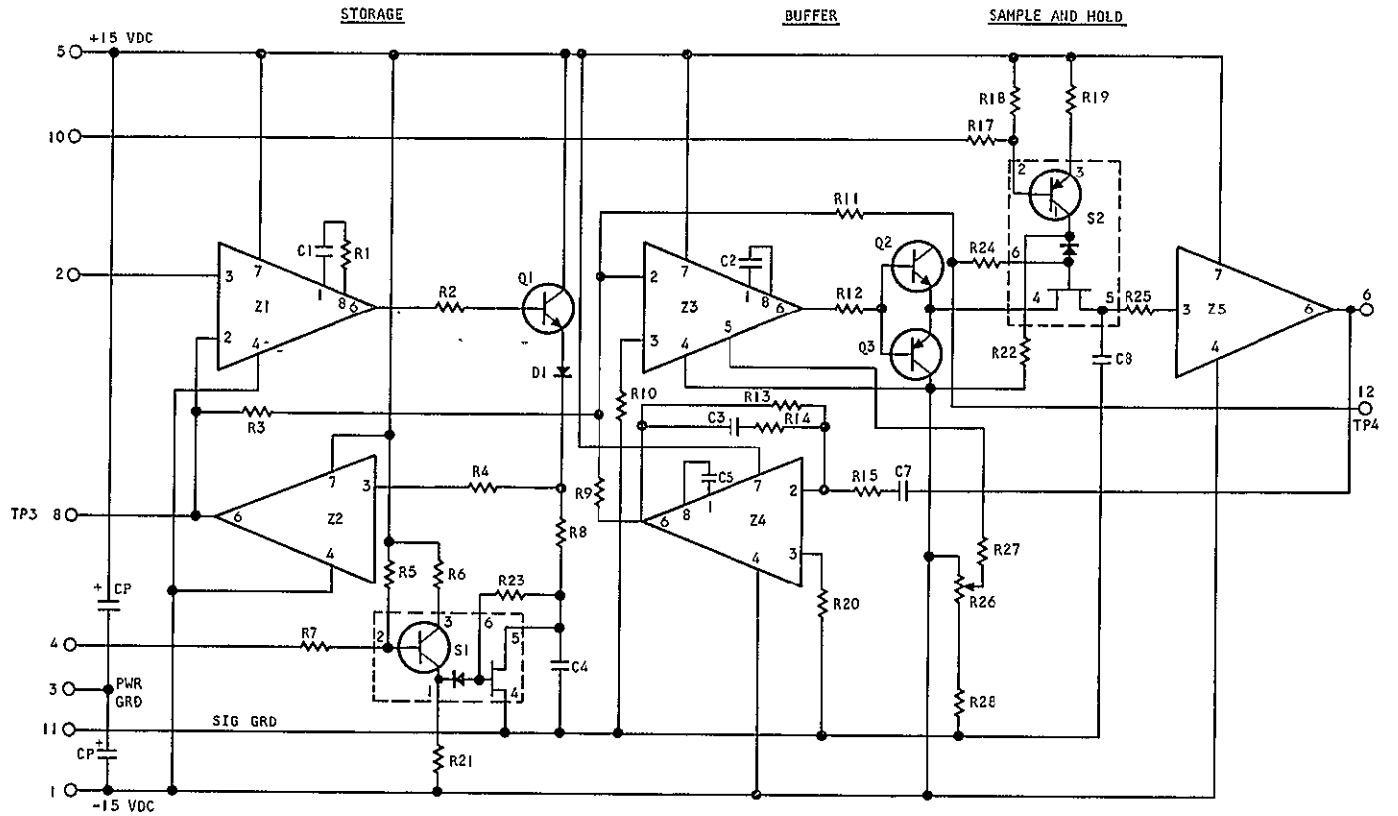


PARTS LIST

Z1	LM101	R1	R13	5 K		±0.1%	10 PPM/°C	R25	28 K		±1.0%	10 PPM/°C	J10,12,14
Z2	μ726	R2	R14	5 K		±0.1%	10 PPM/°C	R26	9.1 K	RC07			
Z3	μ709	R3	R15	10 K		±0.1%	10 PPM/°C	R27	62 K		1%	10 PPM/°C	
S1	2110BE	R4	R16	30 K	RL07	±2%		R28	20 K		1%	10 PPM/°C	
Q1	2N4392	R5	R17	1 MEG	RC07	±5%		R29	20 K		1%	10 PPM/°C	
Q2	2N2453A	R6	R18	6.2 K	RC07	±5%		R30	10 K TRIM POT			±50 PPM/°C	
C1	30 pf/50 V	R7	R19	1 K	RC07	±5%		R31	1.5 K	RC07	±5%		
C2	82 pf/50 V	R8	R20	1 K	RC07	±5%		R32	750 Ω	RC07			
C3	500 pf/50 V	R9	R21	1 MEG	RC07	±5%		R33	45 K		±0.1%	10 PPM/°C	
C4	20 pf/50 V	R10	R22	27 K	RC07	±5%		R34	75 Ω		±0.1%	10 PPM/°C	
		R11	R23	5 K		±0.1%	10 PPM/°C						
		R12	R24	5 K		±0.1%	10 PPM/°C						

Figure L-8. Offset and Thermocouple Amp

334<



R26	50 K	POT
R27, 28	200 K	RC07
R23	1 MEG	RC07
R24	1 MEG	RC07
R25	3 K	RC07
R1	200 Ω	RC07
R2	510 Ω	RC07
R3	10 K	±0.1%
R4	10 K	RC07
R5	1 K	RC07
R6	1 K	RC07
R7	6.2 K	RC07
R8	30 Ω	RC20
R9	10 K	±0.1%
R10	3 3 K	RL07
R11	10 K	±0.1%
R12	510 Ω	RC07

