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A DESIGN OF A

PROPULSION RESEARCH LABORATORY

THESIS

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by
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Preface

This design study was done at the request of my thesis advisor, Lt. Col. William W. McKenna, and Professor Harold Wright of the Mechanical Engineering Department, Air Force Institute of Technology.

The system design process was made easier by the very generous assistance given by the staffs of the rocket test agencies visited during a field trip made in support of this design. I am particularly indebted to Aerojet General, Rocketdyne, and United Technology Center for their continued assistance by letter and by personal contacts.

Circuit and equipment recommendations are to a certain extent flavored by my own experience in experimental testing gained during my service with the Central Experimental and Proving Establishment of the Royal Canadian Air Force.

I am especially indebted to Lt. Col. McKenna for his interest, advice, and direction, in particular, during the evolution of the system design.

I also thank my loyal and constant assistant, my wife Lorraine, for serving as my typist during the preparation of the first draft.

Douglas A. Fretts

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Symbol	Description	Units
A	Amplifier	
A_t	Throat area	ft^2
C_D	Discharge coefficient	
C_v	Flow coefficient for valves	
C^*	Characteristic velocity	ft/sec
E_1	Input voltage	volts
E_o	Output voltage	volts
F^o	Fahrenheit	
g	Gravitational constant	ft/sec^2
K	Electrical relay	
K	Electrical potentiometer	
K	Flow resistance coefficient	
K	1000 ohms	
M	Meter	
meg	Megohm	
P_1	Pressure upstream	lb/in^2
P_2	Pressure downstream	lb/in^2
R	Resistor	
R	Regulator (pneumatic)	
r	Mixture ratio (mass)	
S	Switch	
V	Valve	
v	Volts	volts
$\dot{w}$	Mass flow rate	lbm/sec
μa	Microammeter	

Abbreviations

Symbol	Description
ac	Alternating current
BNC	Miniature coaxial connector
cps	Cycles per second
dc	Direct current
DPDT	Double pole double throw (switch)
GF	Gaseous fuel
GN2	Gaseous nitrogen
GO	Gaseous oxygen
pc	Patch cord
psia	Pounds per square inch, absolute
psig	Pounds per square inch, gauge
nc	Normally closed
scfm	Standard cubic feet per minute 14.7 psia and 70 F°
SPDT	Single pole double throw (switch)

Abstract

This report describes in detail a system design for a propulsion research laboratory intended to support graduate studies at the Air Force Institute of Technology. The system supports experimental rocket motors up to 500 pounds thrust. Major design considerations were the state-of-the-art, flexibility, safety, and low direct cost. A gaseous propellant system employs two stages of pressure regulation and sonic venturi flow metering. The completely electrical control system uses a flow chart control console layout and features a manually stepped control sequencer and an analog computing circuit for the real time calculation and display of propellant mass flow rates. The measurement instrumentation achieves maximum flexibility by means of a patch panel for the selection of transducers, signal conditioning circuits and oscillograph recorder channels. The signal conditioning system has been designed for local fabrication at relatively low cost and includes manually operated multi-step calibration circuits. The report includes in its appendices recommended implementation schedule, system safety considerations, a tentative operating procedure, and a visit report made in support of this design.

A DESIGN OF A PROPULSION RESEARCH LABORATORY

I. Introduction

Background

The Air Force Institute of Technology (AFIT) places considerable emphasis on the aero-space technologies and, consequently, has a requirement for a propulsion research laboratory to support research studies of graduate students and faculty members. This requirement was satisfied in part in 1961 when three AFIT graduate students assembled a gaseous propellant rocket test facility in an unused test cell. This building was acquired from Wright Air Development Center (now Research and Technology Division) (Ref 1:1).

This system was fabricated from salvaged components acquired from the former occupants of this test cell. Through the efforts of these students, a system emerged that was simple and effective and therefore considered suitable for elementary tests. Creditable studies have been performed in the past using this facility. However, these were frequently limited in scope by basic system limitations or failed to yield conclusive results because the measurement instrumentation system lacked the necessary sensitivity and precision.

General Requirements

If a propulsion research laboratory is to be a true research facility, capable of supporting original investigations, it is necessary that the control and measurement system be sufficiently refined to support such activities. Although dimensions of investigations are not critical, some upper limit must be defined that gives due consideration to such factors as operating cost, safety, and site location. Restricting a test engine to about 500 pounds thrust and the duration of test runs to 10 to 20 seconds operation is not a severe limitation. Although one-man studies do not require a high test rate or costly data reduction facilities, the researcher should be spared as much of the tedium of extensive data reduction as possible. Should the organization participate in a full scale research and development program, many persons become involved; then, a high test rate is necessary and the need for automatic data processing becomes urgent.

A propulsion feed and control system, which includes the plumbing and control console respectively, should be reasonably aligned with the current technology. The measurement instrumentation system must be sufficiently refined to make precise measurements of the required test parameters; however, it should not impose limitations on a test because of lack of capacity, accuracy, or flexibility. A single instrumentation system usually serves all of the test activities in a test cell. This practical economy measure should not force compromises on the test engineer or restrict the scope of his investigations. The instrumentation system should be easy to use, flexible, incrementally simple, reliable, and practical with a minimum of sophistication.

A dual role is served by the academically oriented propulsion research laboratory. It must not only support the research activities but must train personnel in order to prepare them for their place in the technology. Up-to-date techniques are required in the name of progress, efficiency, and safety.

Therefore, the ground rule for the development of a laboratory is to have an attainable objective in terms of the organization's resources and requirements. The laboratory must conform to the state-of-the-art even at the expense of limitations in dimensions, scope, or areas of investigations. Without these, the laboratory becomes a demonstration or training facility incapable of supporting serious research activities.

AFIT Laboratory Design Requirement

Scope. The scope of the propulsion research activities at AFIT is presently confined to gaseous, non-toxic propellants such as oxygen, hydrogen, and methane. Beyond this, studies are planned involving the use of the more stable liquid propellants, with possible extension of investigations into the area of solids and solid-hybrids. Typical investigations are concerned with injector configuration, spherical rocket motors, thrust vector control, and, beginning in the spring of 1965, supersonic combustion and detonation waves.

Broad Specification. The system design must conform to present technology levels; however, it must not be overly sophisticated. The system operation and use must conform to the standard techniques and practices employed in rocket testing and must demonstrate standard safety and operating procedures. The system must include necessary safety devices. Options, such as engine cutoff devices, which might not be required for limited dimension tests, should be included as a training aid.

Overriding considerations are the present facility, cost, safety, ease of construction, and flexibility.

Capability. The system capacity and scope of the test activities are defined as follows:

(1) The system must permit operation of test engines using gaseous oxygen and hydrogen up to 500 pounds thrust over a reasonable range of mixture ratios. Nominal test engines will operate at approximately 100 pounds thrust.

(2) Normal system operating pressures will be about 300 psia, with a maximum of 500 psia.

(3) The system must include an accurate means of flow control and measurement.

(4) The system must have rapid response in terms of normal system control and operation, and also in regard to safe and rapid shut-down (both emergency and normal).

(5) The system must be capable of modification to permit the use of non-cryogenic liquid propellants.

(6) The system must be capable of supporting the following investigations with minimum modification:

(a) General performance tests of engines and propellants

(b) Thrust vector control

(c) Throttling engines

(d) Injector studies

(e) Detonation wave studies

(f) Supersonic combustion studies

(g) Combustion instability studies

(h) Heat transfer studies

(i) Solid fuel and solid-hybrid engines.

Measurement Instrumentation System Requirement. A reliable, self-calibrating instrumentation system is required for measurement and recording of test parameters. Oscillograph recorders, supplemented with camera-equipped oscilloscopes may be used initially. The system must be capable of meeting the measurement requirements of separate experiments without compromise, without need of complete system calibration, or without lengthy setup procedures. The design must conform with current techniques and be capable of providing reliable data of sufficient accuracy to meet the test requirements. Oscillograph systems can deliver 2% data accuracy; this tolerance is usually acceptable for most propulsion experiments (Ref 2:9).

Propulsion Feed System Requirement. The propulsion feed system must use a common metering and control system to feed up to four test stands using the same propellants. The system must accurately control and measure the mass flow rate of the propellant gases and must allow engine throttling. The propellant and purge lines must be valved at the test stand for safety and for rapid response and fast positive shutdown. Normal configuration test engines must use in-chamber spark ignition.

Propulsion Control System Requirement. The propulsion control system must be safe, flexible, and capable of being readily adapted to meet new requirements. The feed system and standard test practices must govern the design of the control system. Practical conveniences for the assistance of the test engineer will be included where practical.

Present Facility Status

The present facility, described in detail by Macko (Ref 1), remains virtually unchanged since its installation in 1961. The measurement instrumentation system has been modified, but its operation and accuracy have not been significantly improved.

The flow of gaseous propellant is controlled by a single pneumatically operated dome regulator valve. There are hand-operated valves at the supply manifold and at each of the four test stands. This regulator valve serves both as an on-off control and as a flow regulating device. It is remotely loaded by hand-operated loader valves located in the control room. Two possible flow rates for each propellant are available to the operator; these are selected by means of a three-way solenoid valve which applies pressure from one of two loader valves to the controlling dome regulator. A common purge is effected by the injection of nitrogen gas into the propellant lines immediately downstream from the control regulator and flow metering orifices. External ignition is used; that is, a flow of fuel is ignited outside the engine and the flame drawn into the chamber when the flow of oxidizer is initiated.

The control console includes conventional controls and a system of sophisticated electrically operated safety and sequence interlocks. This console is suited to routine operation of conventional test engines.

The measurement instrumentation system consists of an 18-channel oscillograph, transducer balance network, and the necessary minimum strain gauge transducers. Temperatures are measured by means of a simple thermocouple circuit using an ice bath reference junction. The signal conditioning system which is of fixed configuration, offers no signal sensitivity control or means of electrical calibration. The transducer reference voltage is drawn from a storage battery and is monitored by a simple voltmeter.

Objectives of This Report

The objectives of this report are to develop a system design for the AFIT Propulsion Research Laboratory and to offer that design in sufficient detail for its construction. While complete assembly, final wiring, and layout details are beyond the scope of this report, it is intended to offer enough detailed design and supplementary information to enable experienced technicians to assemble, check out, calibrate, and operate this research laboratory.

II. Design Discussion

Approach to the Design Problem

Little specific design information is available in the formally published literature; therefore, a visit was made to a number of active rocket research and development test agencies. Rather surprisingly, the visit proved that within many of these agencies, detailed system design information is vague and sketchy. Systems are defined by a basic system block diagram; beyond that, they are assembled from components and sub-systems using a basic, but flexible electrical or plumbing system as applicable to a requirement. Valuable advice was received on the selection and use of system components, and the general system philosophy as discussed in the introduction to this report. A report on this visit is given in Appendix D.

Manufacturers of recommended components and assemblies provided engineering, design, and application information relative to their products. This information plus the advice received on the field trip from experienced test and instrumentation engineers provided the basis for the system design offered in this report.

As the design was being finalized, past and present users of the existing AFIT facility and engineers with experience in rocket testing and research were consulted. A partial list of the agencies and the individuals consulted is given in the supplementary references.

The system design study began with the analysis of the required propulsion feed system and the compromises involved in achieving the necessary capacity and selection of components. The propulsion control system design was dictated by the requirements for system flexibility, rapid and positive control, conformity with accepted operating techniques, and system safety. The measurement instrumentation system design was approached with the intention of achieving maximum flexibility and data confidence with a minimum of sophistication and direct cost.

Propulsion Feed System

The early design concept was based on the possibility of realizing a closed loop mass flow control system. This implied the use of a mass flow transducer that could be used in a relatively simple control system. The agencies visited, including Jet Propulsion Laboratories (Ref Appendix D), acknowledged the existence of several prototype gaseous mass flow transducers but could not recommend any for a routine application. An alternate suggestion was the use of a volumetric turbine flow meter with temperature correction circuits; but, to modify this signal for control valve feedback would prove excessively complex for the AFIT system. In addition, turbine flow meters have poor response to changes in gas flow.

Of the various direct and indirect means of gas flow control, the sonic choke appeared to have the most promise since it provided both measurement and control on the basis of essentially one parameter. A sonic choke, in the form of a venturi nozzle, has a pressure loss of about 10 to 15%. Its flow characteristics are described by the familiar mass flow equation for sonic nozzles (Ref 3:62).

$$\dot{w} = \frac{P_1 A_t C_D}{C^*} \qquad (1)$$

where $\dot{w}$ is mass flow rate, P_1 is upstream total pressure from the nozzle, A_t is throat area, C_D is discharge coefficient, and C^* is characteristic exhaust velocity. Thus, through C^*, the mass flow varies inversely as the square root of absolute temperature; errors resulting from assuming that the gas is at ambient temperature are small. For example, a 10^oF change in gas temperatures causes a 1% variation in the mass flow rate.

A gas control system with two stages of regulation and sonic orifice metering was selected as the basic system (Fig. 1). The first stage of regulation provides the second control regulator with a constant inlet pressure, thus ensuring closely controlled pressure at the inlet to the sonic orifice.

This propellant circuit has two flow metering sonic chokes; one is used for the control of the start-up flow and the second, which is adjustable, controls the running flow rate. A solenoid valve, in series with each choke, allows the selection of three possible mass flow rates, thus providing a throttling capability. The mass flow of the propellant gas is controlled by varying the throat area of the sonic choke or, to a lesser degree, the upstream pressure. The throat area is selected to allow sonic flow with minimum losses across the nozzle.

The selection of system components is difficult if high mass flow rates are required. In order to minimize pressure losses, tubing diameters must be large, and pressure losses across regulators and valves must be kept as low as possible. A practical upper limit, with respect to system cost, is soon reached. In an effort to meet the system specification and yet keep the cost within acceptable limits, one inch outside diameter stainless steel tubing and nominal one inch valves were selected. Minimizing pressure losses may be expensive initially, but long term savings in operating costs can be realized because the gas pressure bottles may be run to a lower pressure. Double pressure regulation allows system precision to be maintained at low supply pressures.

The first stage pressure regulators are located outside the test cell near the supply manifolds, allowing the use of components with lower pressure ratings (and lower cost) within the test cell. These low pressure components are protected from being inadvertently over-pressurized by the use of relief valves and blow-out diaphragms.

Rapid shutdown response is desired. This is achieved by locating the propellant valves and purge injection "T" as close as possible to the test engine. This means that each test stand must have remotely operated solenoid valves for the propellant and purge lines. Operating costs are reduced because only a short length of line must be purged to initiate or terminate a run.

Complete design details including recommended parts list are given in Appendix A.

Propulsion Control System

A completely electrically controlled system has been selected because it offers faster response and greater ease of modification than a pneumatic system.

The control system is fail safe; that is, all propellant control solenoid valves are normally closed. Several positive steps must be made before the system can be operated or propellants allowed to flow into the test engine. These steps are:

(1) Main 28 vdc power must be applied

(2) Test stand selector and safety plug must be installed

(3) System Ready switch must be selected

(4) Key operated Arm switch must be selected.

At each of the above steps, more of the system may be readied or actuated, but only after the system has been Armed can the propellant valves be opened and the igniter operated. In addition, door interlocks and system cutouts must be satisfied before the system may be Armed.

To achieve the desired system flexibility, the control panel is fabricated from a series of sub-panels connected to the remainder of the system by means of short cables and suitable terminal strips. This will allow control system modification without complete re-work. The control console is designed so that each valve in the system may be operated separately without defeating system safety measures. There are several features included in the system that permit the console to be programmed for simplified control; these include a self-sequencing Auto-Stop circuit and a programming matrix board that reduces engine operation to pushing a row of interlocking push buttons.

Control switches, as well as selection indicator lights, are displayed on a flow chart layout simulating as nearly as possible the propellant feed system. This makes system operation more readily understood and its status easier to interpret. The operator display includes propellant pressure gauges, low pressure warning lights, and test parameters displayed in engineering units, including computed mass flow rates.

An emergency shutdown (ESD) switch included in the system removes electrical power from the Ready and Arm busses closing all system solenoid valves. Because normally closed valves are used throughout the system, power must be applied to the engine purge valves and to the valves which vent the dome of the control regulator and the line downstream from that regulator. Therefore, a second pair of contacts on the ESD switch applies power to these latter valves completing the system shutdown. In the event of power failure, the required voltage is drawn from an emergency power supply (an aircraft 28 volt battery), which is automatically switched into the circuit.

Test cell deluge valves are normally closed thus reducing the possibility of inadvertent deluge. These valves are operated from guarded switches that draw the necessary power from the 28 volt mains or directly from the emergency power supply.

Complete details of this system, including schematics, fabrication notes, and suggested parts list are given in Appendix B.

Measurement Instrumentation System

The oscillograph recording technique offers acceptable accuracy (1 to 2%) and is reliable, simple, and very flexible. The oscillograph record does not yield its data easily because the record must be manually read point by point. In an application where the parameters are being frequently changed, this imposes no more hardship than reprogramming of automatic data reduction equipment. When frequency response requirements are beyond the range offered by DC amplifiers and high frequency galvanometers, other recording means are necessary. The most readily available means of recording high frequency data is the laboratory oscilloscope equipped with a Polaroid camera or a continuously-moving-film camera. Oscilloscope records do not offer good time resolution unless the oscilloscope is equipped with a raster generator; even this alternative is not suitable for long duration, high frequency recordings. The remaining alternative is a magnetic tape recorder. Although more complex, the magnetic tape recorder offers the advantages of readily reproducible records, time scale expansion, and direct input into automatic data reduction equipment.

Instrumentation flexibility is best achieved by the utilization of a system programming patch panel. The patch panel permits the pre-selection of transducers, signal conditioning equipment, and recorders without changing the basic system. Therefore, a number of different tests may be performed using the same recorders and the same instrumentation system. Changeover requires only the insertion of a pre-programmed patch panel and making non-critical balance and voltage settings.

A variety of signal conditioning equipment is commercially available which can be used to build up a complete instrumentation system. With the exception of complex electronic equipment such as DC amplifiers and analog-to-digital converters, much of the basic signal modifying circuits can be locally fabricated at considerable direct cost savings. Functionally equivalent assemblies such as bridge balance and control circuits and voltage calibration circuits can be built by reasonably experienced technicians. Manually switched electrical calibration is practical when experiments involve no more than 25 analog test parameters. A larger number of test parameters would justify the addition of automatic calibration circuits to the instrumentation system.

The instrumentation system design offered in Appendix C of this report gives detailed schematics and fabrication notes for an oscillographic recording system which is based on the preceding discussion and the requirements stated in the introduction.

<u>Laboratory Safety</u>

Rocket testing and related experiments involve the use of considerable quantities of explosive or flammable materials that present extreme hazard to personnel and property. Every practical precaution must be taken to reduce the probability of fire, explosion, or escape of these propellants; in addition, precautions are required to minimize the damage and risk to personnel should such an event occur.

Mechanical precautions involve the design integrity of the basic propellant system. This includes the safe and reliable operation of components which must have adequate safety factors and must be compatible with the environment and the propellants in use. Mechanical precautions include the isolation of the more hazardous elements by distance or by barriers which reduce the propagation of fire and fragments.

Operational safety precautions are required to afford maximum personnel safety even though they may have by-passed some of the mechanical safety precautions, i.e., working in a danger area. Various safety devices and measures, such as key-operated arming switches, safety plugs, and access interlocks can be used to prevent accidental system actuation and reduce risks while personnel are present in the test cell or danger area. These devices are only reminders to the operating personnel to observe the test cell safety rules which are the individual's best protection.

Mechanical and operational safety devices and precautions have been applied where possible in the system design. The mechanical precautions include flame shields around possible fire sources and relief valve and blow-out diaphragm protection for propulsion system components. Additional precautions are the use of stainless steel or bronze components, filtering of propellant gases, and the use of normally closed solenoid valves. Operational precautions include sequence and safety interlocks, safety plugs, locking arm switch, fire and explosive gas detectors.

The design safety precautions are included in the appendices detailing the design of the propulsion feed and control systems, respectively (Appendices A and B). These precautions are summarized in Appendix F, which also lists oxygen handling precautions and details safety considerations that apply to the test cell environment.

III. Summary

The proposed design given in detail in the appendices meets the AFIT requirement as given in the introduction. It offers a complete system which is flexible, versatile, and capable of expansion and refinement to meet future requirements. The design offers nothing that is new; the techniques and practices proposed have been proven in similar or related installations. It offers AFIT a means of realizing an up-to-date propulsion research laboratory at minimum direct cost. It can be implemented at once or in stages spaced over several years.

The system design compares favorably with those in use at other test sites; while it does not have the sophistication or automation, it is equivalent in accuracy, scope, and flexibility. It can be summarized in the following points:

(1) The propulsion feed system offers rapid response, fail safe operation and accurate control of mass flow rates with a precise throttling capability. Ample capacity of system components allows maximum utilization of the pressurized gas supply. All reasonable safety precautions have been taken for the protection of personnel and property.

(2) The propulsion control system allows considerable operational flexibility without compromising system safety. The system includes safety interlocks and cutouts and the positive safety afforded by a key-operated Arm switch and a safety plug. A manually stepped sequencer simplifies system operation and allows the operator to preselect the firing sequence. The operator's control console, which has a flow chart layout, includes

indication of system status and the display of pertinent test parameters, e.g., mass flow rate of propellants, thrust, and chamber pressure.

(3) The measurement instrumentation system design reflects the current techniques used in rocket testing. A programming patch panel provides a flexible, accurate system that will serve several projects at the same time without compromise. Designs are offered for signal conditioning equipment which can be locally fabricated at low cost. Ample capacity has been allowed so that replacement of components within the system will not be necessary if the system is enlarged.

(4) Maximum laboratory safety is achieved by application of safety devices and precautionary techniques normally employed in larger and more hazardous installations. The inclusion of safety interlocks, automatic and emergency shutdown circuits, normally closed solenoid valves, test stand safety plug, and key-operated arming switch afford optimum operational safety. Test cell safety is realized by the use of pressure relief valves, blow-out diaphragms, explosive mixture and fire detectors, and the application of strict oxygen handling precautions.

IV. Recommendations

It is recommended that:

(1) The system design offered in this report be implemented as soon as budget considerations permit. A suggested implementation schedule is given in Appendix E.

(2) AFIT engage the services of an experienced technician to fabricate, assemble, and check out the system,

(3) An experienced instrumentation technician be assigned to the Propulsion Research Laboratory to train users, supervise the use of the system, and perform modifications and refinements as necessary,

(4) A short series of lectures be given semi-annually to system operators by an experienced instrumentation engineer,

(5) The system be refined by the addition of a magnetic tape recorder complete with necessary accessories. This will increase the laboratory capability as well as provide AFIT with a very useful recording instrument.

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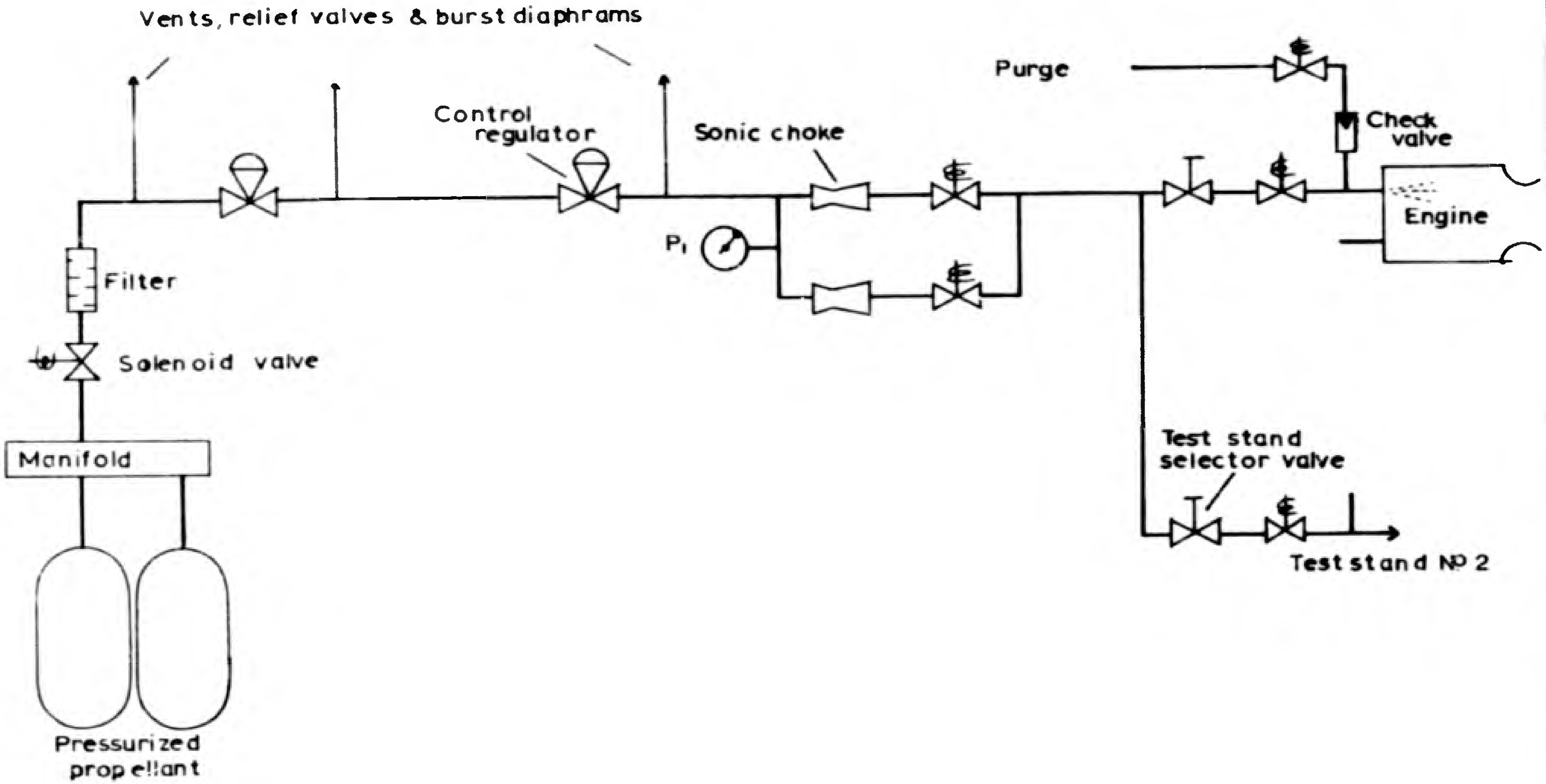


Fig. 1 Simplified Schematic of Single Propellant Circuit

Appendix A

Propulsion Feed System

System Design

The gaseous propellant feed system offered in Fig. A-1 has been designed to meet the AFIT requirement as stated in the introduction to this report. For the purpose of the design calculations, the following assumptions were made:

Engine thrust	500 pounds
Injector pressure	350 psia
Fuel	Hydrogen gas at 70°F
Oxidizer	Oxygen gas at 70°F

A specific impulse of 350 seconds was assumed for a typical hydrogen-oxygen engine yielding a required mass flow rate of 1.43 pounds per second. On the basis of the above information, and considering mixture ratios of r = 1, 3, and 8, the hydrogen and oxygen flow parameters have been calculated and summarized in Tables A-1 and A-2.

Table A-1

Hydrogen Flow Characteristics for 500 Pound Engine

Note: Smooth tubing, 0.9-inch internal diameter

r	$\dot{w}_F$ (lbm/sec)	Flow (scfm)	Reynolds Number	Velocity at 400 psia (ft/sec)
1	0.72	8280	20.3×10^5	1150
3	0.36	4160	10.4×10^5	575
8	0.16	1340	4.6×10^5	256

Table A-2

Oxygen Flow Characteristics for 500 Pound Engine

Note: Smooth tubing, 0.9-inch internal diameter

r	$\dot{w}_o$ (lbm/sec)	Flow (scfm)	Reynolds Number	Velocity at 400 psia (ft/sec)
1	0.72	532	9.1×10^5	70
3	1.07	775	13.5×10^5	105
8	1.27	918	16.0×10^5	125

System Description

Gas Flow. A gaseous propellant is supplied to the gas manifold from a series of high pressure gas containers or trailers which are located outside the test cell (see Fig. A-2). Gas is admitted to the system through solenoid valve V1 (see Fig. A-1); with this valve open, the portion of the line upstream from the first pressure regulator (R1) is pressurized to manifold pressure. This pressure is displayed on gauge G1 for the operator's information and sensed by pressure switch PS, which is closed when the system falls below an adjustable, preset pressure. Valve V7 permits venting of gases that may be trapped between valve V1 and regulator R1. Hose coupling HC and valve V6 allow complete system purging for maintenance and other purposes. Filter F1 accepts filtering elements capable of removing particles as small as two microns from the gas stream. This size filter will remove most of the suspended contaminants found in oil pumped hydrogen (Ref. Appendix D).

Regulators. Regulator R1 is a high pressure regulator which supplies control regulator R2 with a constant upstream pressure. The regulator manufacturer quotes approximately 5 psi change in regulated pressure for each 100 psi variation of inlet pressure. Consequently, for accurately controlled pressure at the flow metering sonic choke or venturi, two stage regulation is necessary. The regulator R1 is set to a nominal dome pressure, approximately 110 psi greater than that required at the metering venturi, by means of needle valves V10. High pressure nitrogen gas is admitted to the regulator dome through one valve and released through the other valve of the V10 pair. Pressure gauge G2 on the dome circuit indicates the dome pressure while the other gauge displays the regulated pressure.

Valve V8 is provided to vent gases that may be trapped between regulators R1 and R2. A pressure relief valve, adjustable between 1000 and 2200 psi, protects downstream components from excessive pressures that might build up if regulator R1 develops a very slow "whisper" leak. In the event of a gross failure of regulator R1, the excess pressure is relieved through a burst diaphragm which is set at 10% above the pressure relief setting.

The system components upstream of regulator R2 are located outside the test cell and are grouped for easy control and operation during the pre-run checkout. System status is visually assessed by means of the pressure gauges and the quarter-turn hand-operated valves.

For operator protection the hand-operated valves of the oxygen system (V6, V7, and V8) must be fitted with flame shields and extension handles. Similarly, the dome loading valves V10 of the oxygen regulator R1 should be located remote from the regulator (Ref. Appendix F).

Regulator R2 is a critical regulator which controls the mass flow rate of the propellant gas. The regulating dome pressure is controlled by two solenoid valves, V11, which are actuated from the control console.

To pressurize the dome, load valve V11 is opened and gas slowly admitted through a restricting orifice in the valve coupling, and the charging is continued until the desired pressure is indicated on precision gauge G3 located in the control room. In the event that the desired pressure is exceeded, vent valve V11 is briefly opened as well as solenoid valve V9. These valves vent both the regulator dome and propellant line downstream from R1. Load valve V11 is again actuated to approach the desired pressure. A pressure relief valve, adjustable between 600 and 1200 psi is located in this regulated line to protect downstream components. This protection enables lower pressure and more economically priced components to be used in the lower pressure portion of the system.

Flow Control. Sonic chokes S1 and S2 provide flow control and measurement capability. The mass flow through this sonic choke is given by (Ref 3:62).

$$\dot{w} = \frac{P_1 A_t C_D}{C^*} \tag{1}$$

For a fixed nozzle, $A_t C_D$ is known and variations in C^* are approximately 1% for each 10°F change in gas temperature (ambient); hence, mass flow of the gas propellant is taken as a direct function of the upstream pressure P_1. The throat area of choke S2 is selected to give the required "run" mass flow at a pressure that will ensure approximately 20% pressure drop across the choke. This sonic choke, referred to as a cavitating venturi by the manufacturer (Fox Valve Corporation), is an accurately machined venturi with a discharge coefficient (C_D) very nearly unity (0.99). This choke is supplied in either fixed or variable area models complete with calibration data. The manufacturers, as well as users of this choke (Ref Appendix D) claim pressure losses of 10 to 15% (Ref 4).

The throat area of choke S1 is selected to give a suitable starting flow rate and mixture ratios at the pressure established for S2. The pressure upstream from the sonic choke is displayed in the control room on precision gauge G3. A pressure transducer and temperature probe provide outputs which may be recorded on the oscillograph for permanent record.

The controlled mass flow of gas can be directed to the desired stand by opening manual valves V4 on the test stand. Solenoid valve V5 is actuated at the same time V2 or V3 is energized; however, V5 cannot be operated until the system is "Armed" (Appendix B). Valve V5 and the "T" connection of the purge gases are located as closely as possible to the test engine to ensure minimum shutdown time and conservation of propellant gases.

Purge System. The purge system provides gas for quenching the test engine, purging the system for maintenance purposes, and provides regulated gas pressure for pressurization of dome regulators. The purge gas, nitrogen, is admitted to the system through V2 and filtered by F2. This filter may be locally constructed and packed with glass wool to ensure that no foreign particles enter the system. Gauge G1 displays manifold pressure and pressure switch PS provides a low pressure warning to the control room. Regulator R3 controls the purge pressure, which is usually set to about 80% of the propellant injector pressure. Valve V44 admits purge gas to the test stand in use, and valves V12 admit purge gas to the propellant lines through check valve C1. Regulator R4 is a small, low capacity regulator which controls the gas pressure used to pressurize the dome regulators. The main purpose of this regulator is to prevent accidental over-pressurization of the dome regulator and to give more uniform response to operation of the respective loading valves.

Test Stand Connection. At each of the selected test stand locations, an angle iron and sheet steel frame is rigidly attached to the test cell floor. On this frame are mounted the propellant and purge valves, microswitches, as well as the test stand igniter. These components are mounted on and behind the steel plate which protects them from a possible engine fire. Only igniter terminals and tubing couplings protrude through this metal plate. Suggested dimensions are a 1/8 inch steel plate about 18 inches square, mounted about three feet above the floor on two inch angle iron. This plumbing termination is located beside the proposed test stand location so that a minimum length of flexible or rigid tubing is required to reach the engine connections. This side location would not interfere with the location of a lengthy thrust measuring stand. This means of terminating the propellant lines can reduce some of the plumbing clutter and also reduce the number of joints, elbows, etc., that are associated with more makeshift arrangements. Figure A-2 gives a recommended component and laboratory layout.

Igniter. The propulsion control system includes provision for a 28-volt dc igniter at each test stand. An ideal device for this purpose is the T-33 jet engine spark ignition system. A small aircraft or motorcycle spark plug can be fitted to the test engine for in-chamber ignition.

System Efficiency. A schedule of pressure losses for the propellant feed systems at maximum capacity, i.e., operation of a 500 pound thrust engine is given in Tables A-3 and A-4 and Figs. A-3 and A-4. Pressure drops and total system losses are acceptable with the exception of the high pressure drop in the hydrogen system at a flow of 0.72 lbm per second, corresponding to a mixture ratio of r = 1. From this data, it is evident that some pressure loss is experienced in the second stage of pressure regulation, but this will be offset by improved system accuracy and a general reduction in operating costs. The greatest system losses are encountered at the low pressure portion of the system, in particular, across the final propellant solenoid valves and flow metering sonic choke. These calculations allow for 20% pressure loss across the choke where in many cases it may only be 10% when operating at optimum throat area. Sample calculations of pressure losses are given at the end of this appendix. It should be noted that the pressure drop across some of the solenoid valves is based on a specified flow coefficient rather than the coefficient of a particular manufacturer's valve. This topic is discussed further in the section of this appendix which concerns component selection.

System Response. The design of the system allows rapid response since propellant gases at the preselected pressure and mass flow rate are present at valve V5. This valve is located as close to the engine as practical, about five feet in most cases, so that rapid system response is achieved even at low gas velocities.

Because the purge valves are located close to the test engine, purge time is reduced and rapid shutdowns achieved at low pressures. A purge pressure of about 300 psi will give a 0.2 second shutdown. Of course, less rapid response is realized at lower purge pressures.

Throttling. This system as shown in Fig. A-1, is intended for short duration runs at accurately controlled mass flow rates. Three mass flow rates are possible during a test run:

(1) start rate

(2) run rate

(3) start and run rate.

For tests where a greater degree of throttling control is required, the following system modifications are possible.

The first and most practical modification is to install additional sonic chokes in parallel with the existing start and run chokes. Three chokes would give seven accurately known flow rates on selection from the control console.

A second modification would be to use servo driven variable orifices; this is not as straight-forward as the first system, but it is being successfully employed at United Technology Center.

Additional means of controlling mass flow would be to adjust the dome pressure during a test run. This could best be accomplished by connecting the regulating domes of the respective propellant regulators together, thus permitting the same dome pressure variations to be sensed by both regulators. This technique would rely heavily on nearly identical regulator characteristics and consequently would be of dubious accuracy.

Safety. The system as described gives maximum component protection. This is achieved by the use of pressure relief valves, blow-out diaphragms, and regulation of dome loading pressure. Pressure switches located on the supply manifold warn the operator of insufficient pressures for reliable and safe operation. These switches operate interlocks to prevent the system from being operated should the supply pressures be too low. Valves V1, V2, V3, and V5 are all normally closed valves and can be closed simultaneously on emergency shutdown or on power failure. The control and operation of these valves will be discussed fully in Appendix B. Pressure gauge G3 is equipped with a pneumatic transmitter that precludes propellant gases from the control room. In addition, the indicating gauge is housed in a blow-out proof housing.

Electrical safety in the test cell is a compromise between absolute safety, cost, and flexibility. The unofficial accepted rule in the rocket testing field recommends explosion-proof lighting and permanent fixtures such as exhaust fans, etc., which use 115 volts ac. All control circuits to the test cell are operated on 28 volts through adequate wiring and properly fused circuits. Non-sparking devices, such as solenoids, are not afforded explosion-proof housings but are equipped with spark suppressing diodes. All cable connectors are "potted" to prevent sparking as a result of cable wear or abuse. Sparking sources, such as microswitches and relays, are enclosed in vapor-proof housings.

Other precautions are adequate ventilation, explosive concentration detectors (see Appendix F), and such common sense rules as apply to aircraft circuits.

Component Selection

A detailed study of the literature from a number of gas system component manufacturers was made in order to arrive at the best compromise between system cost, required capacity, desired efficiency and response, and the usable components of the existing system. This led to the selection of high capacity, nominal 1.0-inch components and 1.0-inch outside diameter stainless steel tubing. Wherever possible, stainless steel or other oxygen inert materials are specified for the propellant system as well as the purge system. This involves higher initial cost; however, it ensures a virtually maintenance free system with a minimum of internal corrosion.

The hand-operated valves in the system were specified as quarter-turn ball valves. This type of valve has maximum flow coefficient (C_v). The quarter-turn handle allows positive visual indication of valve position. The manual valves V10 which are used to pressurize the dome of regulator R1 are specified as needle valves for ease of control.

The selection of solenoid valves is made difficult by the fact that high capacity solenoid valves, suitable for gaseous oxygen or hydrogen service, are expensive. Only one or two types of solenoid valves were, without reservation, recommended by experienced personnel at Wright-Patterson AFB. The Marrota valve, which is qualified for flight and space applications, is one such valve; however, its cost is beyond the present AFIT budget. A more moderately priced valve, the Atkomatic, has been selected on the basis of the manufacturers specification. For the purpose of design calculation and determination of system pressure losses, a C_v of 10 has been specified for the solenoid valves in the propellant system. The Atkomatic valves have sufficient capacity; however, if an alternate valve is selected, it should have a C_v rating of no less than 10 if system pressure losses are to meet the estimates.

A recommended parts list for the propellant system is given in Table A-5. This list does not include miscellaneous hardware such as tubing, adapters, etc.

Possible Compromises

The propellant feed system cost may be reduced if only one stage of pressure regulation, regulator R2, is used. However, poor system regulation and varying mass flow rates will result. Additional funds may be saved should only one test stand be equipped with 1.0-inch propellant valves and the other stands fitted with 0.75-inch components. One inch outside diameter tubing should be used throughout the system so that the rated system capacity may be realized by the installation of the larger capacity valves.

Should one set of propellant and purge solenoid valves be used to operate all of the test stands, at least 25 to 30 feet of propellant line would be required between the propellant valves and purge injection "T" and the test engine. This length of line increases the system response considerably, thus reducing the effectiveness of the proposed engine protecting cutouts. Propellant gases would be wasted while purging the system both at start-up and shutdown. In addition, engine start-up is apt to be erratic due to unknown starting mixture.

Table A-3

Propulsion Feed System - Oxygen Pressure Losses

		$\dot{w}_o$ = 0.72 (lbm/sec)		$\dot{w}_o$ = 1.07 (lbm/sec)		$\dot{w}_o$ = 1.27 (lbm/sec)	
Item	C_v	P_2	ΔP	P_2	ΔP	P_2	ΔP
Tube 5 ft.	27**	350	1	350	2	350	4
Valve V5	10	351	8	352	18	354	25
Valve V4	35	359	1	370	1	379	2
Tube 15 ft.	15**	360	4	371	8	381	11
Valve V3	10	364	8	379	16	392	24
Choke S2	*	372	74	395	79	416	84
Tube 5 ft.	17	446	2	474	6	500	8
Regulator R2	7.5	448	18	480	25	508	30
Tube 20 ft.	13**	466	4	505	8	538	12
Regulator R1	7.5	470	16	513	22	550	28
Filter F1	18	486	2	535	4	578	8
Valve V1	10	488	5	539	9	586	12
Tube and Manifold	16**	493	2	548	5	598	8
Min. Manifold Pressure		495		553		606	

Note: P_1 at injector = 350 psia

* ΔP (maximum) across choke is 20% P_1

** equivalent (calculated)

Table A-4

Propulsion Feed System - Hydrogen Pressure Losses

		$\dot{w}_F$ = 0.16 (lbm/sec)		$\dot{w}_F$ = 0.36 (lbm/sec)		$\dot{w}_F$ = 0.72 (lbm/sec)	
Item	C_v	P_2	P	P_2	P	P_2	P
Tube 5 ft.	27**	350	1	350	4	350	17
Valve V5	10	351	7	354	33	367	120
Valve V4	35	358	1	387	3	487	9
Tube 15 ft.	15**	359	5	390	14	496	60
Valve V3	10	364	7	404	30	556	90
Choke S2	*	371	74	434	86	646	129
Tube 5 ft.	12	445	3	520	16	775	35
Regulator R2	7.5	448	8	536	25	810	90
Tubing 20 ft.	13**	456	4	561	16	900	38
Regulator R1	7.5	460	8	577	23	938	80
Filter F1	18	468	2	600	6	1018	22
Valve V1	10	470	3	606	8	1040	35
Tube and Manifold	16**	473	3	614	6	1075	12
Min. Manifold Pressure		476		620		1087	

Note: P_1 at injector = 350 psia

* P (maximum) across choke is 20% P_1

** equivalent (calculated)

Table A-5

Propulsion Feed System, Recommended Parts List

Description	Item	Manufacturer and Part Number	Each	Est. Cost Ea. ($)	Remarks
Main H.P. valve	V1	Atkomatic HPSS 8404 1.0 in.	2	240	24 Vdc, nc
Purge H.P. valve	V2	Jamesbury HP33GT 1.0 in.	1	55	
Vent valves	V6,7,8	Jamesbury HP33GT 0.25 in.	7	24	
Manual loader valve	V10	Imperial-Eastman 700-cs-.25	6	5	
Stand valve	V4	Jamesbury A33GT 1.0 in.	2	35	two per test stand
Stand valve, purge	V44	Jamesbury A33GT 0.75 in.	1	30	one per test stand
Load and vent valves	V9,11	Hoke 0.25 in.	6	25	24 Vdc, nc
Start valve	V2	Atkomatic SS8300 0.75 in.	2	160	24 Vdc, nc
Run valve	V3	Atkomatic SS8400 1.0 in.	2	220	24 Vdc, nc
L.P. propellant valve	V5	Atkomatic SS8400 1.0 in.	2	220	24 Vdc, nc two per test stand
H.P. regulator	R1	Grove 448-06	2	570	
Control regulator	R2	Grove GB 326-06	2	230	

Table A-5 (continued)

Description	Item	Manufacturer and Part Number	Each	Est. Cost Ea. ($)	Remarks
Hose coupling	HC	Snap-tite	3	20	
Burst diaphragm	BD	Local manufacture	4	-	

Note: Prefix designating propellants is omitted from item listing.

Item list refers to Fig. A-1.