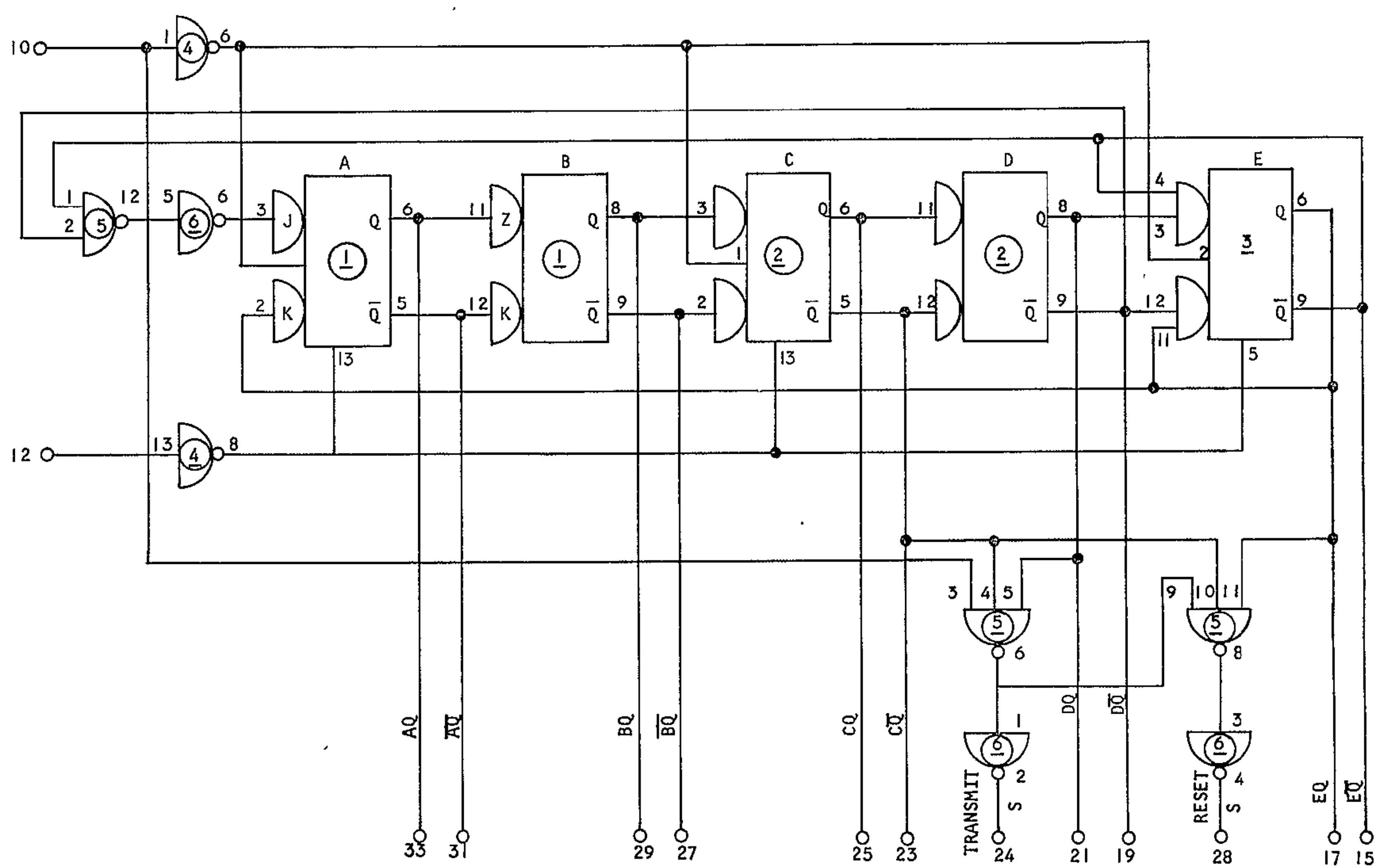
R13	1.13 MEG Ω	±0.1%, 10 PPM/°C
R14	1.75 MEG Ω	±0 1%, 10 PPM/°C
R15	714 K	±0.1%, 10 PPM/°C
R16	1.5 K	RC07
R17	6.2 K	RC07
R18	1 K	RC07
R19	1 K	RC07
R20	56 K	RL07
R21	27 K	RC07
R22	27 K	RC07

C1	30 pf/50 V
C2	30 pf/50 V
C3	0.022 µf, 05PL223D, COMP RES
C4	1.0 µf ±2%, 50 V
C5	30 pf/50 V
C7	0.1 µf, 05PL104D, COMP RES
C8	0.33 µf, 05PL334G, COMP RES
CP	0.02 µf/35 V TAN
Z1	LM101
Z2	LM102
Z3	LM101
Z4	LM101
Z5	LM102
S1, S2	2I108E
D1	CD1141
Q1	2N2222
Q2	2N2222
Q3	2N2907

J11,13,15,17

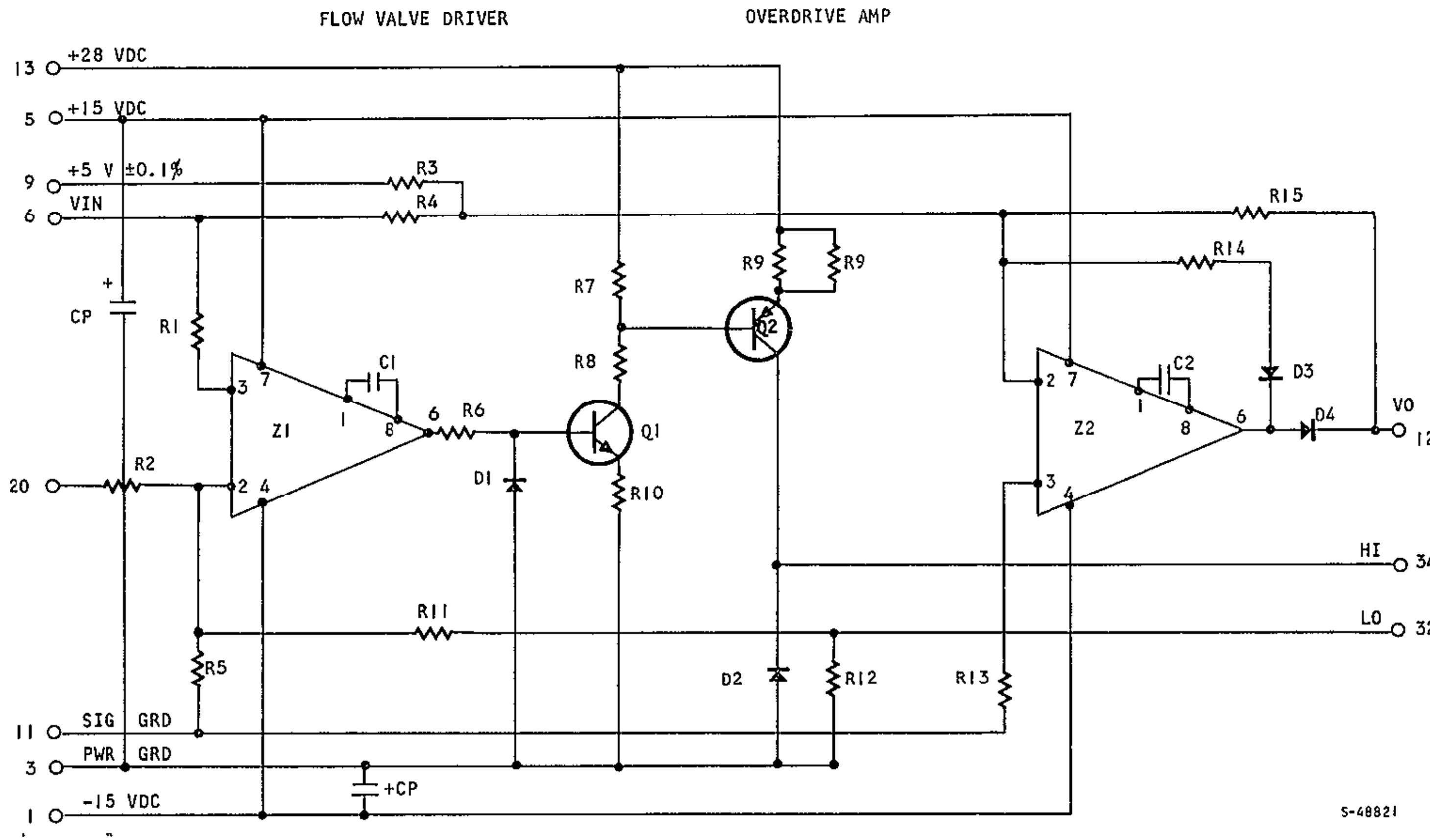
S-48873

Figure L-9. Storage, Buffer, Sample and Hold Filter Circuits



S-48848

Figure L-10. T.C. Timing Control Schematic



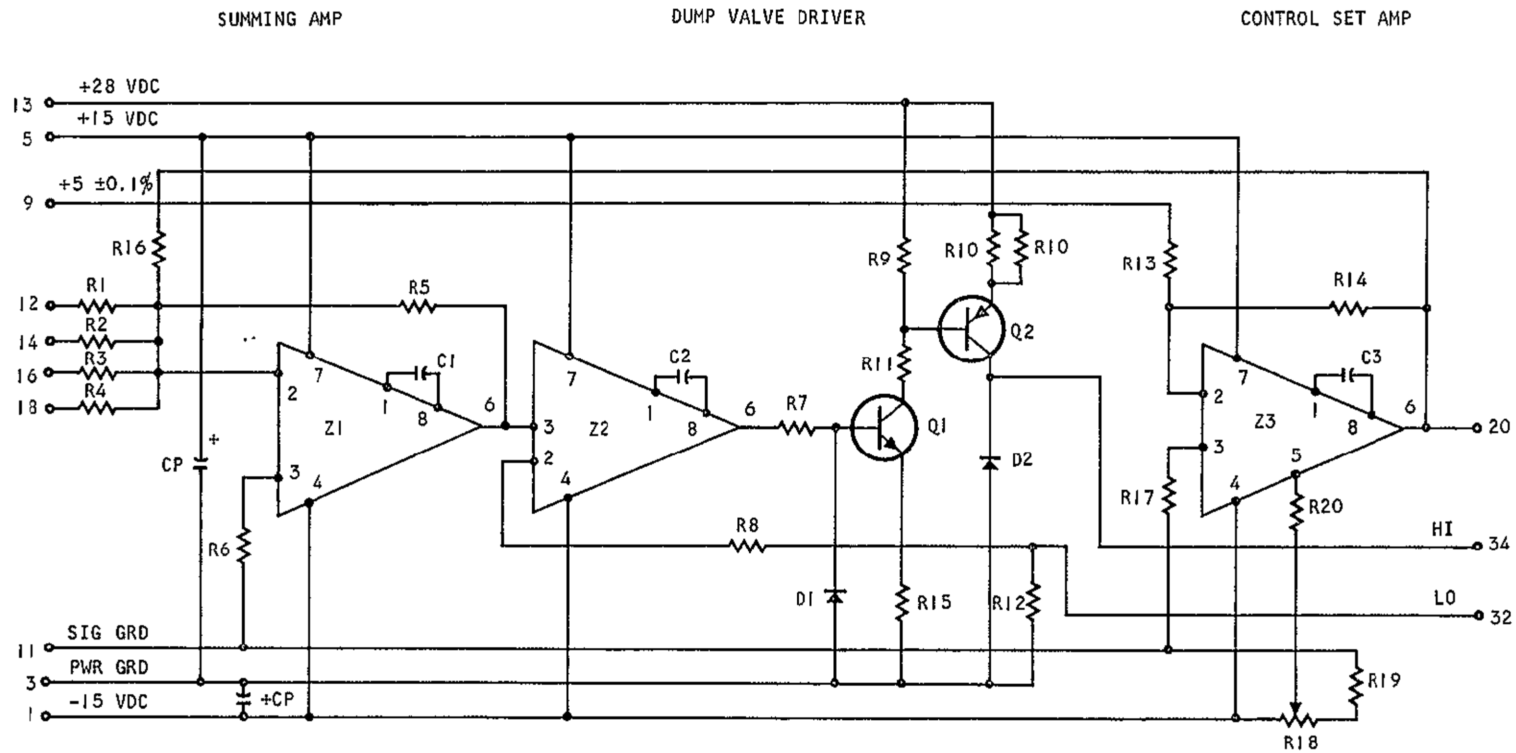
R1	4.3 K	RC07	
R2	8.17 K, ±0.1%		10 PPM/°C
R3	10 K, ±0.1%		10 PPM/°C
R4	8.91 K, 0.1%		10 PPM/°C
R5	444 K, ±0.1%		10 PPM/°C
R6	1 K	RC07	
R7	470 Ω	RC07	
R8	330 Ω	RC07	
R9	(2) 22	RC20	
R10	390 Ω	RC07	
R11	10 K, ±0.1%		10 PPM/°C
R12	15Ω, NLS 2A		20 PPM/°C
R13	3.3 K	RC07	
R14	1 K	RC07	
R15	100 K, ±0.1%		10 PPM/°C