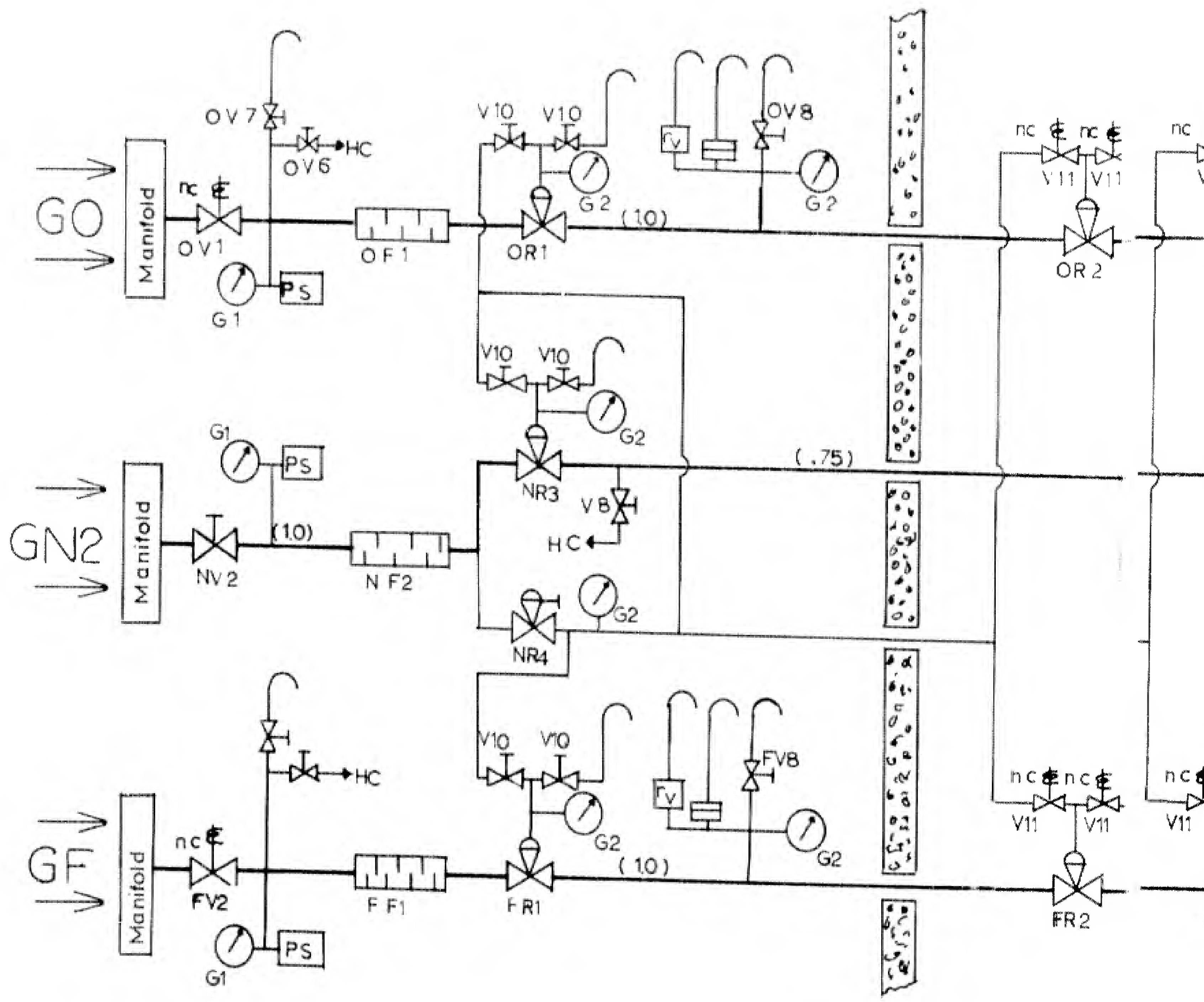
H.P. High pressure

L.P. Low pressure

nc Normally closed

Table A-5 (continued)

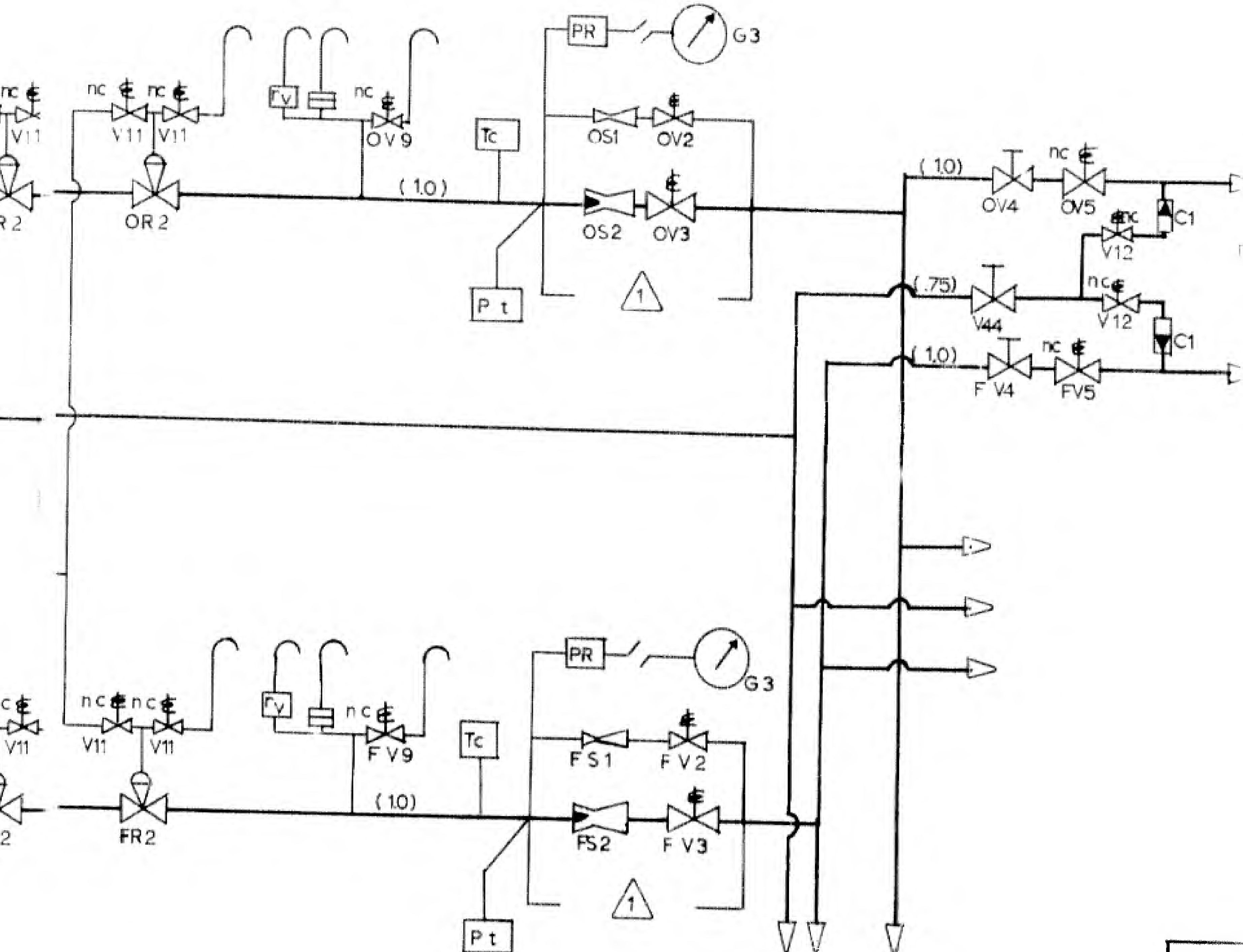
Description	Item	Manufacturer and Part Number	Each	Est. Cost Ea. ($)	Remarks
Purge regulator	R3	Grove WBX 204-03	1	-	on hand
Regulator	R4	Victor welding regulator	1	60	or equivalent
Filter	F1	Microporous 4727 1.0 in.	2	350	"T" configuration
Filter	F2	Glass wool pack	1	-	local manufacture
Purge check valve	C1	Circle seal 2495-6pp .75 in.	2	30	
Gauge	G1	US Gauge 0-3000 psi	3	10	
Gauge	G2	US Gauge 0-2000 psi	6	10	
Gauge	G3	Ashcroft gauge 1377A	2	42	0.5
Pneumatic repeater	PR	Ashcroft 1260A	2	114	0.5
Sonic choke	S1	Fox cavitating venturi .75 in.		80	size to flow requirement
Sonic choke	S2	Fox adjustable venturi 1.0 in.		500	
Pressure switch	PS	Barkedale B1T-H32	3	38	
Relief valve	RV	Manatrol RA-600-4	2	30	1000-2200 psi
Relief valve	RV	Manatrol RA-400-3	2	30	600-1200 psi



Note: (1) Numbers in parenthesis refer to outside diameter of tubing.

(2) Vent and control lines to be 0.375 in. outside diameter of tubing.

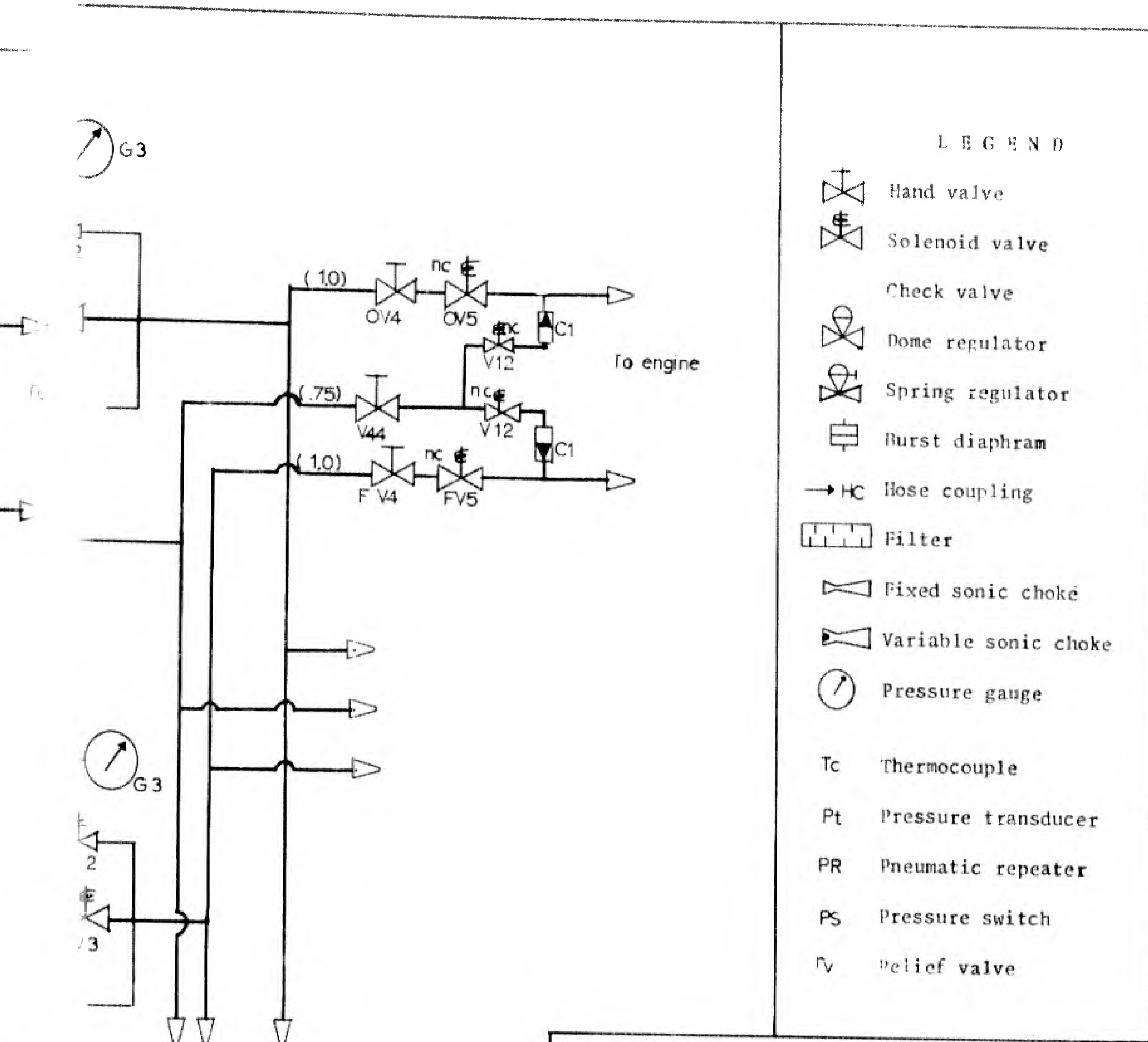
A



(3) Vents must be carried to the roof of the test cell, separately or in a suitable common stack.

(4) Loading valves V10, associated with regulator OR1 must be at least ten feet from the regulator.

B



1 A third sonic choke and valve may be added here for greater throttling capability.

1 of the test cell,

ck.

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Fi

Fig. A-1 Propulsion Feed System

C

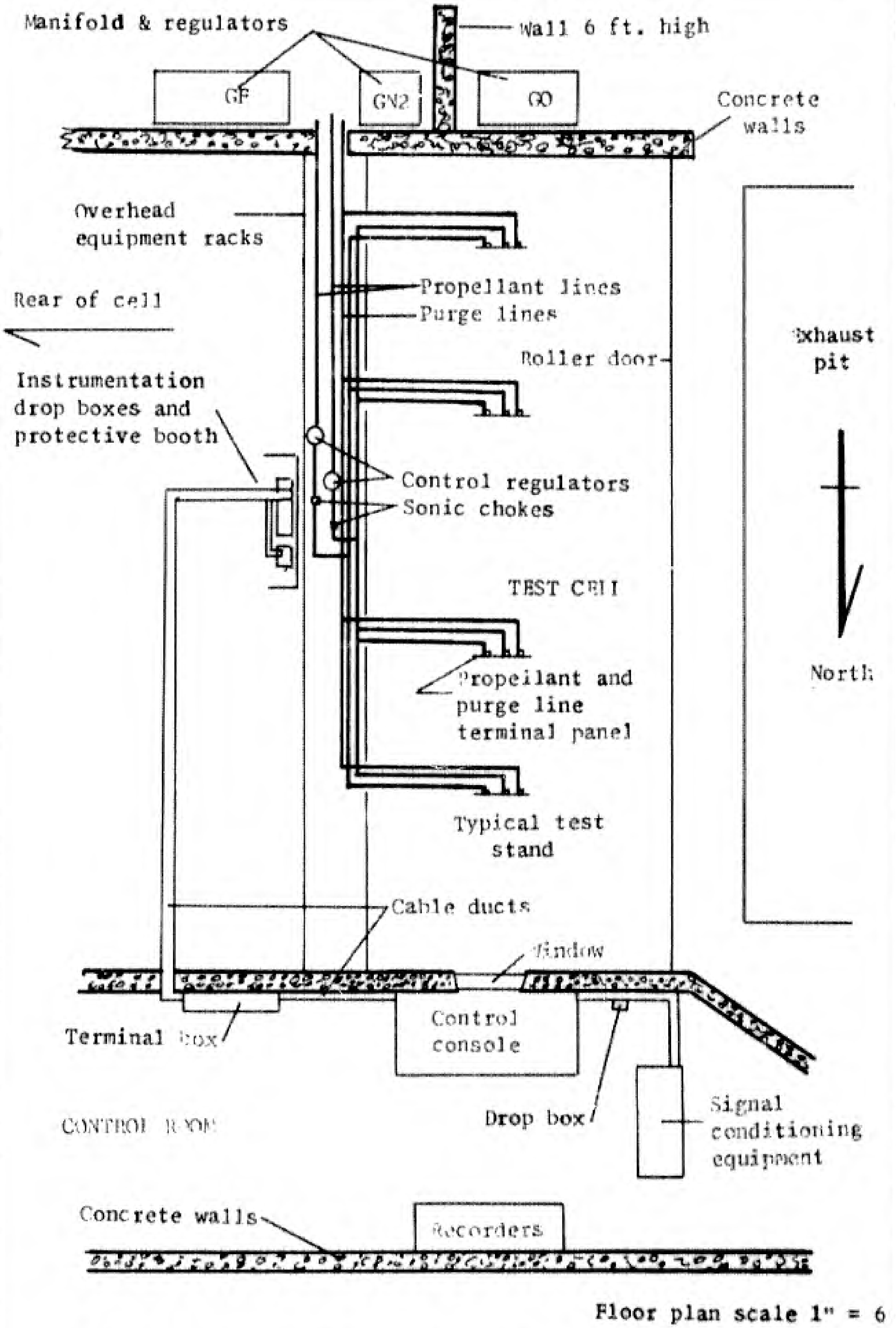


Fig. A-2 Proposed Layout Propulsion Laboratory

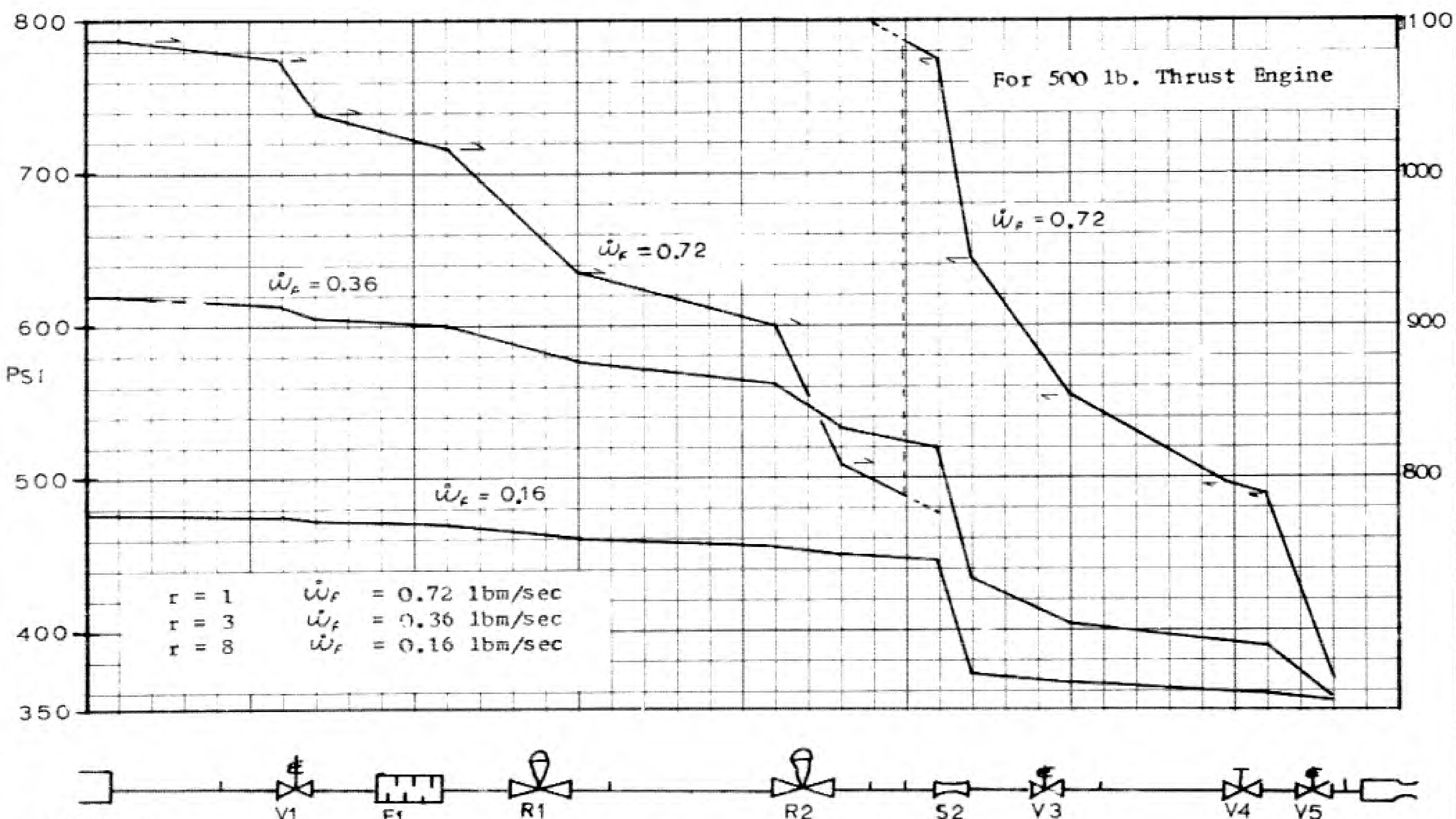


Fig. A-4 Hydrogen System Pressure losses

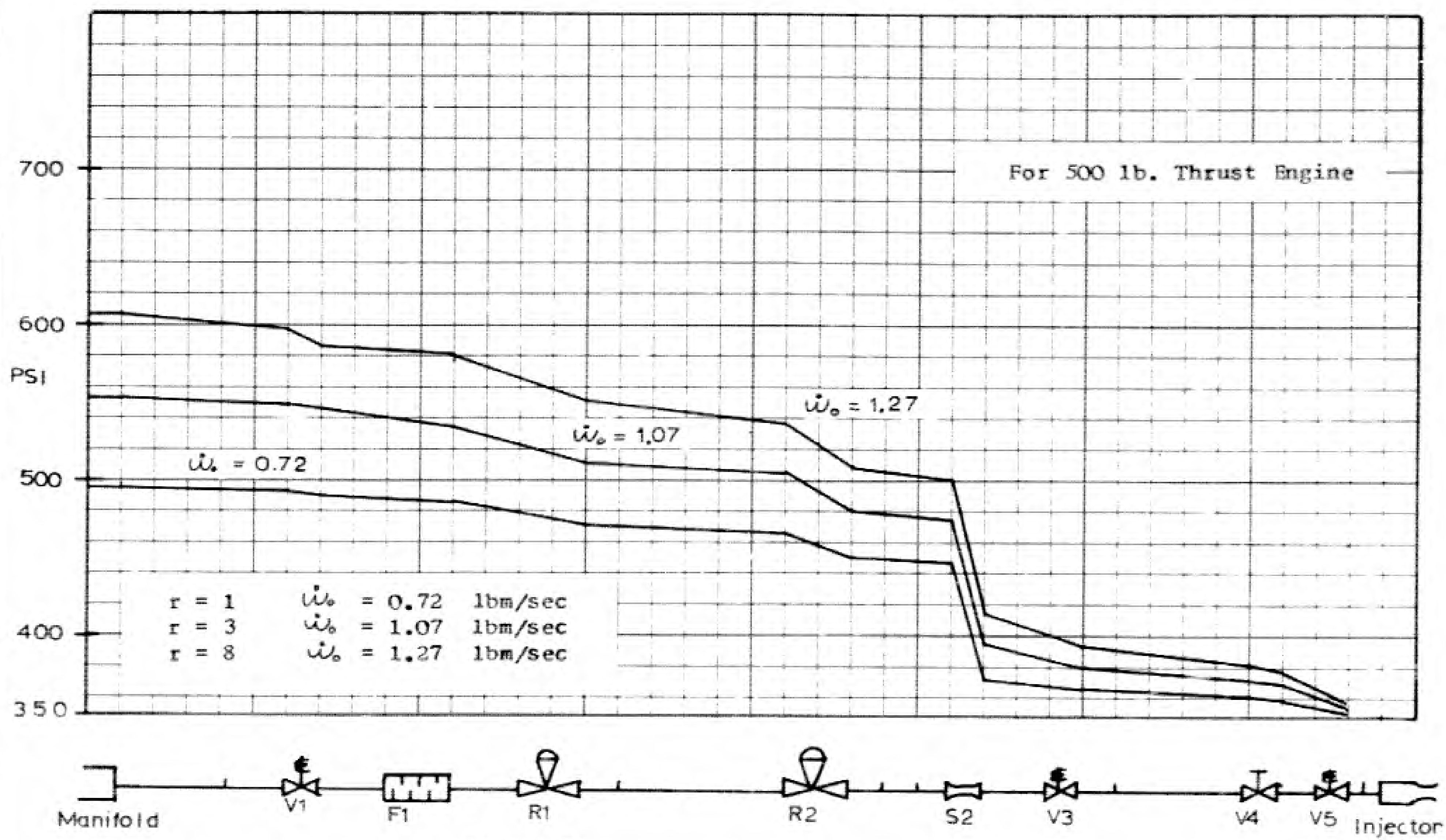


Fig. A-3 Oxygen System Pressure Losses

Sample Calculation

The following is an example of how the pressure drop across a component or length of tubing with fittings was calculated.

The estimation of the system pressure losses given in Tables A-3 and A-4 was expedited by the use of a "Valve Slide Rule" manufactured by the Worthington Corporation and the nomographs published in the Crane Company Technical Paper 410. This publication entitled, "Flow of Fluids Through Valves, Fittings, and Pipes," contains a number of nomographs based on the Darcy-Weisbach or Fanning equation.

The pressure drop across a valve with a known C_v is determined directly from the "Valve Slide Rule" by setting the gas specific gravity, mass flow, operating pressure, flow coefficient (C_v), and reading the pressure drop in pounds per square inch.

The pressure drop of a 15-ft. length of tubing (0.9 in. ID) with one flow-through "T" is determined as follows:

Oxygen flow = 0.72 lbm/sec

= 2590 lbm/hr

Oxygen specific gravity at standard conditions

(14.7 psia and 70 F^o) = 1.10

Friction factor f = 0.011

(Crane A-32)

L/D equivalent for flow-through "T" = 20

(Crane A-30)

Using relationship for resistance coefficient K

$$K = f\ L/D \qquad \text{(Crane 3-4)}$$

where L/D is equivalent length in pipe diameters.

$$K = \frac{0.011 \times 15 \times 12}{0.9} + 0.011 \times 20$$

$$K = 2.53$$

from nomograph (Crane A-32), equivalent flow coefficient C_v = 15.

"Valve Slide Rule" settings:

$$C_v = 15$$

specific gravity = 1.10

operating pressure = 360 psi

yields pressure loss, Δp = 4 psi.

Appendix B

Propulsion Control System

Introduction

The propulsion control system (Fig. B-1) has been designed to operate the propulsion feed system with safety, flexibility, and ease. The system description follows the approximate operating sequence from the application of system power, through engine operation, to shutdown. Additional system features, parts lists, and fabrication notes are given at the end of this appendix.

System Description

Power. The main system power is drawn from a 50 ampere, 28 volt dc supply located in the control room. Upon closing Power switch (S6), a circuit breaker switch, power is applied to the control console, to valve position indicators, pressure switches and to the emergency power supply charging circuit (a 28 volt aircraft battery). Power to the remainder of the system passes through the normally closed Emergency Shutdown (ESD) switch (S3) to the three position Ready switch (S1).

System Preparation. The Ready switch is selected to one of two positions, "Ready manual" or "Ready sequencer". The closing of the Ready switch (S1) permits system check-out and preparation, engine purge, and valves V1 on the oxidizer and fuel system to be opened; it also permits the control pressure regulators R2 to be loaded to the required pressure. Switch SV11 in load position (L) admits nitrogen to dome of the regulator R2; reversal of this switch to (V) vents the dome of the regulator R2 and the line downstream. The line downstream of valves V2 and V3 may be vented by operating either of these valves as desired. While the system is in Ready status, momentary switch (S7) may be operated to purge the test engine.

Safety Plug. A single Safety plug (Js) (Fig. B-1 and B-2) is provided which performs two functions. In addition to serving as a safety plug, it permits selection of the test stand to be operated.

Plug (Js) is a single male connector with appropriate pins shorted within its shell. This plug is inserted in its socket on the control console only when the system is about to be used and when the test cell is clear of all personnel.

Engine Run. The propulsion system is prepared and operating pressures established while the system is in Ready status; however, final system propellant valves V5 and the system igniter cannot be operated until key-operated Arm switch (S2) is closed. Closing of the Arm switch actuates relay K11 and, one-half second later, relays K3 and K4, permitting valves V5 to be operated in parallel with valves V2 or V3. The safety interlock relays K1 and K12 must be closed before the power from the Ready buss reaches the Arm buss. Safety interlocks such as door switches, explosive vapor detectors, will operate the interlock relay K1 and prevent the system from being Armed. Engine firing is accomplished by actuating the fuel and oxidizer switch (SV2-O and SV2-f) and Igniter switch (S5). Changes in propellant mass flow rates are realized by the operation of switches (SV3-O and SV3-F) and (SV33-O and SV33-F) if a third control venturi and valve are included in the propellant line. Power relays PK5-O and PK5-F have a short delay before drop-out to accommodate break-before-make switch S10, which is explained later.

Non-Combustion Cutoff. Pressure switch SP2, installed on the test engine, operates in conjunction with relays K8 and K12 to provide an automatic cutoff if combustion has not commenced within two seconds after the opening of main propellant valve V5. The armature circuit of relay K12 is completed through delay relay K8 or pressure switch SP2. If the pressure switch has not been closed before relay K8 opens (two seconds after operation of V5), the ground is removed from relay K12 and the Arm circuit opens. This event is indicated by a malfunction light on the control console. Switch S12 is provided to defeat this pressure switch; alternately, if this cutoff is not desired by an operator, plug-in relay K12 can be replaced by a suitably wired male octal connector. For some applications an automobile brake light switch, which operates between 50 and 80 psi, has been found suitable for use as a pressure switch.

Engine Shutdown. If desired, the system may be shut down by closing Purge switch (S7), quickly followed by opening switches (SV3-O and SV3-F) in the order required to achieve a smooth shutdown.

The system may be more conveniently shut down by pressing momentary Auto-Stop switch (S4). This switch removes the short circuit from the coil of 12 volt relay K2, permitting it to operate. This allows the operation of time delay relay K7, which applies a two-second (adjustable between 0 and 5 seconds) purge to the system. At the same time the purge commences, relay K3 opens, cutting off system fuel; approximately one-half second later, time delay relay K4 opens, cutting off the oxidizer flow. Relays K3 and K4 are plug-in type and may be interchanged to permit delay (adjustable) operation of one or both relays as required for smooth system shutdown.

Emergency Shutdown. An emergency shutdown (ESD) of the test engine is accomplished while the system is in Ready status. The ESD switch

(S3), in series with the Ready switch (S1), removes power from all normally closed valves in the propulsion feed system. In addition, it applies power from the main power buss, or emergency battery supply in case of power failure, to the purge system and vent valves V11 and V9. These valves remove pressure from the dome of control regulator R2 and the line downstream. System purge will continue as long as the ESD switch is actuated; however, purge (and venting) may be terminated by turning off Ready switch (S1).

In order to prevent the engine from restarting after a momentary power interruption or deactivation of the ESD, an interlock has been incorporated which will open the Arm buss if power has not been restored in the proper sequence. Relay K10 is a 0.5 second delay operate relay. If the Ready switch (S1) is closed within 0.5 seconds after closing Power switch (S6) or the ESD switch (S3), power will be drawn from the Ready buss, mechanically latching relay K9. This situation is indicated by a malfunction light on the control console. Relay K9 operates relay K1, opening the Arm buss. Relay K11 is a 0.5 second delay operate relay which delays activation of the Arm buss, preventing possible pulsing of valves V5 while relays K9 and K1 are in the process of opening the Arm buss. Latching relay K9, located on the control console vertical panel, must be manually released before normal system operation can be resumed.

<u>Deluge</u>. Selective deluge is achieved by closing appropriate Deluge switches (S14), which are located adjacent to the fire warning lights. The deluge is available at any time by operating the desired switch, power being drawn from the Power buss, or in its absence, directly from the battery which is connected to the deluge circuit automatically when the main Power buss is off.

System Check Out Switch. System check out switch (S8) may be opened to permit a control console check. This switch removes the ground return from all the solenoid valves in the test cell. The system may now be "operated" including "firing" and "ignition", ESD, Auto-Stop, etc., and the results observed by the operation of the console pilot lights. This check obviously will not prove valve functioning but will permit confirmation that switches are being properly operated and sequenced. Removal of the Safety plug (Js) will provide an additional safety measure during this check.

Sequencer Operation. A manually stepped sequencer which will permit and encourage "heads up" operation of the control console has been devised. It consists of the Amp matrix board and a row of interlocking illuminated push buttons (S10). This push button selector permits the depression of only one button at a time, similar to the familiar auto radio push button operation. The test to be performed is programmed on the matrix board by inserting pins in the appropriate holes so that top-to-bottom operation of the push buttons will control all phases of the system operation including instrumentation, ignition, throttling, and shutdown. Programming cards are available which may be placed over the matrix pin board. This card is pre-punched so that each hole is filled with a pin and step functions inscribed thereon. The use of this sequencer in no way negates the safety or shutdown features of this system.

The extreme convenience and utility of this switching technique permits the operator to plan his operation well in advance and to perform rapid switching with confidence and minimum opportunity for error. From the schematic (Fig. B-1), it is evident that selector switches (SV2 to SV33) are inoperative when "Ready sequencer" is selected.

The row of switches (S10) and the matrix board invite the use of an automatic sequencer to provide the time base for the operating sequence. The Eagle Signal Company Multiflex Timer, which is an adjustable six circuit electro-mechanical sequencer can be used to replace S10 for fully automatic sequencing.

System Indicators and Interlocks. The hand operated valves V2, V4, and V44 (Fig. A-1) are fitted with vapor-tight microswitches which will provide a selection indication to the control console. The micro-switches on the hand valves at each test stand are wired in series so that positive indication is provided only if all three valves are opened. This indication is given on the respective pilot lights on the control panel.

A variety of system interlocks can be operated in parallel to actuate normally closed interlock relay K1. The "malfunction" panel on the control console (Fig. B-2) is provided to indicate the interlock status.

Application of a voltage to relay K5 will operate the Auto-Stop circuit which will automatically and smoothly terminate an engine run. This cutoff voltage may be derived from access interlocks if so desired, but a more appropriate source would be a rough combustion cutoff unit, low propellant pressure switch, or a meter-relay that senses excessive engine temperature.

Control Console. The system control console (Fig. B-2) contains all of the electrical control switches and associated circuitry for the remote control of experiments in the test cell. The directly controlled variable, the pressure upstream from the flow metering sonic chokes, is displayed on precision gauge G3. This pressure can be converted to a mass flow rate and displayed to the operator by the simple computing circuits included on the sub-panel marked $\dot{w}_o$ or $\dot{w}_F$. Details of this computer are given in this appendix and in Fig. B-3. Panel space has been allocated and the circuits proposed (Fig. B-4) for the display of other test parameters in engineering units, such as thrust, chamber pressure, etc. These signals would be derived from the measurement instrumentation circuits.

A flow chart type of console layout has been used as far as possible. This permits ease of system operation and evaluation of its status. This type of control panel layout is being used at some of the newer rocket test sites and has long been used in industry for process control. The panel layout and system circuits are designed so as to impose minimum operating restrictions on a test and still incorporate all of the conventional safety devices. Considerable experimental flexibility is afforded by this system as designed. Modifications can be readily incorporated by removal of a sub-panel from the console complete with its switches, etc., and installing a new panel made up for the special purpose. The ample use of screw lug terminal strips and spare wires will permit such changes to be made with ease.

An access door in the control console allows access to the safety plug receptacles and the plug-in time delay relays. These relays may be adjusted or selected to meet a particular test requirement.

Test Parameter Display. Some test functions, in particular chamber pressure and thrust, are very useful when displayed to the system operator. The propulsion system control console (Fig. B-2) has provision for the display of such test functions. These functions are derived from the instrumentation system and are conditioned by the circuit given in Fig. B-3. This circuit accepts the paralleled output from the strain gauge or other signal conditioning circuits. An operational amplifier is necessary to prevent the display indicator from loading the transducer output and to provide the necessary current to operate the panel meter.

The panel meter may indicate system output or it may be a meter-relay which can operate as a cutout control. This meter has a dual scale, i.e., 0 - 50 and 0 - 100, to facilitate scale calibration. A series resistor in the meter circuit, as well as the amplifier gain can be adjusted to allow the meter to indicate the test function in engineering units.

The amplifier recommended is the Burr-Brown 1507 transistorized operational amplifier which can be operated on a battery power supply. This precludes problems that may arise from multi-point grounds in the instrumentation system (Ref 5:55).

<u>Mass Flow Computer</u>. An analog computing circuit using a low cost transistorized operational amplifier mechanizes the mass flow equation (1)

$$\dot{w} = \frac{P_1 A_t C_D g}{C^*} \tag{1}$$

The real time computation will aid the experimenter in setting up the experiment and establishing mixture ratios. This mass flow computer designated $\dot{w}_0$ in Fig. B-2 can be built up on a single small chassis and mounted directly in the control console. The operational schematic of this computer is given in Fig. B-4

The output from the strain gauge pressure transducer located upstream from the flow metering sonic choke (Fig. A-1) is proportional to the pressure P_1. This signal, normally ranging from 20 to 40 millivolts, is amplified, isolated, and scaled by amplifier A1. The output from this amplifier is multiplied by A_tC_D, set on potentiometer K1. The value of C^* is set on K3, and amplifier A2 performs the division and outputs the voltage E_o.

A relay operated by the sonic choke selection circuits of the control console allows the computer to display the mass flow rate through the sonic choke in use. The A_tC_D values of these chokes are set on potentiometers K1 and K2, respectively.

The computer is calibrated by closing switch S1, thus providing a voltage equivalent to a known pressure. The instrumentation calibration circuits will provide an equivalent signal. Potentiometer K1 or K2 is set to a calibrated value, and the potentiometer Ra is adjusted to give the proper reading on the indicating meter.

A graph, or other suitable table, is used to determine the values of C^* as a function of temperature for each propellant gas so that an exact value of C^* may be set on potentiometer K3.

This design is based on analog computer theory (Ref 6:133, 159), but it has not been demonstrated. The exact values of the resistors and potentiometers to be used must be confirmed by simulation on an analog computer and by experiment with the actual operational amplifiers purchased. The computer input impedance must be maintained at a high value to ensure that the transducer is not loaded by the computer.

A stable supply voltage of + and - 15 volts is required for the recommended operational amplifiers. This may be derived from mercury cells or a regulated electronic power supply.

Fire Detector. A simple fire detector design is offered (Fig. B-5). The operation is simple; the fuse link, made of fine solder enclosed in a plastic sheath, is strung about the area to be sensed. Heat will melt the solder at about 460°F, opening the circuit and permitting the sensitive plate relay to operate a warning bell and a signal light on the control console (Fig. B-2).

System Wiring

Conventional techniques apply to the construction and wiring of the system, both within the control console and in the test cell. Control cables should be carried in a separate enclosed and pressurized cable duct, similar to that used for the instrumentation system (Ref. Appendix C). This cable duct should be attached to the lower side of the overhead equipment rack. The control system shall be referred to its own ground buss, which is taken to the test cell earth connection by a separate cable. Further details are offered in the fabrication notes.

Fabrication Notes

The following notes are offered for the guidance of the technicians assembling the system:

(1) Terminal strips must be used to make terminations from all switches, pilot lights, relays, and connectors, e.g., no direct wiring from switch to relay or solenoid valve. Terminal strips and electrical connectors must be 20% oversized.

(2) Use color coded wires wherever possible to show Ready, Power, Arm circuits, etc. Test cell cables and individual wires must be numbered.

(3) The use of spade lug connections at the terminal strips will facilitate subsequent modifications.

(4) Safety plug (Js) must be a "Cinch Jones CCT" male connector with shell and wired to "jumper" the respective halves of the mating receptacle.

(5) Microswitches and sparking sources in the test cell must be vapor proof construction.

(6) Connectors to solenoid valves and other components in the test cell must be "potted".

(7) Cables from the duct to the components must be covered with plastic sleeving and have a strain relieving rubber sleeve extending six inches back along the cable from the connector.

(8) Cables to control elements must have ample current rating, 10 amps minimum and be a twisted pair within an insulated sheath.

(9) Each circuit must be properly fused in relation to the load and wire capacity. Fuses or circuit breakers should be of slow blow type.

(10) Spark suppressing diodes must be installed across all solenoids and relay armatures. This diode must be installed as close as possible to the inductance; in the case of solenoid valves, an attempt should be made to install the diode within the shell of the electrical connector.

Table B-1

Propulsion Control System, Major Components Parts List

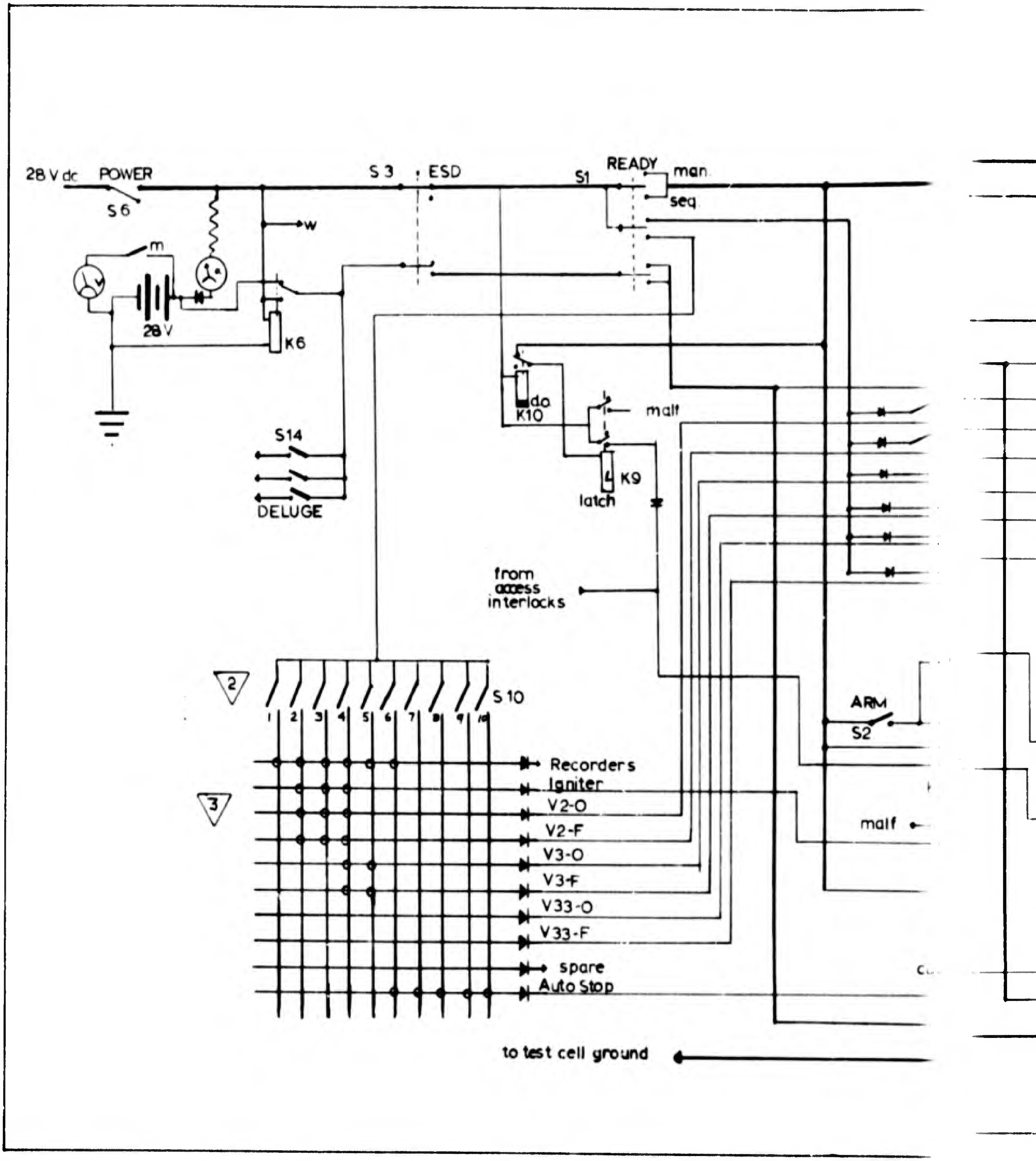
Item	Function	Description	Each	Cost Each
PK	Power relay	Potter-Brumfield KRP5DG24	14	$ 5.00
K1	Power relay	Potter-Brumfield KRP5DG24	1	5.00
K2	Relay	12 Volt DC G.P. relay DPDT	1	5.00
K3	Delay relay	Octal base SPDT 24v, 0-2 sec. delay release	1	20.00
K4	Relay	No delay, same contacts as K3	1	7.00
K5	Relay	Potter-Brumfield KRP5DG24	1	5.00
K6	Relay	Potter-Brumfield KPR5DG24	1	5.00
K7	Delay relay	Same as K3	1	20.00
K8	Delay relay	Same as K3	1	20.00
K9	Latching relay	Potter-Brumfield Latching relay MA	1	15.00
K10	Relay	Potter-Brumfield KRP5DG24	2	5.00
K11	Delay relay	Octal base SPDT 0.5 sec. delay operate	1	20.00
K12	Relay	Potter-Brumfield KRP5DG24	1	5.00
	Diodes	Solenoid protection 1N2070		0.90
	Diodes	Relay protection and logic 1N538		0.60
R1	Resistor	Same as resistance of relay K2	1	0.50
S1	Switch	3PDT center off rotary 15 amp	1	3.00
S2	Switch	Key lock rotary Allen-Bradley	1	10.00
S3	Switch	DPDT guarded, toggle	1	
S4	Switch	SPDT push button, guarded	1	
S5	Switch	SPDT push button, guarded	1	
S6	Switch	Breaker switch 20 amps	1	

Table B-1 (continued)

Item	Function	Description	Each	Cost Each
S7	Switch	SPDT push button, guarded	1	
S8	Switch	SPDT guarded 20 amps	1	
S10	Switches	Switchcraft 211000 + lock bar + switch stacks	1	$40.00
	Matrix	AMP 10 x 10 matrix 397066-2 + pins	1	25.00
SP2	Pressure switch	40-60 psi pressure switch (Auto brake-lite, suggested)	4	