Z1	LM101
Z2	LM101
D1	1N457
D2	1N457
D3	CD1141
D4	CD1141
C1	30 pf/50 V
C2	30 pf/50 V
CP	0.02 μf/35 V
Q1	2N2222
Q2	2N3740

J19, 21, 23, 25

Figure L-11. Flow Valve Driver and Overdrive Amp

337<



R1	12.23 K, 0.1%, 10 PPM/°C, 1/4 W
R2	12.23 K, 0.1%, 10 PPM/°C, 1/4 W
R3	12.23 K, 0.1%, 10 PPM/°C, 1/4 W
R4	12.23 K, 0.1%, 10 PPM/°C, 1/4 W
R5	2.63 K 0.1%, 10 PPM/°C, 1/4 W
R6	1 K, RC07
R7	1 K, RC07
R8	10 K, RC07
R9	470 Ω, RC07
R10(2)	33 Ω, RC20
R11	330 Ω, RC07
R12	15 Ω, DALE, NLS2A
R13	10 K, 0.1%, 10 PPM/°C, 1/4 W
R14	20 K, 0.1%, 10 PPM/°C, 1/4 W
R15	390 Ω, RC07
R16	10 K, 0.1%, 10 PPM/°C, 1/4 W
R17	6.8 K, RC07

C1	30 pf/50 V
C2	30 pf/50 V
C3	30 pf/50 V
CP	0.02 μf/35 VDC
Z1	LM101
Z2	LM101
Z3	LM101
D1	1N457
D2	1N457
Q1	2N2222
Q2	2N3740
R18	50 K TRIM POT
R19, 20	200 K RC07

Figure L-12. Summing Amp, Dump Valve Driver, and Control Set Amp

338<

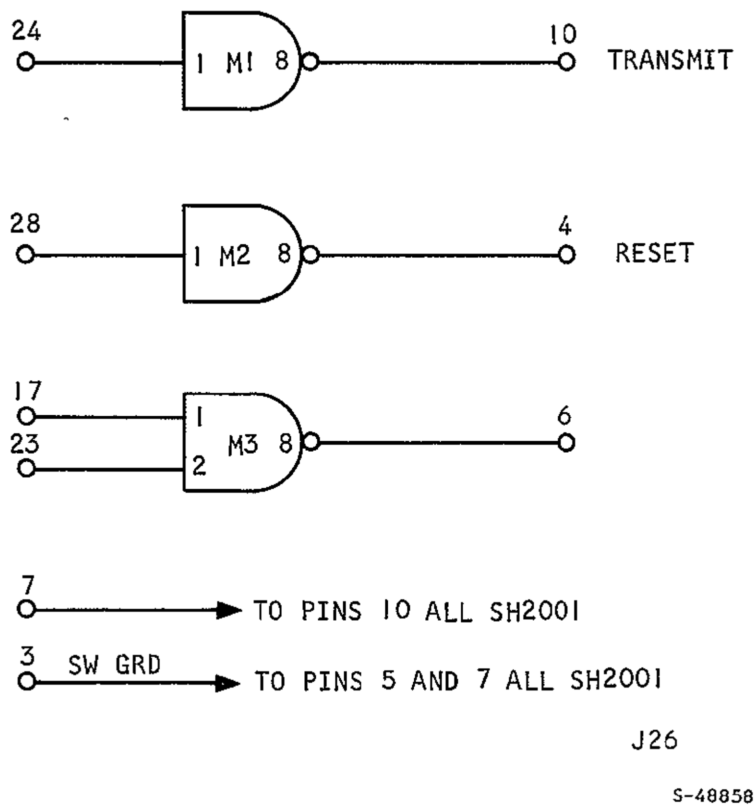


Figure L-13. M1 Through M3, SH2001