Note: Items refer to Fig. B-1

Unspecified components not critical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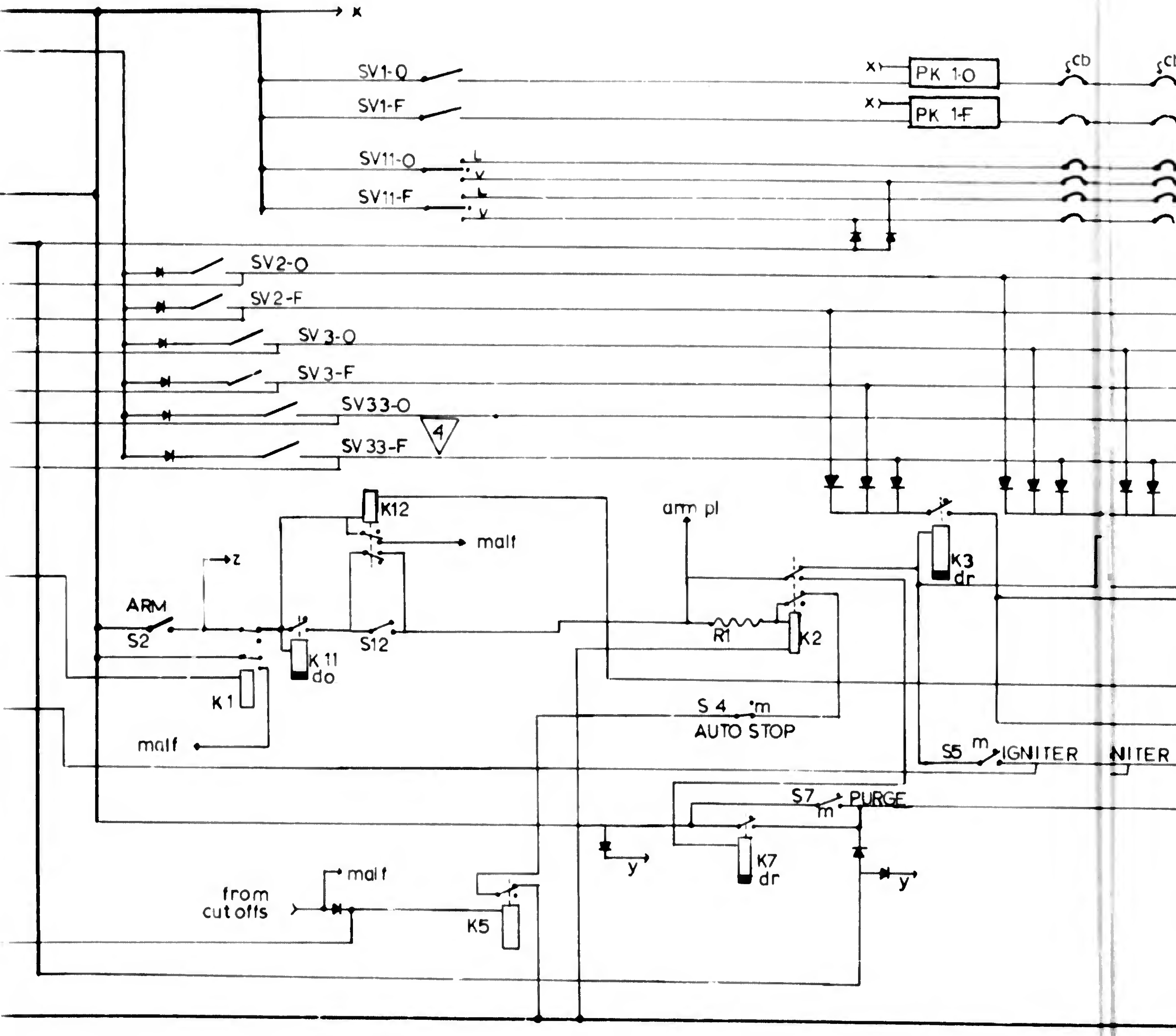
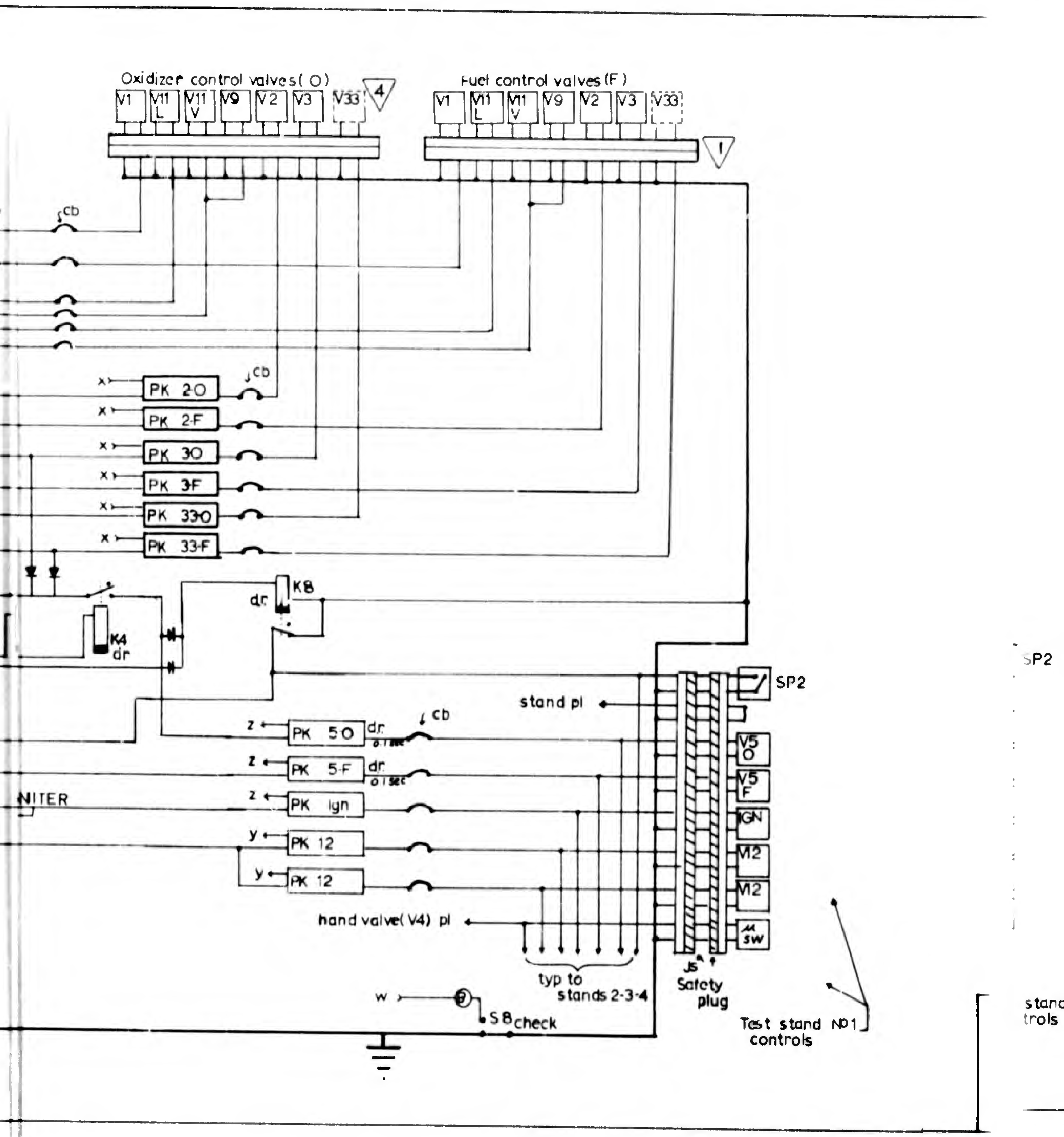
POWER
S 6
S 3
ESD
S1
READY
man
seq
w
m
28 V
K6
do
K10
malf
K9
latch
S14
DELUGE
from
access
interlocks
S 10
ARM
S2
Recorders
Igniter
V2-O
V2-F
V3-O
V3-F
V33-O
V33-F
spare
Auto Stop
malf
to test cell ground

A


x
SV1-O
SV1-F
SV11-O
SV11-F
PK 1-O
PK 1-F
cb
SV2-O
SV2-F
SV 3-O
SV 3-F
SV33-O
SV 33-F
4
K12
malf
arm pl
z
ARM
S2
S12
K 11
do
K1
malf
R1
K2
K3
dr
S 4
m
AUTO STOP
S5
m
IGNITER
NITER
S7
m
PURGE
K7
dr
y
y
malf
from
cutoffs
K5

B


Oxidizer control valves (O)
V1
V11 L
V11 V
V9
V2
V3
V33
4
Fuel control valves (F)
V1
V11 L
V11 V
V9
V2
V3
V33
1
cb
PK 2-O
PK 2-F
PK 3O
PK 3F
PK 33-O
PK 33-F
x
K8
dr
K4
dr
SP2
stand pl
PK 5-O
PK 5-F
PK ign
PK 12
PK 12
z
y
dr
0.1 sec
NITER
V5 O
V5 F
IGN
V12
V12
SW
hand valve(V4) pl
typ to stands 2-3-4
Safety plug
Test stand No 1 controls
w
S8 check

C

Notes:

(1) Ground returns for relays are not shown except for K2, K5, and K6.

(2) Relays are shown in de-energized position.

(3) All relays and solenoids are protected with spark suppressing diodes.

(4) "malf" - circuits lead to malfunction panel shown in Fig. B-2.

(5) (x-x), etc., these points are interconnected, wires not shown.

▽1 Disconnect plug - control circuit may be applied to a different propellant system.

▽2 Interlocked push buttons - one-at-a-time operation (S10).

▽3 AMP Matrix pin board - shorting pins (o) are inserted to program buttons (S10) in a 1 to 10 sequence.

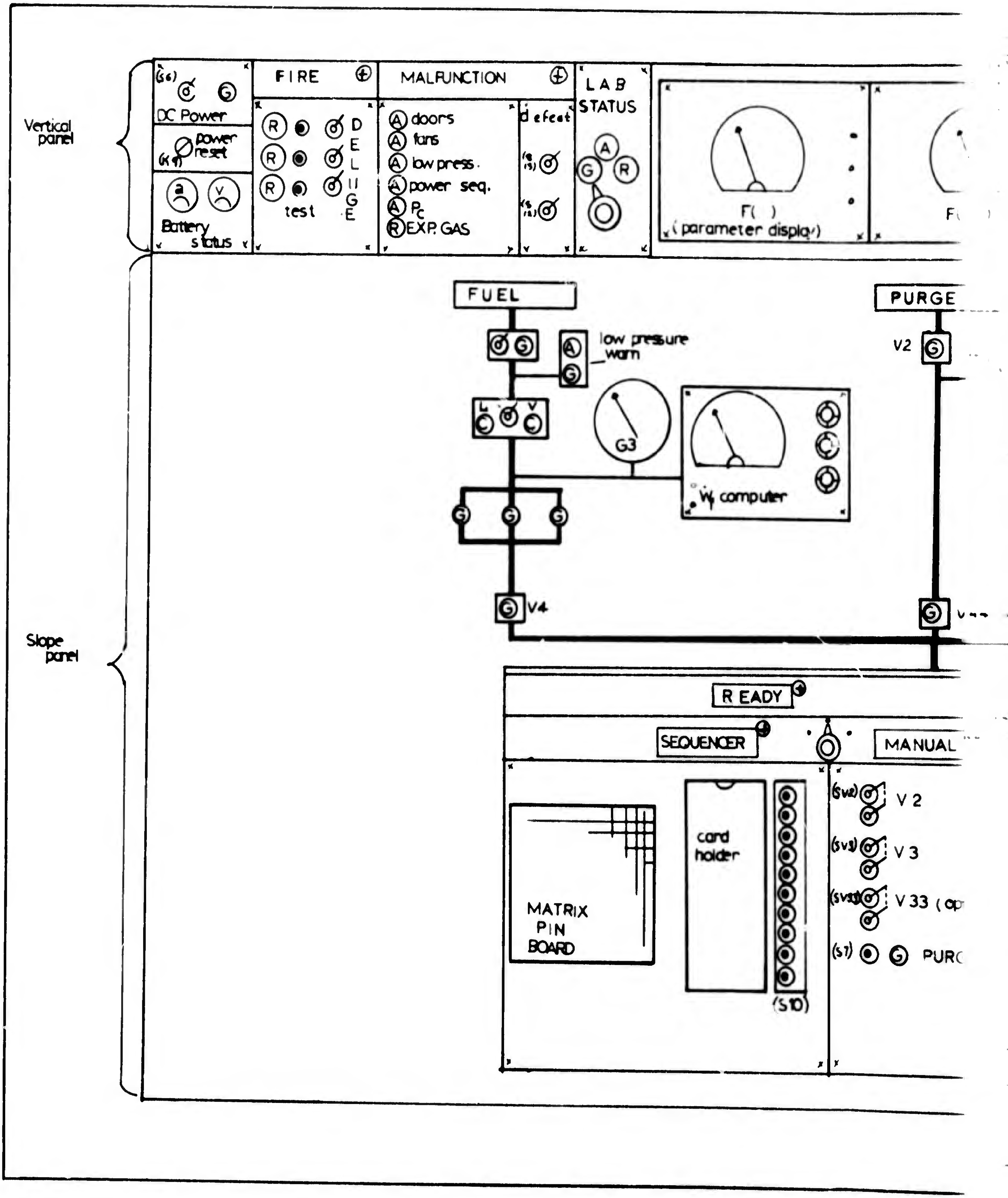
▽4 Valves, switches, and circuit are shown for a third sonic choke which may be added to the propulsion feed system Ref. Fig. A-1.

LEGEND

cb	Circuit breaker
m	Momentary switch
do	Delay operate relay
dr	Delay release relay
pl	Pilot light
malf	Malfunction
μ SW	Microswitch

Fig. B-1 Electrical Schematic, Propulsion Control System

D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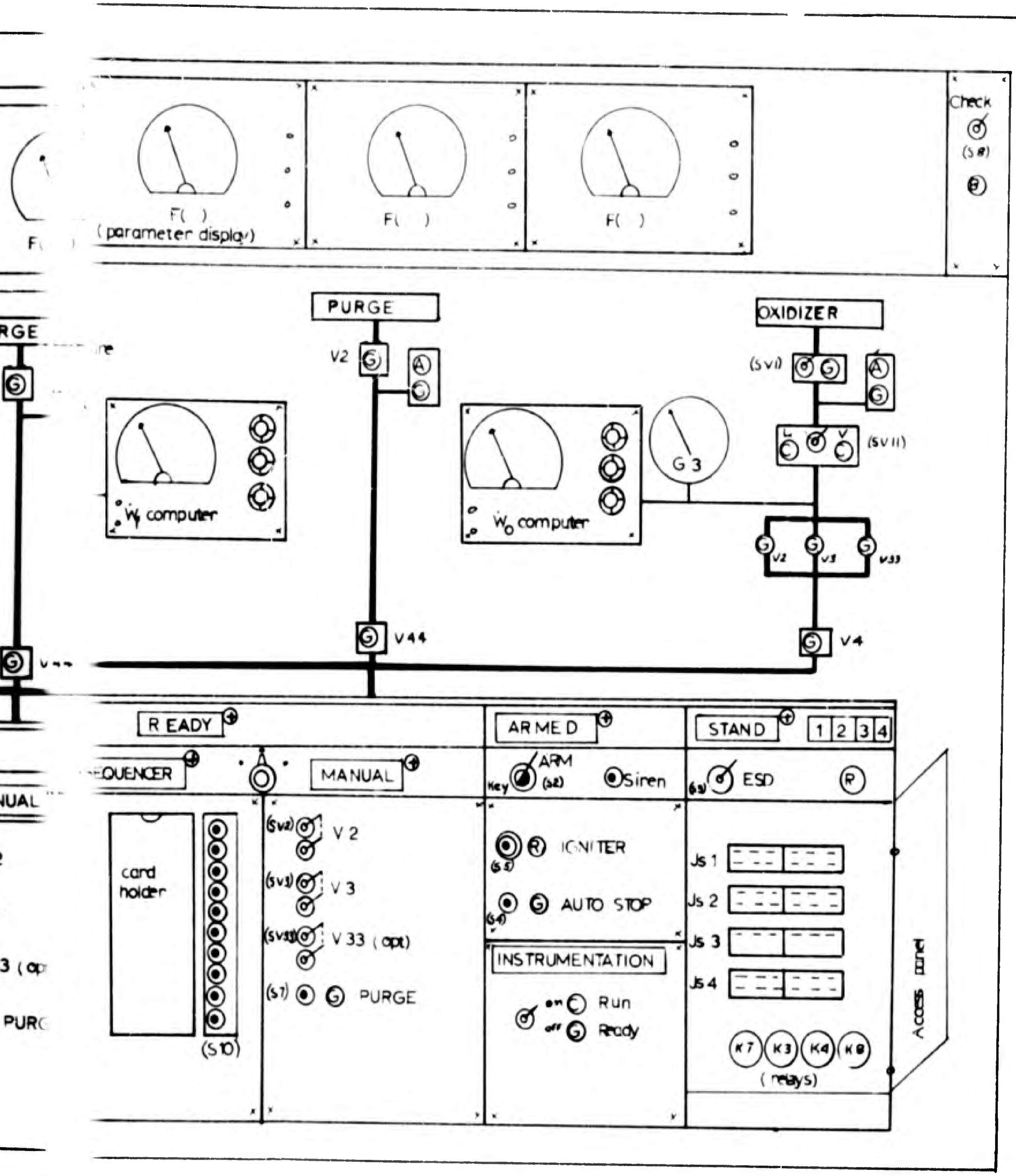
DC Power
power reset
Battery status
FIRE
test
DELUGE
MALFUNCTION
doors
fans
low press.
power seq.
P_c
EXP. GAS
defeat
LAB STATUS
F( )
(parameter display)
FUEL
low pressure warn
G3
W_f computer
V4
PURGE
V2
Slope panel
READY
SEQUENCER
MANUAL
MATRIX PIN BOARD
card holder
(S10)
V 2
V 3
V 33
PURG

A


Check
(S8)
F( )
(parameter display)
F( )
F( )
PURGE
OXIDIZER
V2
(SVI)
(SV II)
Ẇf computer
Ẇo computer
G 3
V2
V3
V33
V44
V4
READY
ARMED
STAND
1 2 3 4
SEQUENCER
MANUAL
ARM
Key
(S2)
Siren
(S3)
ESD
card holder
(S10)
(SV2) V 2
(SV3) V 3
(SV33) V 33 (opt)
(S7) PURGE
(S5) IGNITER
(S4) AUTO STOP
INSTRUMENTATION
on Run
off Ready
Js 1
Js 2
Js 3
Js 4
K7 K3 K4 K8
(relays)
Access panel

B

Notes: (1) ⊕ Words engraved on Plexiglass and edge-lighted by pilot lamps.

(2) Fire panel includes fire detectors, test switches and guarded deluge switches.

(3) Aircraft type switch ganging-bar may be an optional attachment to pairs of switches, e.g., SV2 etc.

(4) A single male plug (Js) serves as a safety plug and test stand selector.

(5) Sockets Js1 to Js4 and delay relays K3, K4, K7, and K8, plus supplementary pilot lights are located in recess beneath access panel.

(6) (S -) Switch number Ref. Fig. B-1

(K -) Relay number Ref. Fig. B-1

(V -) Valve number Ref. Fig. A-1

L E G E N D

Ⓖ	Pilot light, letter indicates color
	Toggle switch
◉	Push button switch (guarded)
	Rotary selector switch
	Key operated switch
	Removable panel

Fig. B-2 Control Console Layout

C

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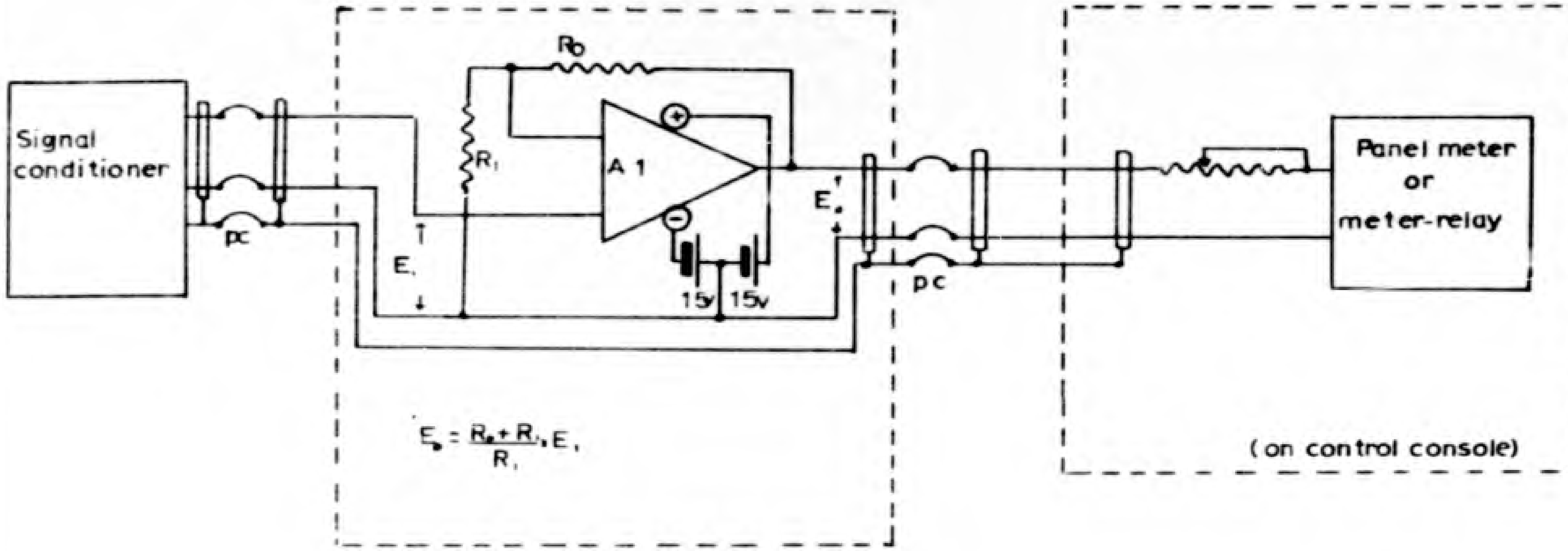
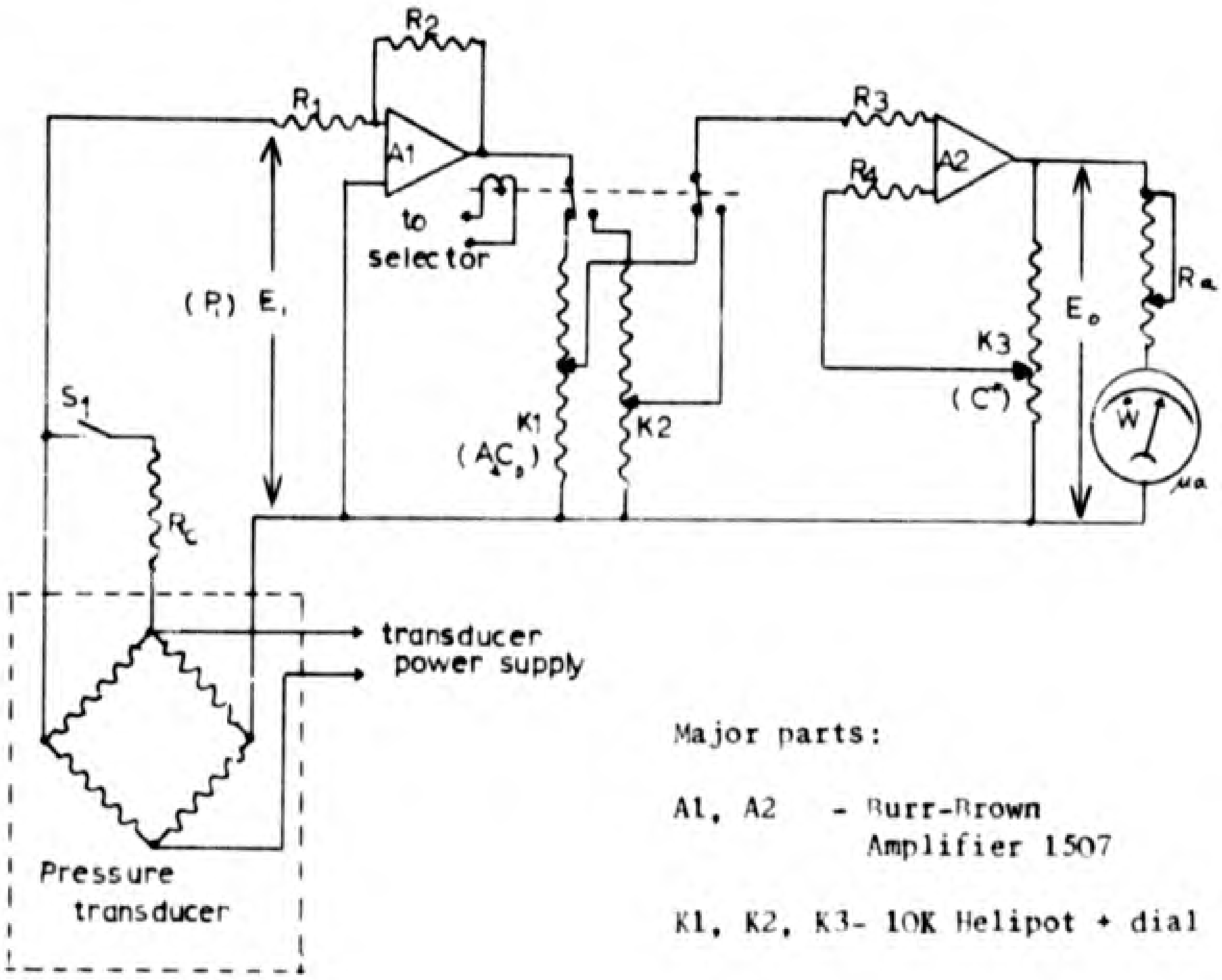


A1	-	Burr-Brown Amplifier 1507
Batteries	-	15 volt, mercury

Fig. B-3 Circuit for Test Parameter Display



Major parts:

A1, A2 - Burr-Brown Amplifier 1507

K1, K2, K3- 10K Helipot + dial

Transfer function : $E_1 = \frac{E_1 K_1 R_2 R_4}{K_3 R_1 R_3}$

Equation to be solved: $\dot{W} = \frac{p_1 A_t C_d g}{C^*}$

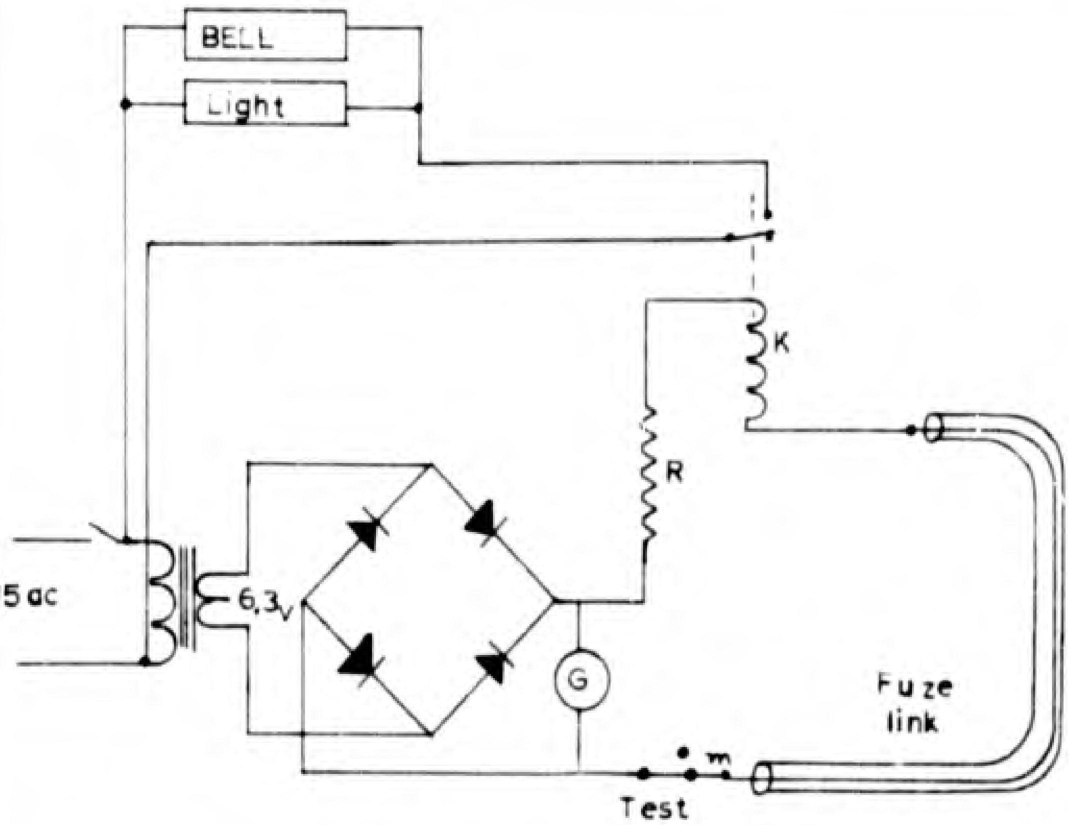
$E_1 \approx p_1$ = upstream pressure

$K_1 \approx A_t C_d$ = throat area x discharge coefficient

$K_3 \approx C^*$ = characteristic velocity

g = gravitational constant

Fig. B-4 Mass Flow Computer



Fuse link: Fabricated from 50:50 fine solder in vinyl spaghetti tubing.

K : Sensitive plate relay.

R : Current limiting resistor.

Fig. B-5 Fire Detector

Appendix C

Measurement Instrumentation System

Introduction

This appendix describes the design for the measurement instrumentation system. Detailed schematics for fabrication of the signal conditioning system are included as well as fabrication notes. An attachment (1) gives a transducer calibration procedure.

System Description

System Layout. The basic system layout is shown in Fig. C-1. All instrumentation signal conditioning equipment and accessories are mounted in standard 19-inch equipment cabinets located in the control room. Test cell transducer inputs are made at the test cell drop boxes (Fig. C-2); from these, signal cables are carried in tightly enclosed ducts through the test cell wall to a control room terminal box. From this terminal box, and a small control room drop box, the signal cables are routed through enclosed conduits and terminated on the rear of the system patch panel.

System Capacity. In order to estimate the required capacity of the measurement instrumentation system, a list of parameters for each of six possible experiments has been prepared. These experiments are listed in Tables C-1 to C-6. On the premise that three or four of these experiments might be run concurrently, and that the number of parameters given in these measurement schedules represents a near maximum requirement, the required capacity of the test cell drop boxes and the patch panel has been estimated (Ref. Fig. C-3).

Drop Box. The main test cell drop box is a metal cabinet which has a hinged and latching door on one face and a removable access panel on the reverse face. The lower sill of the drop box is fitted with a slotted sponge rubber block which allows transducer extension cables to enter the box with the door closed. This seal excludes dust and moisture, thus protecting the cable connections.

The thermocouple reference junction is housed in a drop box of similar construction which is made to accommodate the reference junction selected for the syste .

Both drop boxes described above should be installed about four feet from the floor, and the doors facing the rear of the test cell. To afford some measure of protection from small fires and explosions, a protecting steel plate, about 1/8 in. thickness, should surround the drop boxes in the form of a protective booth. The instrumentation cable duct should be suspended from the ceiling of the test cell and located where it would be exposed to minimum hazard (Fig. A-2).

Cable Ducts. The cable ducts from the main and reference junction drop boxes are made up of tightly enclosed electrical ducting. Square "D", Rain Tight Wire-way duct is suggested for this installation. This duct has a removable side panel for ease in wire stringing and system servicing; however, it can be tightly sealed. This duct pro ects instrumentation cables from abuse, small fires, etc., as well as affording an additional degree of electrical shielding. To prevent accumulation of corrosive or explosive substances in the drop boxes and ducting, a fan pressurizes these ducts and boxes. This fan injects control room air into the duct, see Fig. C-1. In order to direct the air flow to the test cell, a barrier in the duct is required at the duct-terminal box junction. This barrier can be readily fabricated from a series of sponge rubber slabs. The cables are sandwiched between these slabs, thus building up a sponge rubber block that fills the duct, yet admits the cables. A similar, but unpressurized duct, carries the instrumentation cables from the terminal box to the instrumentation equipment cabinets.

Terminal Box. All instrumentation cables, with the exception of the coaxial cables, are broken at the terminal box. The purpose of this break in the signal cables is to facilitate replacement should the system be damaged as a result of a test cell fire.

Grounding. In order to give complete control over system grounds, a one point instrumentation ground is employed. To achieve this, a heavy copper ground buss originates at some convenient ground point in the test cell. A separate ground cable from each test stand runs to this point as well as a ground cable through the instrumentation cable duct to the equipment cabinets. To maintain this one point ground, the cabinets are isolated from the control room floor by a wooden platform. This cable running through the equipment cabinets and wiring ducts and thence to earth of the test cell is referred to as "instrumentation ground". The control console is grounded to the test cell by a similar cable running through the control cable duct and terminated in the control console. Every effort must be exercised in the system construction to prevent interconnection of these grounds, thus eliminating possible ground loop circuits.

Instrumentation System Power. To reduce noise on system signal circuits, certain precautions concerning system power supplies must be observed. The transducer reference power supply must provide a constant voltage, regulated to at least 0.1% with respect to line and load fluctuations. The power supply recommended for this system, the Harrison

Laboratories Model 6201A, is capable of operation as a floated or grounded power supply. For this system, operation with the negative terminal at instrumentation ground potential is suggested. This connection should be made through a switch to facilitate location of stray system noise or to allow for applications where a floating power supply is desired.

The signal conditioning system design as offered in this report does not use relays for signal switching, etc.; however, should relays be required by a system refinement or modification, a separate 28 v dc power supply must be installed in the instrumentation equipment cabinets.

The 115 ac power required in the system to operate the strip chart recorder, temperature reference junction, etc., must be isolated from the main power lines by a shielded isolation transformer and all ac power cables within the cabinet and ducts carefully shielded to reduce ac noise.

Signal Wiring. Connectors at the drop box must be good quality, low resistance, positive latching connectors. For the strain gauge circuits which require connection of six wires plus shields, the Amphenol, 8 contact Blue Ribbon connector is suggested. For the two wire plus shield circuits, the Amphenol series 91, three contact audio connector is recommended. Both connectors have gold plated contacts for minimum contact resistance. The coaxial cables must be terminated with standard BNC connectors.

Belden 8762 two conductor shielded cable is recommended for all system signal wiring. Six wire circuits for strain gauge circuits are made up of three such cables and wrapped together with a spiral-cut cable wrap. Cable shields must be carried through connectors, the patch panel and patch cords, and taken to earth at one point only, preferrably in the signal conditioner chassis for the circuit. All signal cables must be numbered at regular intervals along their length to facilitate tracing. A suitable numbering system must be devised which relates cable numbers, connector numbers, and circuit numbers. Table C-7 and Fig. C-3 detail the quantity and type of recommended measurement circuits.

Patch Panel. The patch panel is the heart of the instrumentation system. This consists of several programming patch panels and a single mating rear panel (receiver). Figure C-3 shows the patch panel in relation to the remainder of the instrumentation system. All signal inputs, except the coaxial cables, from the test cell are wired into the top portion of the patch panel. Input and output connections from the signal conditioning equipment are wired to the lower portion of the panel. Outputs to recorders, system maintenance accessories, and calibration equipment are also terminated on this panel. The patch panel permits changeover from one experiment to another and allows the selection of the transducers to be used and the allocation of signal conditioning equipment and recorder channels. The pre-programmed patch panels and the accurately reproducible control settings on the signal conditioning equipment facilitate conversion of the instrumentation system from one experimental configuration to another.

Of the 1600 positions available on the recommended patch panel, the MAC Model 921, 1309 positions have been allocated in Fig. C-3. The remaining positions are available for system expansion or modifications.

The termination of the signal leads on the patch panel must be laid out with care in order to achieve maximum circuit utilization.

For example, a strain gauge circuit requires six wires plus a shield; however, an 8-pin patch cord (2 x 4 pins) must be used. It is recommended that the eighth pin be attached to a shield as well and that the strain gauge circuit be wired and terminated as shown in Fig. C-4. This arrangement makes it possible to use this cable for two or four wire circuits and still keep the shields separated. When used for a strain gauge measurement, the shield pins are connected within the signal conditioner chassis.

Signal Conditioning Equipment

Introduction. While the instrumentation industry offers a number of styles and configurations of signal conditioning equipment of varying degrees of sophistication, the cost and the basic principles are much the same. Good quality signal conditioning equipment for strain gauge, voltage, and thermocouple signals costs about $150 to $300 per channel. The Endevco Corporation 4400 Series Universal signal conditioning equipment would possibly be the best choice for AFIT application; however, the cost would approach $275 per channel.

This appendix offers detailed designs for signal conditioning equipment which can be fabricated by the AFIT workshops at a very low direct cost per channel (Ref. Appendix E). These designs are based on proven and accepted techniques used in the rocket testing industry (Ref 7, 8, 9, 10).

Strain Gauge Transducer Signal Conditioner. A strain gauge signal conditioning system that will control and calibrate any 350 ohm strain gauge transducer is shown in Figs C-5 and C-6. This six-wire, shunt calibrated system is widely used and offers optimum system accuracy (Ref 7).

The operation of this signal conditioner is straightforward. Balance potentiometer (R3) balances the transducer while in a no-load status. This defines the electrical zero of the transducer and system cabling. The signal level is defined by scaling or span resistor (R2); this sets the transducer excitation voltage and, consequently, establishes the level of the output voltage as seen by the galvanometer. Momentary switches (S2 and S3) display the bridge voltage and transducer balance on their respective indicators. The bridge voltage setting is not critical; however, bridge balance is quite critical. Each channel must be carefully balanced prior to each use to allow for possible resistance changes in the system cabling and to ensure that the bridge is operating in its most linear mode, i.e., at or near null. Polarity reversing switch (S4) is provided for operator and data reduction convenience so that first quadrant data display is achieved on the oscillograph. For most sensitive operation, 350 ohm impedance galvanometers should be used.

A precision four-step calibrator is included in this ten channel chassis. Switch SC2 selects the channel to be calibrated and switch SC1 performs that calibration. This calibration is accomplished by placing a precision calibration resistor (Rc) across one arm of the balanced transducer bridge; this simulates the imbalance that the transducer would experience if it were subjected to a load. Thus, if this transducer has been calibrated in terms of percent output or value of shunting resistor (Rc) as a function of applied stimulus, e.g., pressure, then that resistance value causes the recording system to display that level of the operating stimulus. This calibration is a function of the transducer and its balance only and is independent of the galvanometer characteristics and its bridge excitation voltage. One feature of this calibration must be noted: the calibration step is superimposed on any load that may be on the transducer. Therefore, for absolute measurements, the transducer must be balanced and electrically calibrated in a no-load condition.

The strain gauge signal conditioner chassis is built up as a ten-channel unit which includes one calibration circuit. A proposed front panel layout is offered in Fig. C-6.

Thermocouple Control and Calibrate Unit. A typical thermocouple measurement channel is shown in Fig. C-7. The thermocouple metals are carried through a shielded cable to the thermocouple reference junction. The thermocouple output signal is then carried on copper wires from the reference junction through the patch panel to the thermocouple control and calibrate unit. The output of this unit is offered to the recorder galvanometer through a second patch cord.

The thermocouple control and calibrate unit is illustrated in Fig. C-8. Sensitivity switch (S3) and polarity reversing switch (S2) are the controlling switches. System calibration is achieved by generating a known millivolt drop across precision 100.0 ohm calibrating resistor (Rs). By Thevenin's Theorem, the voltage drop across this resistor acts as a voltage source generating a current through the thermocouple circuit. This type of calibration is preferred in systems employing low impedance recorders because the calibration current flows through the complete measuring circuit, thus including all system resistances in the calibration. In addition, this means of calibrating proves the circuit continuity. This type of calibration can only be achieved when there is no output from the thermocouple circuit, i.e., the measuring and reference junction are at the same temperature. While the complete loop calibration is desired, it may not be feasible due to temperature gradients in the system. To overcome this problem, switch S1 substitutes a resistor (Rt) for the thermocouple circuit resistance. The value of (Rt) required in the system is determined by measuring the actual thermocouple circuit resistance.

The thermocouple calibrator consists of a series of precision resistors selected by switch SC3 which control the current flowing through resistor (Rs). Rheostat RC1 is adjusted until a calibrated current is read on meter M1. The calibrator power is provided by a 1.35 volt mercury battery and its polarity controlled by switch SC2. After the calibrator has been set, the channel to be calibrated is selected and the appropriate millivolt signals injected (Ref 10).

Damping resistor (Rd) is shown as being optional. The inclusion of a damping resistor reduces galvanometer sensitivity; however, it may be necessary if critical damping of the channel is desired. Normal thermocouple response is such that critical damping of the circuit is not a major consideration. For high frequency thermocouple measurements, special thin film thermocouples must be used and their output isolated and amplified by a DC amplifier.

The thermocouple control and calibrate unit is built up as a ten-channel unit. The front panel layout should be similar to that given in Fig. C-6.

Thermocouple Reference Junction. While the use of an ice point reference junction has definite advantages, it often proves unsatisfactory in use. The inconvenience of maintaining a supply of reasonably pure ice, the uncertainties in the preparation of the bath and the need for constant attention far outweigh the advantages. A thermocouple reference junction which is maintained at some fixed temperature above ambient, i.e., an oven, is desired in most installations. The Universal Thermocouple Hot Box, manufactured by Research Incorporated, is recommended by the staff of the rocket test site of Edwards AFB, Ref. Appendix D. The particularly desirable feature of this reference junction is that any thermocouple metal may be used without restriction.

Single Resistive Element Conditioner. For measurements requiring the use of a single resistive element, e.g., a single strain gauge or resistive temperature probe, the circuit shown in Fig. C-9 can be used. The principle of operation is similar to that of the four-arm strain gauge bridge (Ref. Fig. C-5). The actual value of resistors used to make up the remaining three arms of the bridge and the values of the calibrating resistors must be selected to match the particular sensing element employed (Ref 11).

This unit must be fabricated in a standard 19-inch rack chassis; each circuit should be laid out on a separate fibre board with suitably located solder lugs for the fitting of the bridge completion resistors. Each channel must have its special calibration switch so that resistor Rc may be installed to suit the particular application.

Signal Attenuator and Galvanometer Control. In order to facilitate system changeover from one operator to another without disturbing system calibration, it is necessary that attenuator settings be accurately reproduced. The signal attenuator and galvanometer control panel shown in Fig. C-10 provides the system operator with a means of accurately controlling the signal attenuation, selection of galvanometer damping resistor, and a polarity reversing switch to change the direction of the trace deflection. All resistor values are fixed with the exception of one which has been replaced with a ten-turn, dial indicating, potentiometer. There is also provision for the installation of special value resistors.

This circuit is also used for monitoring voltages, recording voltage events, and the conditioning of other signals that require only "L" pad attenuation.

This control unit is built up on a standard 19-inch rack panel chassis. The tolerance and values of resistors are not critical; 5% values will suffice. However, they should be stable and not subject to drift. For this reason, metal film resistors are suggested. High quality switches with low resistance contacts must be used.

Voltage Measurement Circuit. Some circumstances may dictate the use of a potentiometric transducer; these are most frequently used for position indications. Figure C-11 shows a signal conditioning circuit for such a transducer, including a calibration network. The transducer, which should be of relatively low impedance, 5000 ohms or less, acts as a voltage divider, the output voltage being derived from the wiper arm of the potentiometer and the lower potential side of the power supply. The output voltage is patched through the attenuator prior to being patched to the recording galvanometer. The excitation voltage should be set sufficiently high, within transducer limits, so that high resistance values are required at the attenuator. This precaution avoids transducer loading.

The calibration network of precision resistors acts as a voltage divider generating output voltages which are exactly known percentages of the excitation voltages. It should be noted that the calibration of potentiometric transducers, in terms of voltage ratio, i.e., voltage output as a function of voltage input, will simplify calibration procedures and yield more reliable results.

This unit should be built in the form of a ten-channel control and calibrate chassis.

Strip Chart Recorder Conditioner. The system includes two strip chart recorders which may be used for the real time display of a test parameter. The circuit shown in Fig. C-12 provides a means of controlling the sensitivity of this recorder as well as suppressing the zero point. The 100 ohm ten-turn potentiometer will provide approximately 50 millivolts bias of the test signal. As an example, this circuit could be used to display temperature only in excess of 1000°F, thus providing greater resolution and reading accuracy (Ref 13:79).

The actual scale calibration is achieved by the calibration circuits in the applicable signal conditioning chassis.

Recorders

The light beam type recording oscillograph is suitable for the recording of most propulsion system test parameters. Most data channels require frequency response no greater than 100 cps. This is within the range of directly driven high performance galvanometers; for higher frequency oscillograph measurements, up to 5,000 cps, special galvanometers must be driven by a DC amplifier. High frequency measurements such as outputs from capacitive or piezo transducers require recorder frequency response as high as 50,000 cps. For only a few channels, in which high accuracy time base is not required, a camera equipped oscilloscope is a convenient and economical recorder. The magnetic tape recorder is particularly suited to the recording of high frequency measurements on a long time base. Tape recorded data can be expanded in time scale, is suited to automatic data reduction, and is readily reproduced in any form desired.

Potentiometric pen recorders are widely used at rocket sites to accurately record (0.5%) and display important test parameters that the test engineer must monitor during a rocket firing. These recorders suffer the disadvantage of low frequency response (0.5 cps), but are suitable for displaying parameters such as chamber pressures, propellant flow rates, or engine wall temperature.

The present AFIT facility uses a Consolidated Electrodynamics Corporation (CEC) 5-124 printout oscillograph. This is an ideal recorder for many applications; however, it has some disadvantages that may not be acceptable for more refined tests. Its capacity is limited to 18 channels on a seven-inch width record which is developed by exposure to room light. This record is not permanent and the trace resolution is inferior to the chemically processed photo record. The real advantage of this recorder is its quick-look capability; a record is available for examination within a few seconds of its exposure.

Recommended Recorders

While the need is not urgent, a larger capacity oscillograph capable of producing both direct print and the high resolution photographic recordings, would be an effective tool. The CEC 5-119 P4V-36 is a 36-channel oscillograph which can produce either direct print or photo processed records on twelve inch paper, depending on the type of paper used in the recording magazines. This recorder would allow system check-out and preliminary test runs to be made on the direct print records and the final data runs on the photo processed record. Trace separation is easier on the latter record, and the reading resolution is better than twice that available from the lower contrast direct print record.

A magnetic tape recorder should be included in the system as more refined experiments are undertaken, in particular, studies on combustion instabilities or propagation of detonation waves. A recorder with the characteristics of the Ampex FR 1300 Portable Instrumentation Tape Recorder is recommended. This is a 0.5-inch, seven-track tape recorder with plug-in record and reproduce electronics.

The Moseley Model 680 strip chart recorder is recommended for use in the laboratory instrumentation system. It has a wide range of paper speeds and contains its own signal scaling circuits. While at the present time this recorder is not mandatory, it would be very useful in assisting the test engineer in conducting his experiments.

DC Amplifiers

In order to make high frequency recordings, from low level signal sources, on the oscillograph, a DC amplifier must be provided for each high frequency data channel. The Bay Laboratories, Cleveland, manufacture a DC amplifier that is reasonable in cost and is recommended by its users in the Wright-Patterson AFB Structures Laboratory. These amplifiers can be readily added to the instrumentation system when data requirements dictate high frequency oscillograph measurements.

Fabrication Notes

In addition to the discussion in the preceding pages and notes included on the respective drawings, the following fabrication notes are offered for the guidance of the personnel fabricating the system:

(1) The equipment racks used to contain the signal conditioning equipment must be fitted with a door on the back of the cabinet.

These racks are to be isolated from all grounds except the instrumentation ground, to which they are to be securely bonded.

(2) All cables in the instrumentation system must be shielded and the shields taken to instrumentation ground at one point only.

(3) Locally fabricated signal conditioning equipment must be very carefully constructed with strict attention paid to shielding. Selector switches used in signal circuits must be premium quality, wiping action, break-before-make.

(4) Precision resistors used in the system calibration circuits must be wire wound or stable metal film resistors. To reduce the cost of obtaining precision resistors of the exact value required, a fixed resistor may be used in parallel with a variable wire wound resistor (Trimpot); this acts as a vernier.