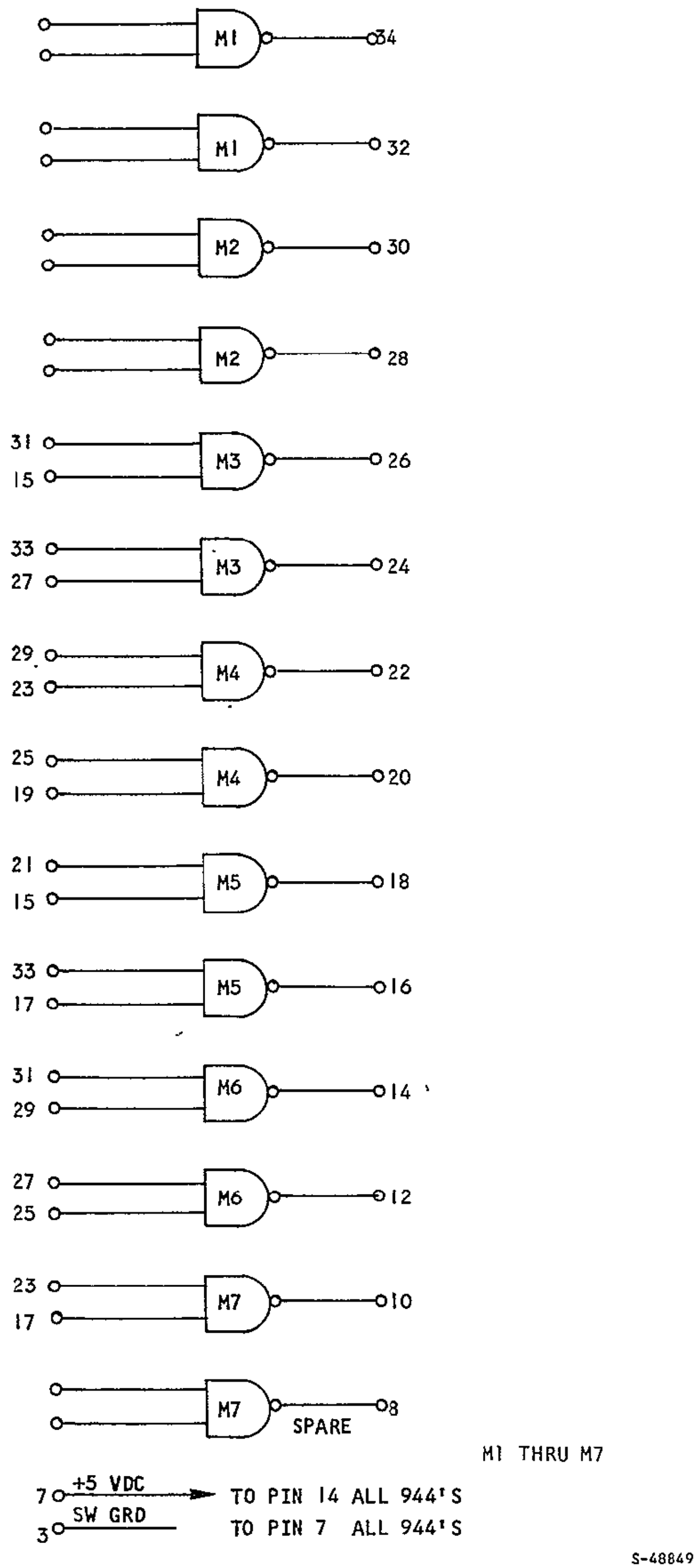


Figure L-14. Decoding Schematic

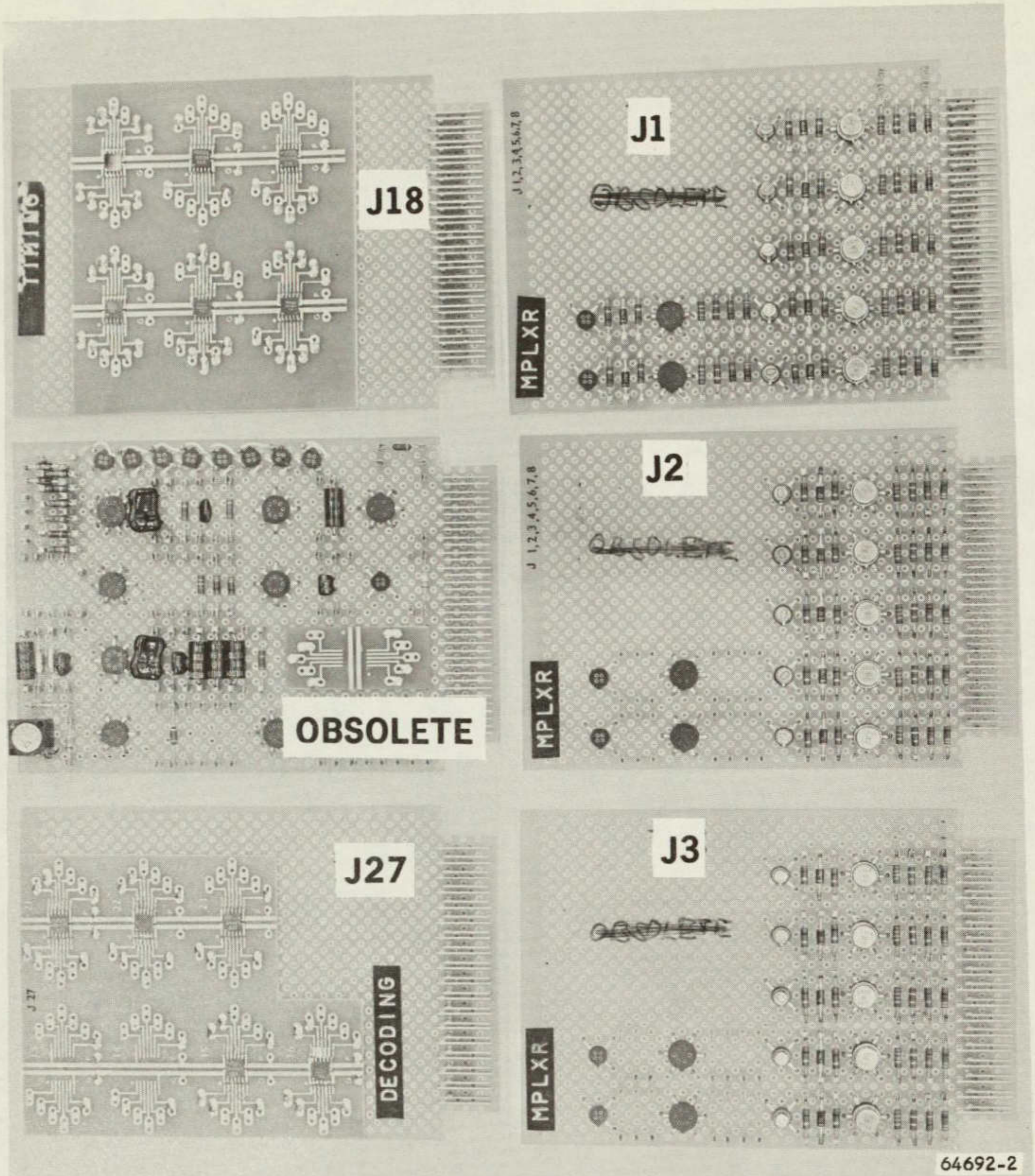