(5) The signal conditioning chassis requires a voltmeter and a null detector for system adjustments. While a sensitive panel meter is suggested for use as a null detector, a more sensitive instrument should be used if it is available. For this purpose, the Kintel Model 202B microvoltmeter may be used through the expedient of an external meter jack, wired in parallel with the existing null meter on each chassis.

(6) Terminations on the rear of the patch panel receiver must be made with the taper pins available from the panel manufacturer. This arrangement permits modification of the patch panel layout without damage to the receiver.

(7) Cables from the receiver must be carried through the cabinets to the back of the rack mounted signal conditioning equipment. These cables must connect to the signal conditioning chassis

through a good quality connector with gold plated contacts. The Amphenol Blue Ribbon connector is ideal for this application. In all cases, sufficient slack must be available in the cables. This will permit the chassis to be partially withdrawn from the rack for system servicing.

(8) The recorders may be located on a table beside the control console, or directly behind the operator as he faces the console. Therefore, cables to such recorders should be of sufficient length to allow this flexibility.

Table C-1

Tentative Measurement Schedule for Combustion Instability Study

Parameter	Measurement			
	Strain Gauge	Thermo-couple	High Freq.	Digital & Event
Press. oxidizer venturi	x			
Press. fuel venturi	x			
Temp. oxidizer venturi		x		
Temp. fuel venturi		x		
Chamber press. (2)	2x			
Chamber press. (4)			4x	
Rough combustion cutoff	x			x
Igniter				x
Chamber temp. (2)		2x		
Thrust Fx	x			
Chamber strain (3)	3x			
Correlation				3x
Total	9	4	4	5

Table C-2

Tentative Measurement Schedule for Thrust Vector Control Experiment

Parameter	Measurement			
	Strain Gauge	Thermo-couple	High Freq.	Digital & Event
Press. fuel venturi	x			
Temp. fuel venturi		x		
Press. oxidizer venturi	x			
Temp. oxidizer venturi		x		
Press. fuel injector (3)	3x			
Press. oxidizer injector (3)	3x			
Chamber temp. (4)		4x		
System valves oxidizer (3)				3x
System valves fuel (3)				3x
High freq. press. chamber			2x	
Thrust 6 component	6x			
Total	14	6	2	6

Table C-3

Tentative Measurement Schedule for Heat Transfer Study

Parameter	Measurement			
	Strain Gauge	Thermo-couple	High Freq.	Digital & Event
Press. fuel venturi	x			
Temp. fuel venturi		x		
Press. oxidizer venturi	x			
Temp. oxidizer venturi		x		
Press. fuel injector	x			
Press. oxidizer injector	x			
Press. chamber (2)	2x			
Temp. chamber (1 to 15)		15x		
Coolant flow (1 to 6)				6x
Valves				3x
Correlation				3x
Cutoff				2x
Total	6	17	0	14

Table C-4

Tentative Measurement Schedule for Nominal Gaseous Propellant Study

Parameter	Measurement: Strain Gauge	Thermo-couple	High Freq.	Digital & Event
Press. fuel venturi	x			
Press. oxidizer venturi	x			
Temp. fuel		x		
Temp. oxidizer		x		
Press. chamber	x			
Press. fuel injector	x			
Press. oxidizer injector	x			
Thrust, Fx	x			
Temp. chamber		x		
Temp. nozzle		x		
Correlation				3x
Total	6	4	0	3

Table C-5

Tentative Measurement Schedule for Detonation Wave Study

Parameters	Measurement			
	Strain Gauge	Thermo-couple	High Freq.	Digital & Event
Press. fuel venturi	x			
Temp. fuel venturi		x		
Press. oxidizer venturi	x			
Temp. oxidizer venturi		x		
Press. chamber (3)	3x			
Press. probes (10)			10x	
Igniter (1)				x
Cutouts (2)				2x
Valves (4)				4x
Total	5	2	10	7

Table C-6

Tentative Measurement Schedule for Liquid Propellant Test

Parameter	Measurement: Strain Gauge	Measurement: Thermo-couple	Measurement: High Freq.	Measurement: Digital & Event
Press. fuel tank	x			
Temp. fuel tank		x		
Press. oxidizer tank	x			
Temp. oxidizer tank		x		
Press. fuel venturi	x			
Press. oxidizer venturi	x			
Press. fuel injector	x			
Press. chamber (2)	2x			
Temp. chamber		x		
Temp. nozzle		x		
$\dot{w}$ fuel				x
$\dot{w}$ oxidizer				x
Thrust Fx	x			
Thrust Fy	x			
Thrust Fz	x			
Correlation valves				2x
Cutouts				2x
Chamber press. high freq.			2x	
Total	11	4	2	6

Table C-7

Recommended Allocation of Measurement Circuits

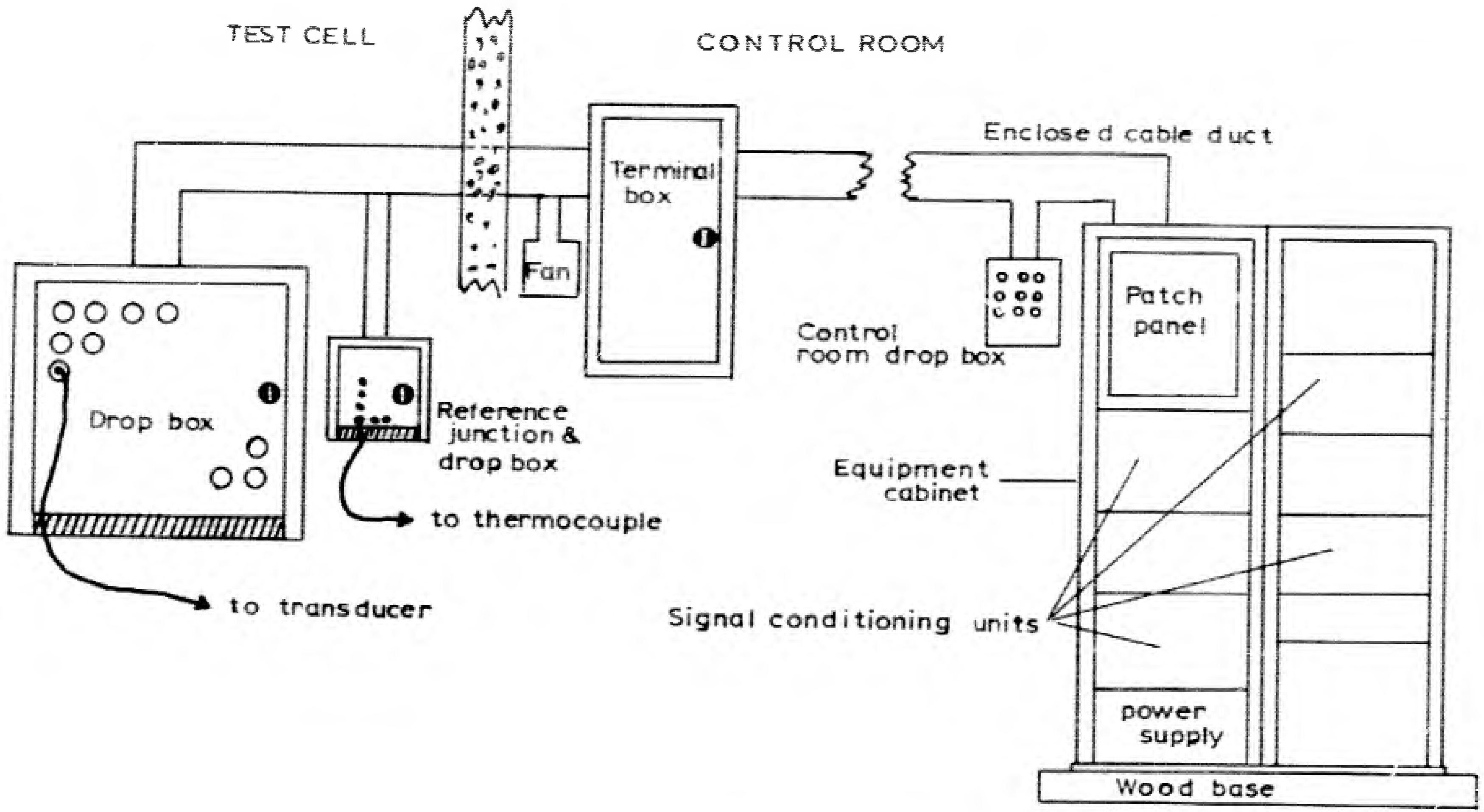
Source	Number of Circuits	Type of Circuit
Main test cell drop box	40	six conductors + shields
	20	two conductors + shield
	10	coaxial
Control room drop box	4	six conductors + shields
	10	two conductors + shield
Reference junction drop box	25 (min)	two conductors + shield

Table C-8

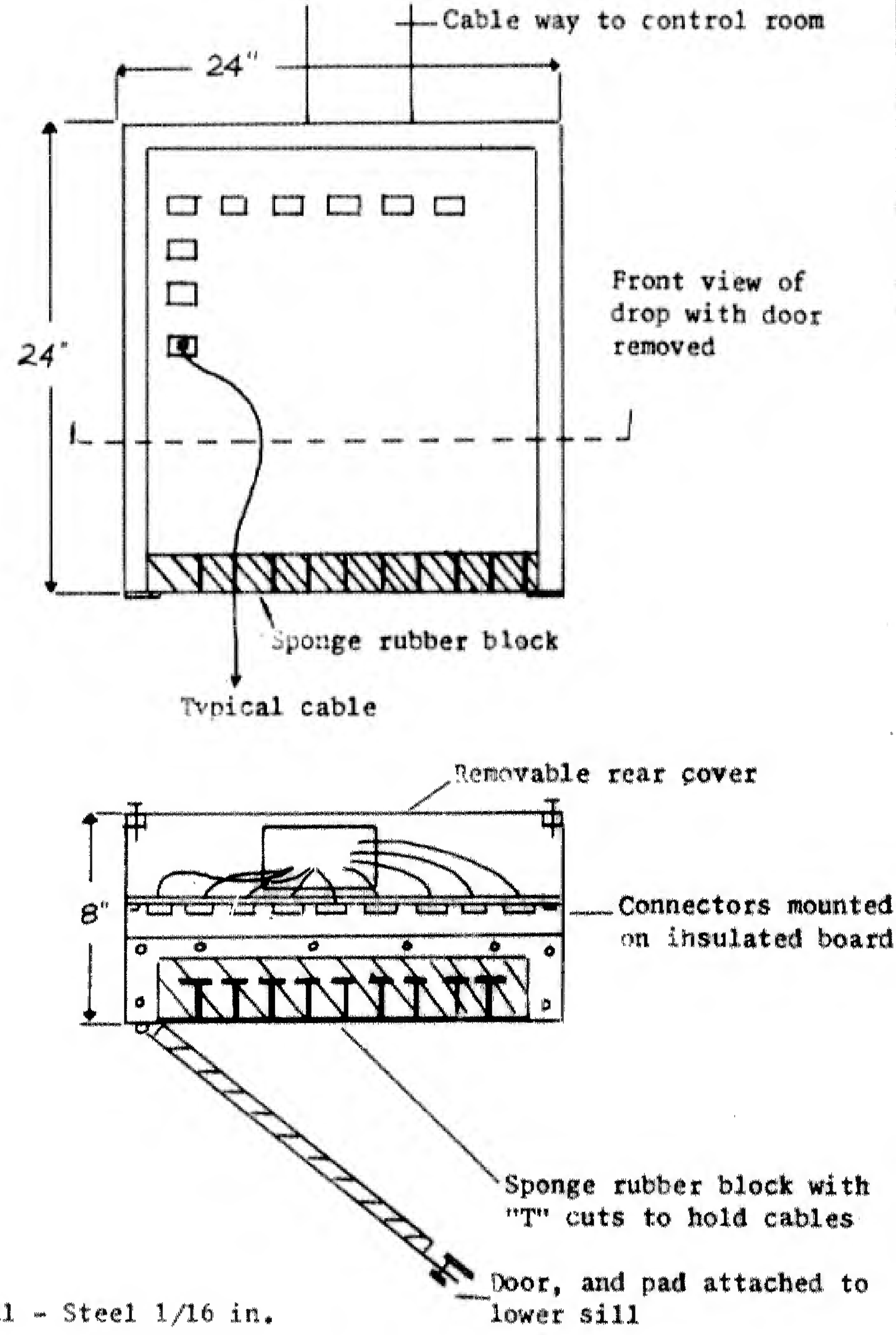
Measurement Instrumentation System, Recommended Major Components

Description	Cost
Research Incorporated, RJ4081, Universal Thermocouple Reference Junction, (Ref. Fig. C-7).	$ 1060.
MAC Panel Receiver Model 921, Part number 109212 (Ref. Fig. C-3).	335.
MAC Panel Plugboard Model 921, Part number 209211, each four required.	23.
MAC Shielded Plug Wires, 2 wire plus shield, 15 in. length, Part number 341502, per 100 req'd.	184.
MAC Shielded Plug Wires, 7 wire plus shield, 15 in. length, Part number 381502, per 25 req'd.	99.
Power Supply, Harrison Laboratories Model 6201A, (Ref. Figs. C-5, C-9, and C-11).	180.
Oscillograph CEC Model 5-119 P4V-36 plus 5-051, exit slot magazine and 5-006 closed magazine.	9000.
Moseley Strip Chart Rocorder Model 680-02, (one millivolt span).	825.
Ampex FR 1300 Portable Instrumentation Recorder, 0.5 inch plus puug-in electronics.	12000.

Note: System accessories and calibration apparatus are listed in the implementation and procurement schedule Appendix E.



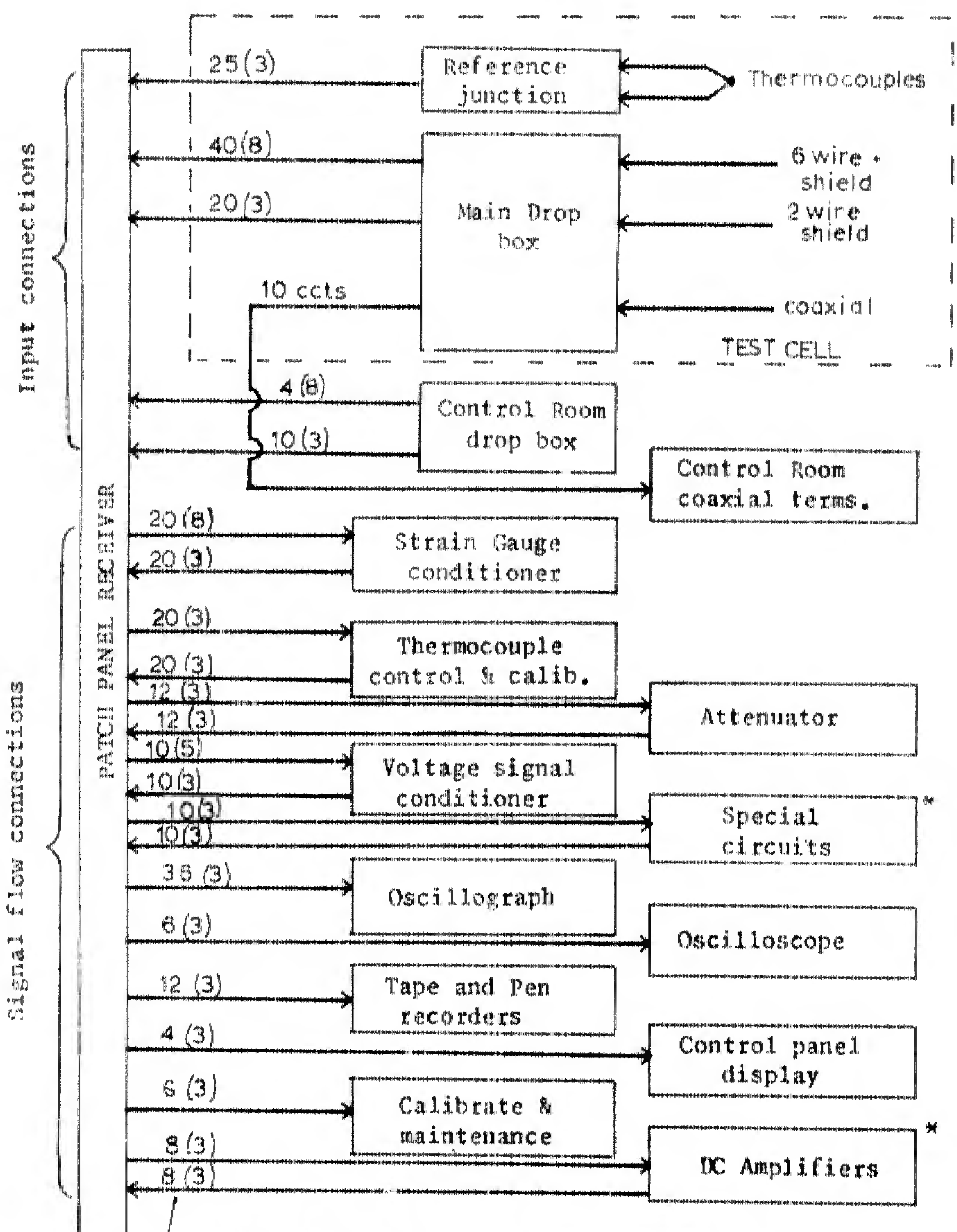
·Fig. C-1 Measurement Instrumentation System Layout



Material - Steel 1/16 in.

(not to scale)

Fig. C-2 Drop Box Construction



Number of circuits, and pins required on patch panel, e.g., 8 (3) = eight circuits using three pins each

* Optional items to be included as required.

Fig. C-3 Instrumentation System Signal Flow and Patch Panel Utilization

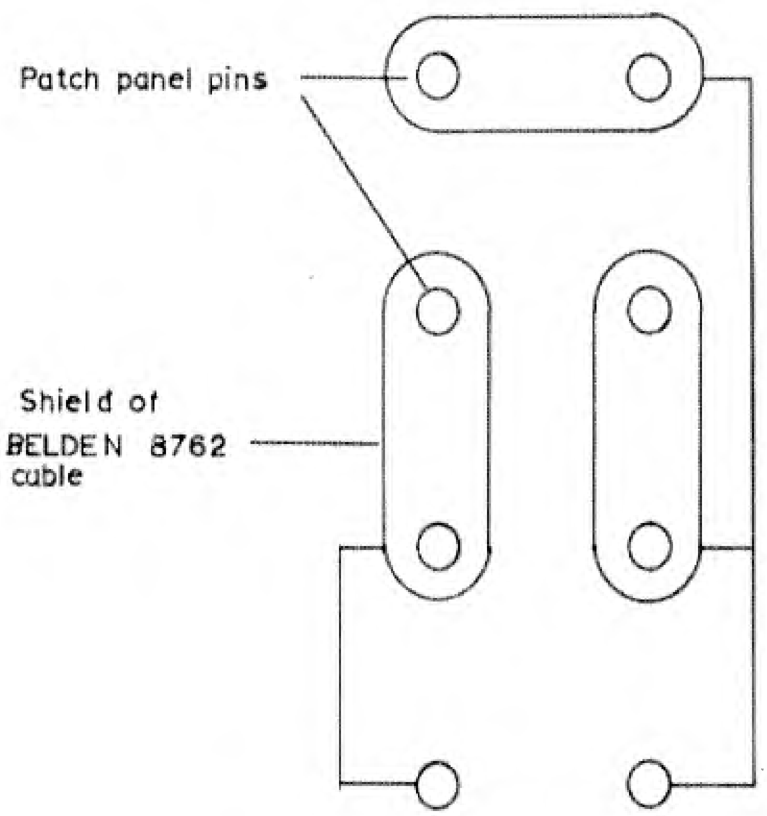
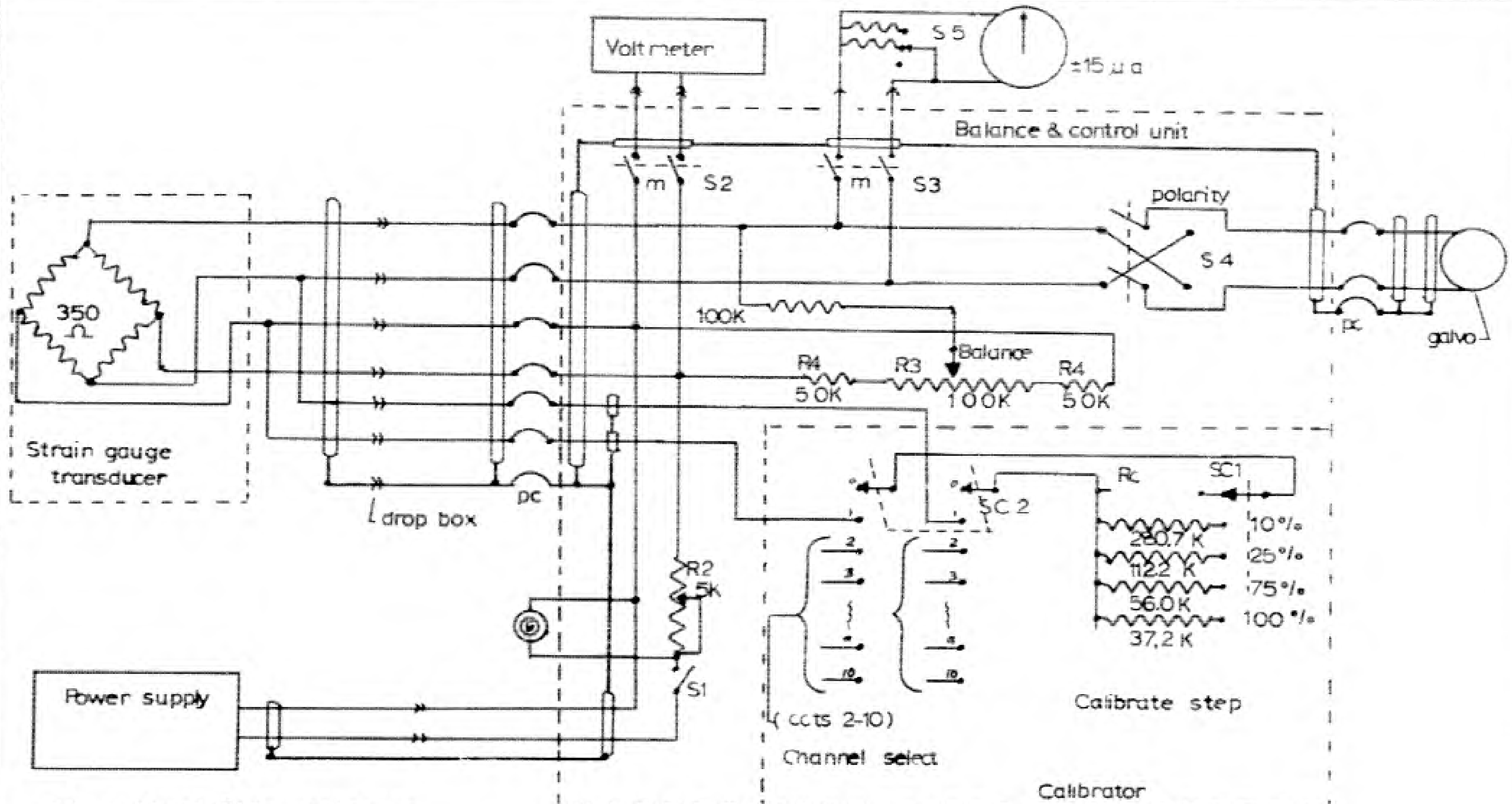