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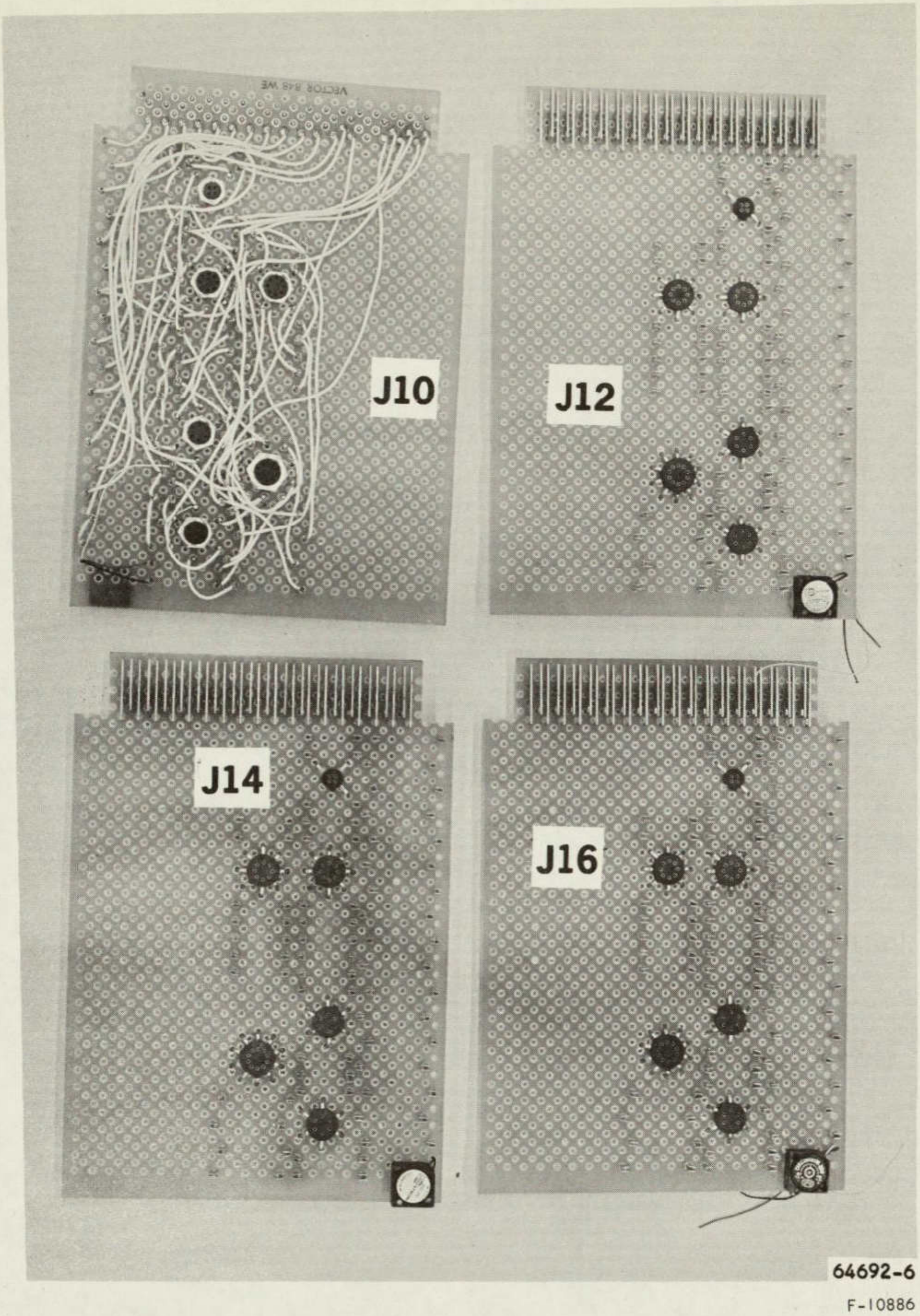
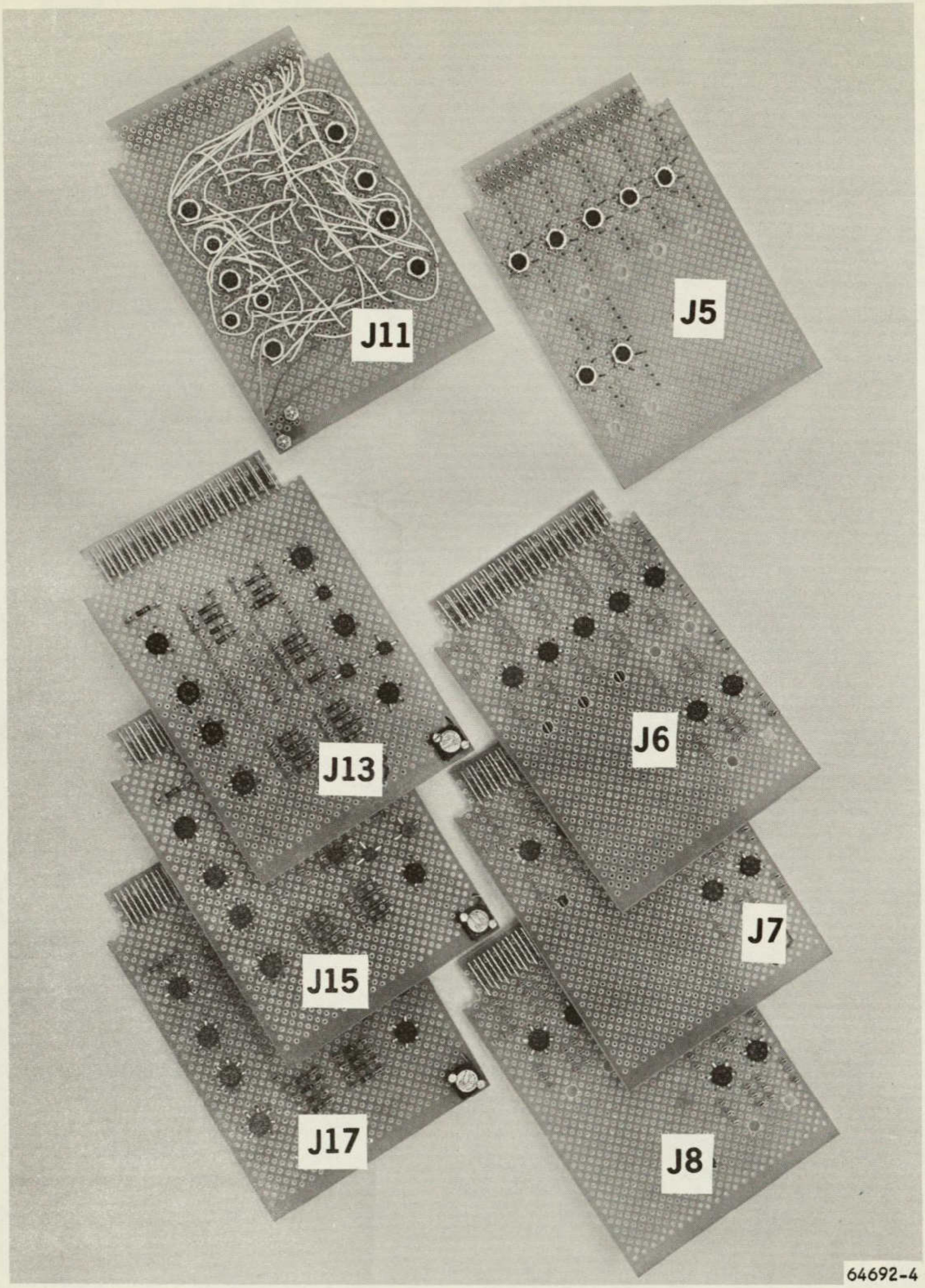
Figure L-15. Breadboard Photograph



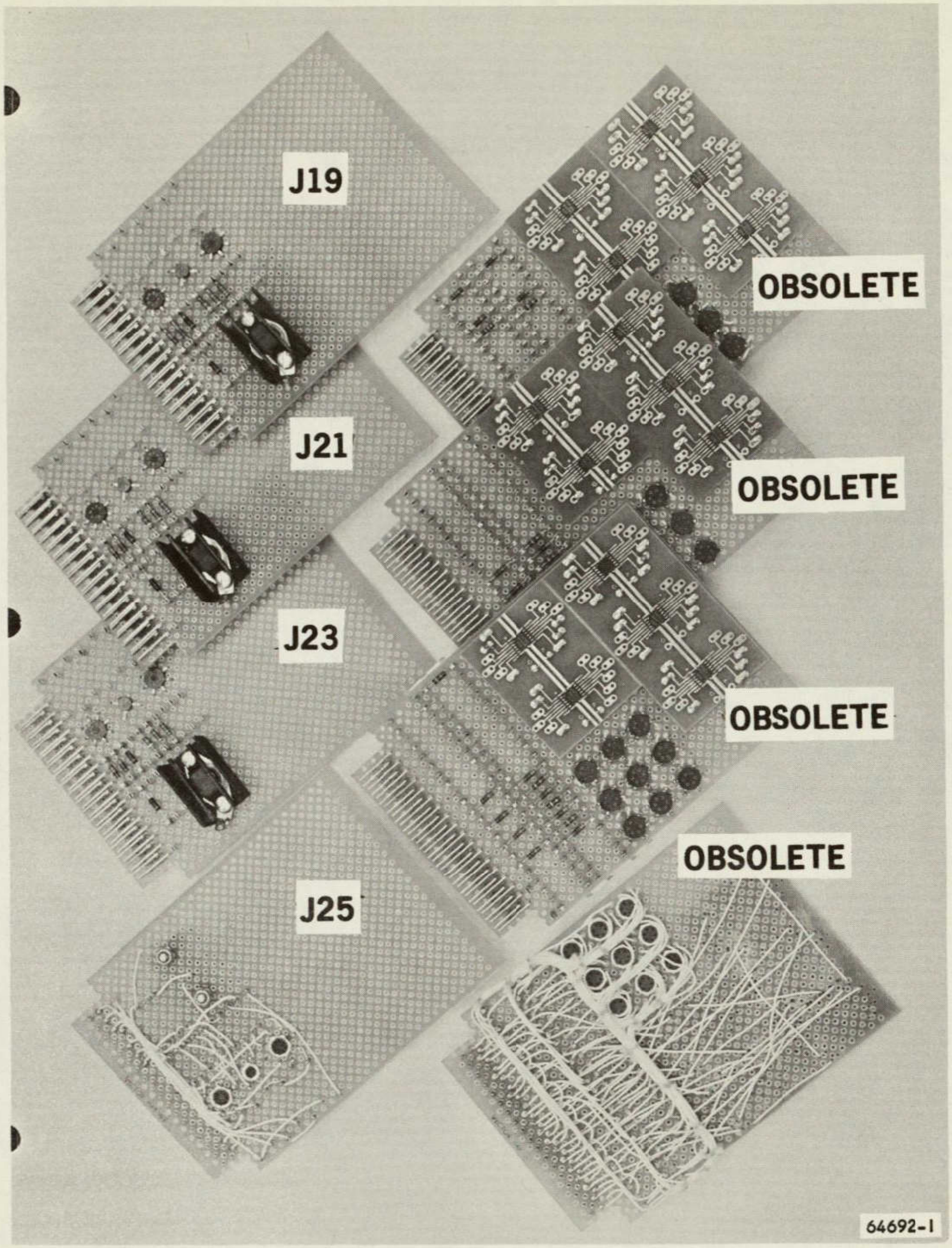
F-10886

Figure L-16. Breadboard Photograph



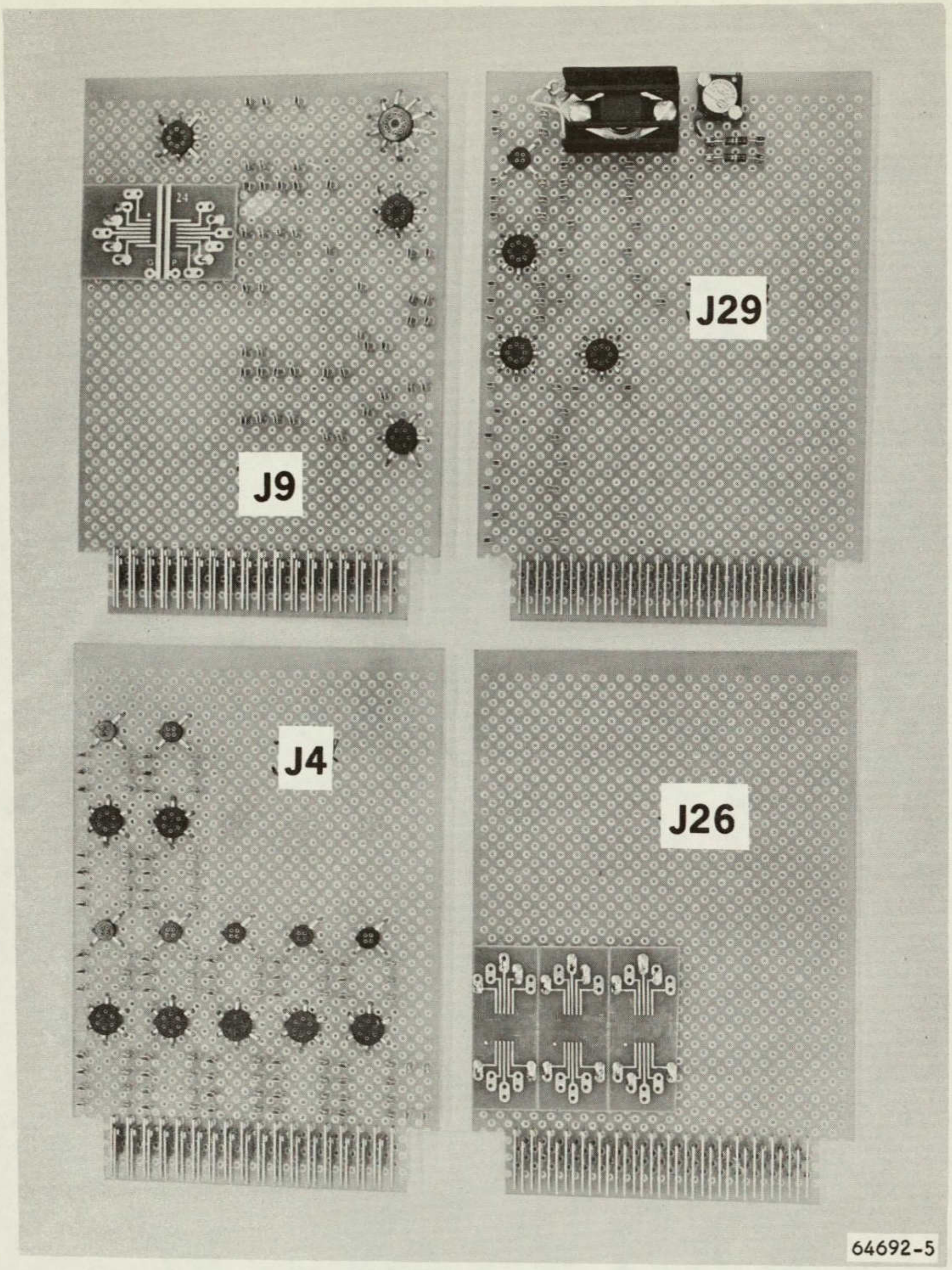
F-10889

Figure L-17. Breadboard Photograph



F-10888

Figure L-18. Breadboard Photograph



F-10887

Figure L-19. Breadboard Photograph