Fig. C-4 Patch Panel Termination of a Strain Gauge Circuit

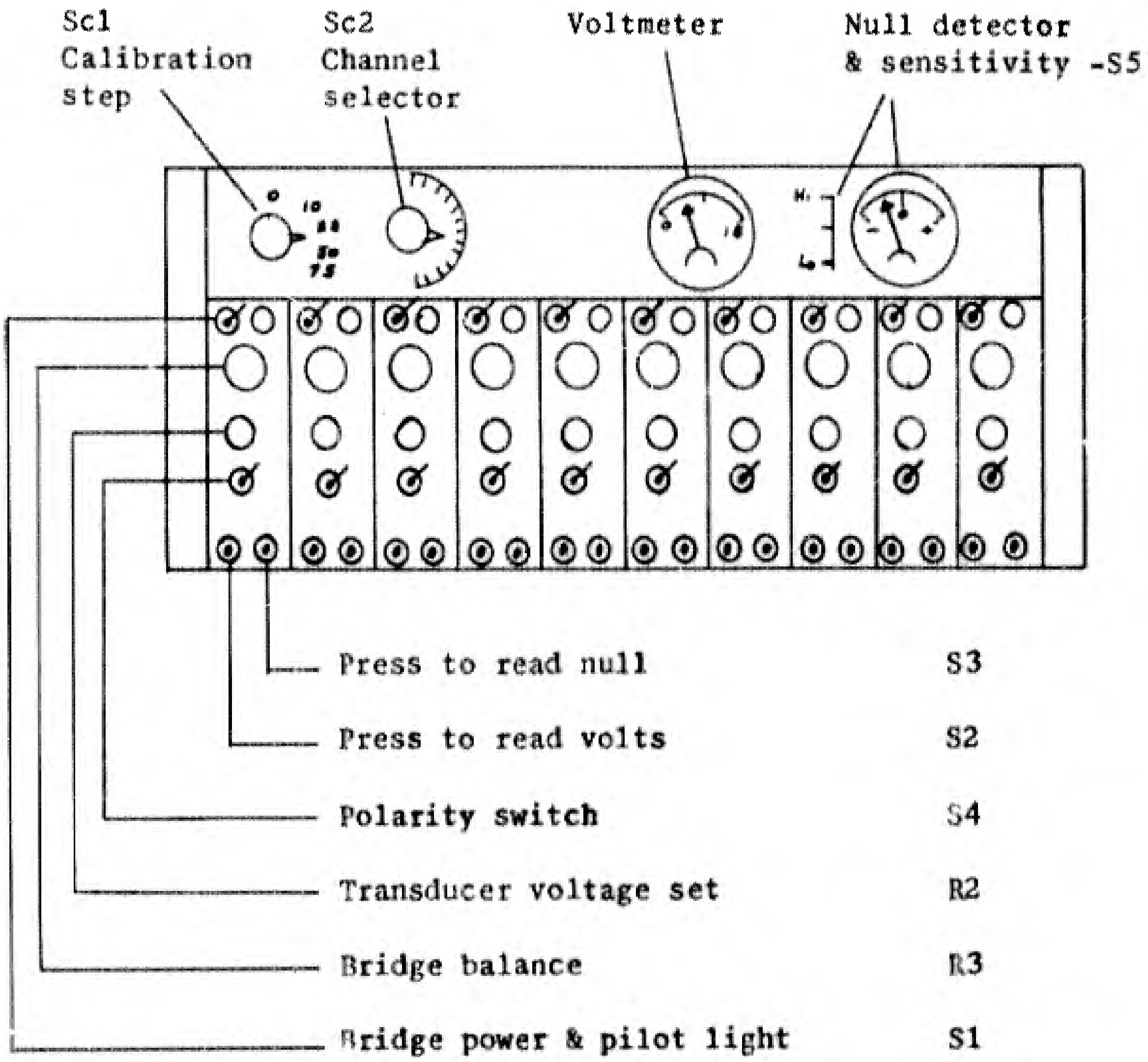


R4 : Fixed film resistors

Rc : 0.1 % wire wound resistors

R2, R3 : IRC type 8000 ten-turn potentiometer

Fig. C-5 Circuit of Strain Gauge Transducer Signal Conditioner



Note: 10 channel bridge balance and control unit plus calibrator mounted in 19 inch rack panel.

Fig. C-6 Panel Layout, Strain Gauge Signal Conditioner

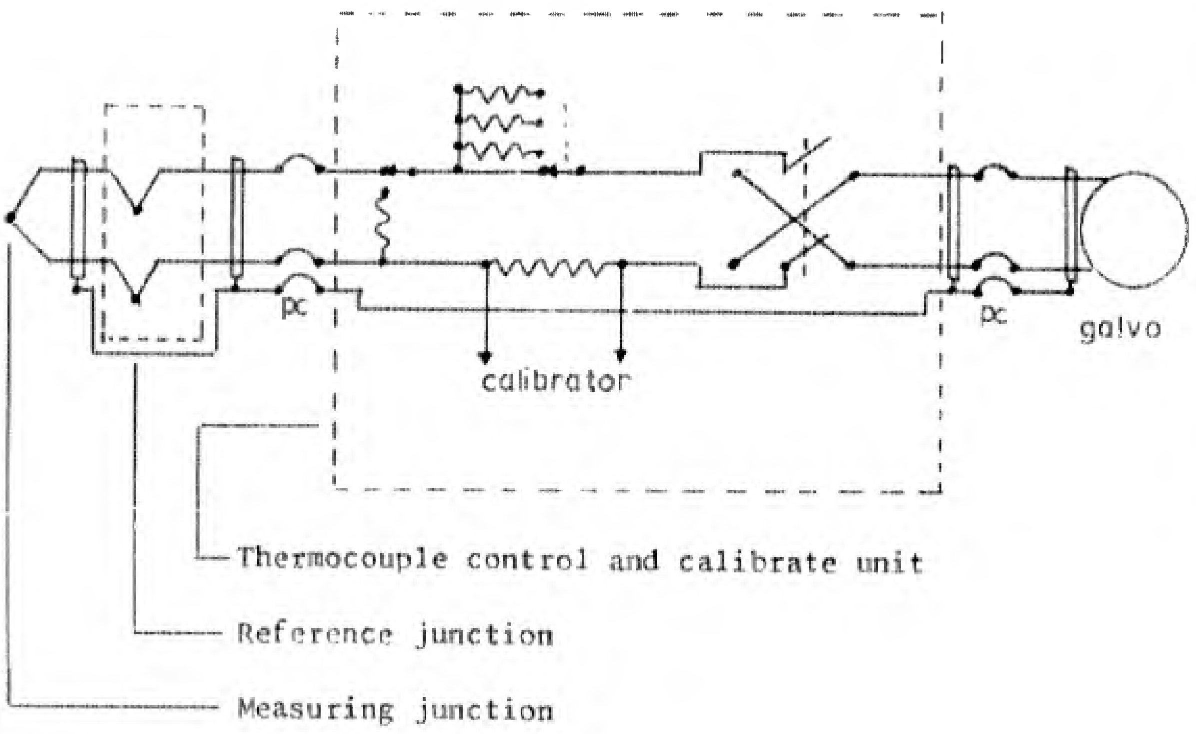
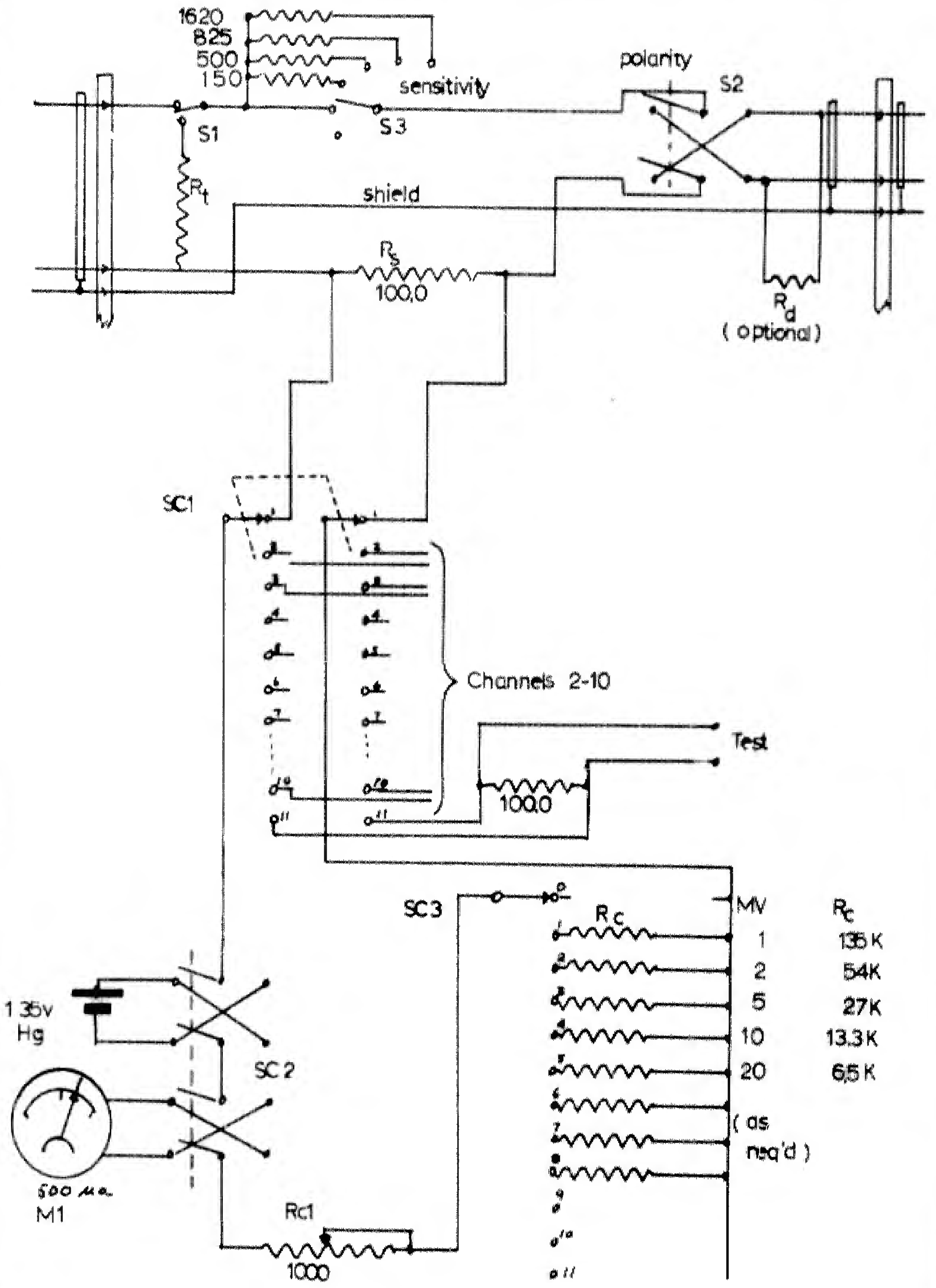
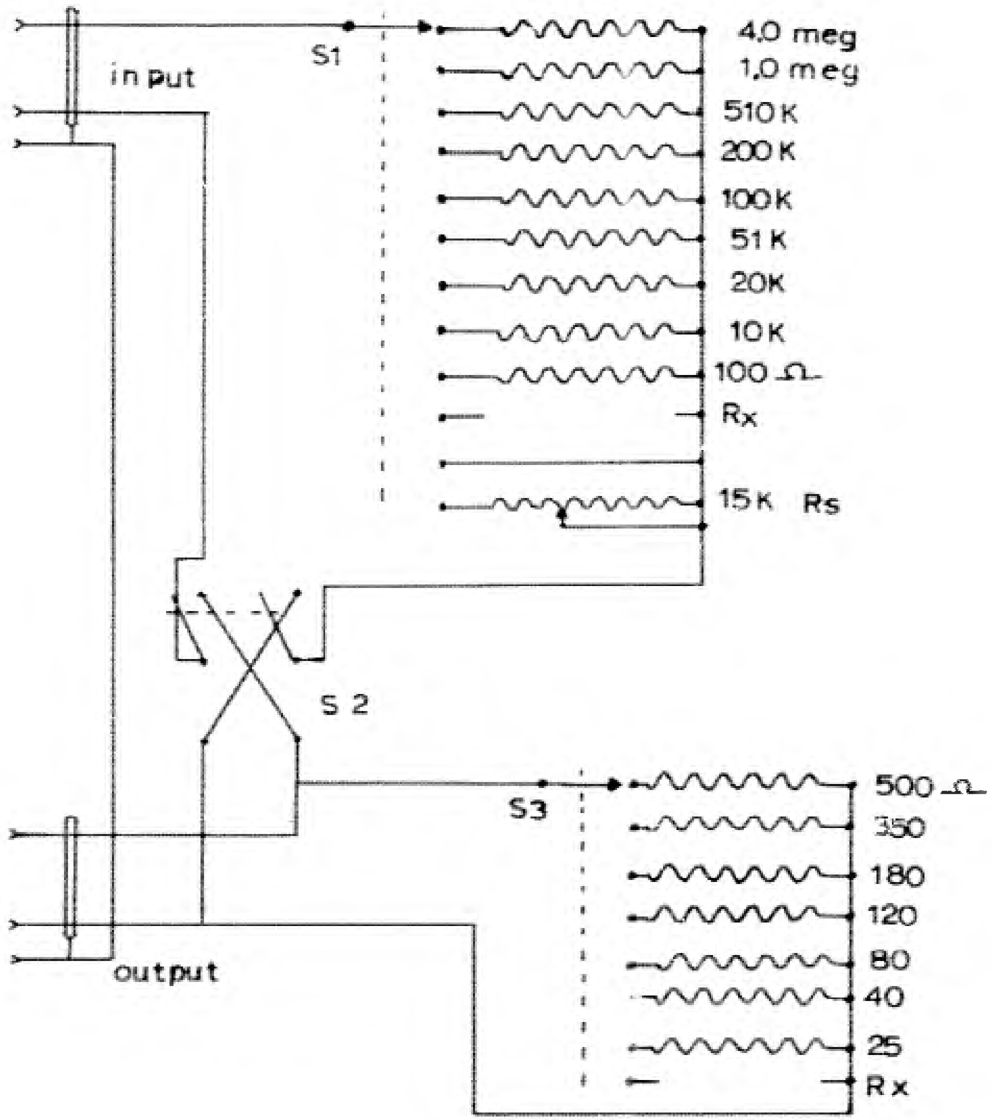


Fig C-7 Thermocouple Measurement Circuit



Note: Rt simulates thermocouple for calibration

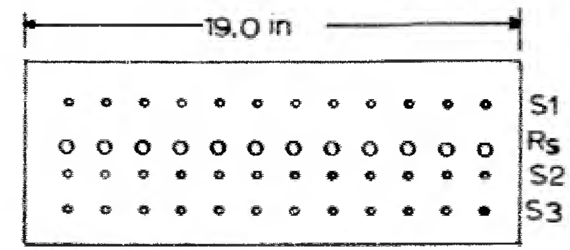
Fig. C-8 Thermocouple Control and Calibrate Circuit



Note: Rs - IRC type 8000 ten-turn potentiometer
Rx - Optional or special value

Schematic is typical of 12 channels

Layout of rack panel



Controls to be labeled:

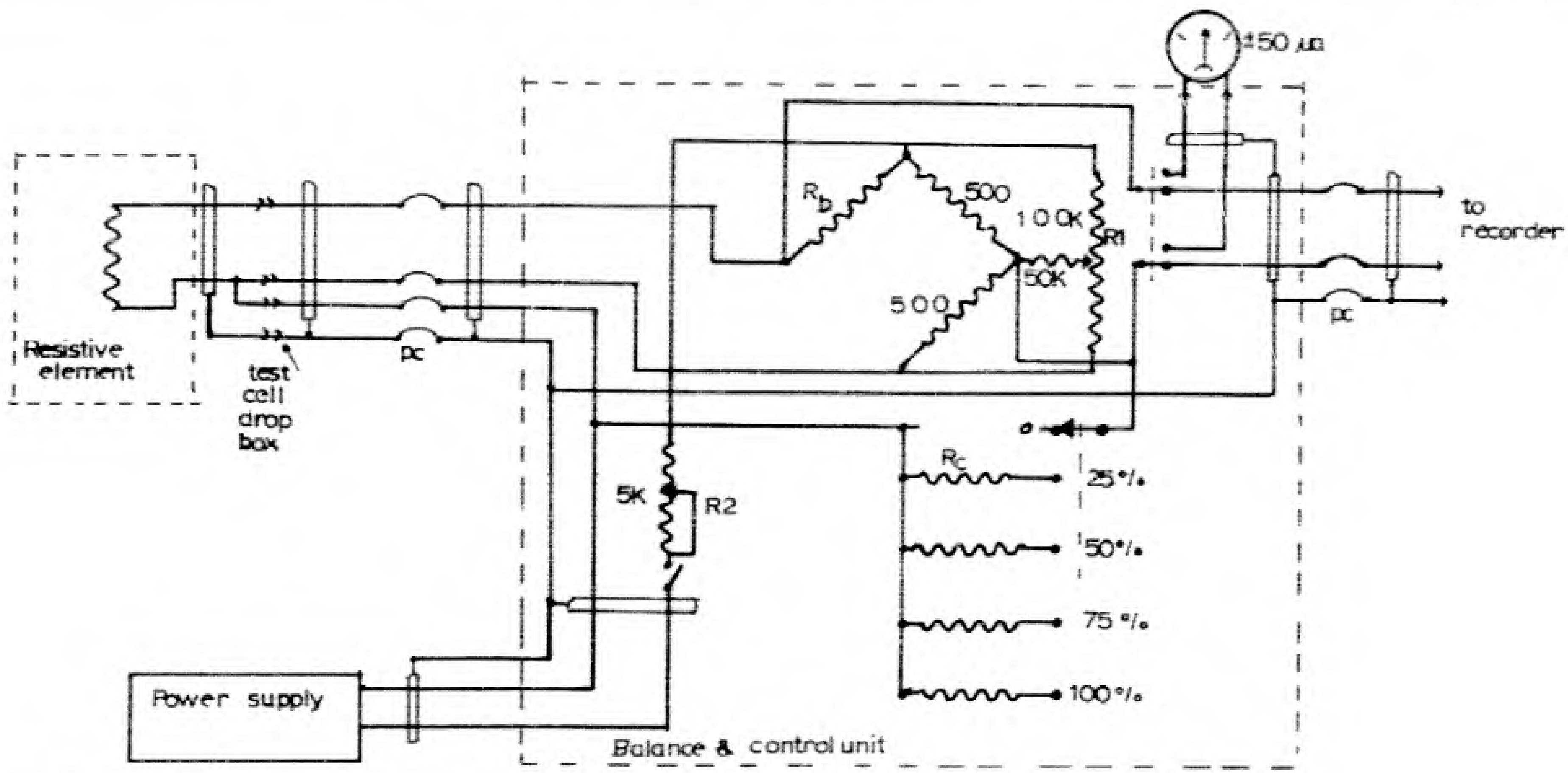
S1 - series resistor

Rs - series resistor, variable

S2 - polarity reversal

S3 - damping resistor

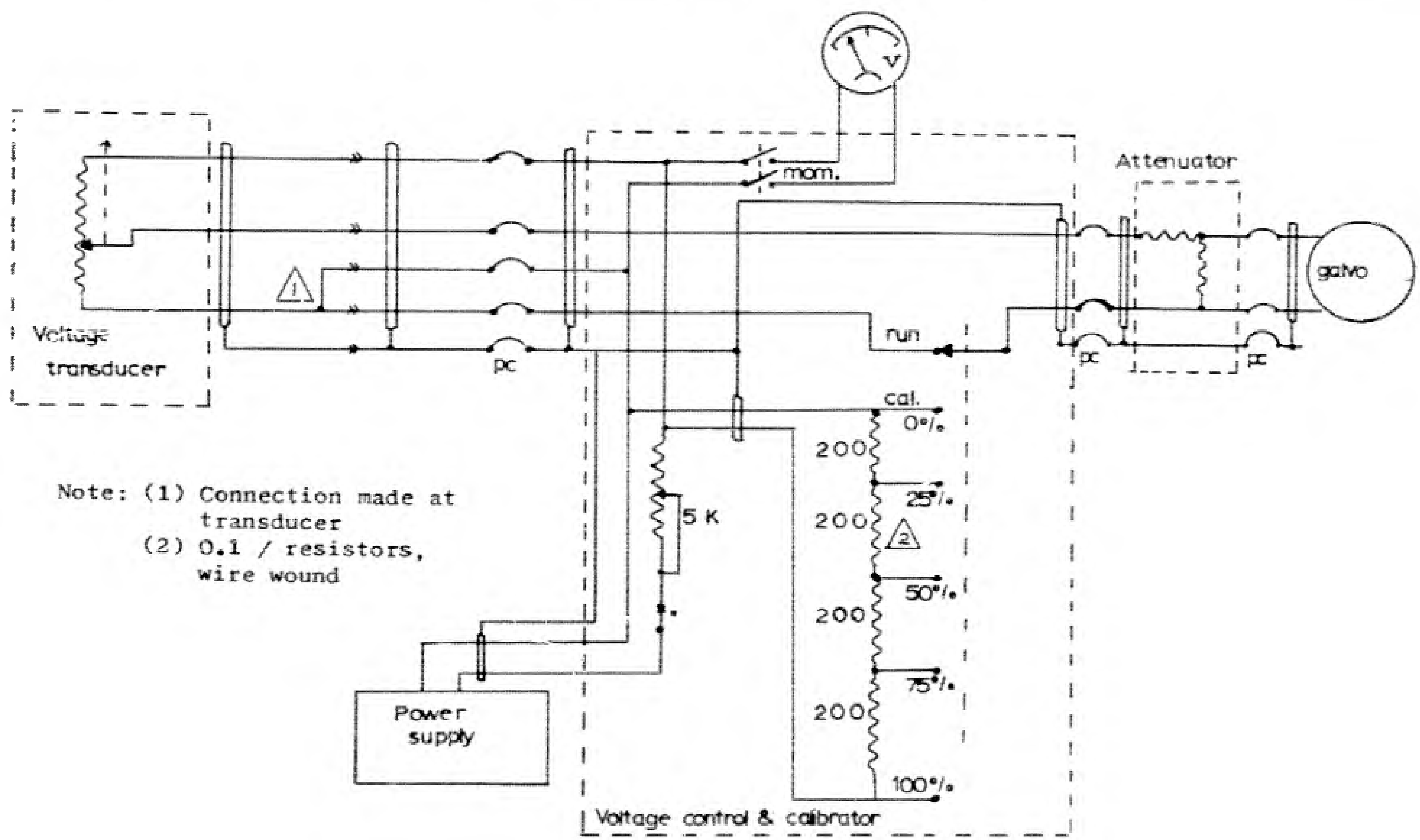
Fig. C-10 Signal Attenuator and Galvanometer Control Unit



Note: (1) Values of Rb and Rc to be selected for application

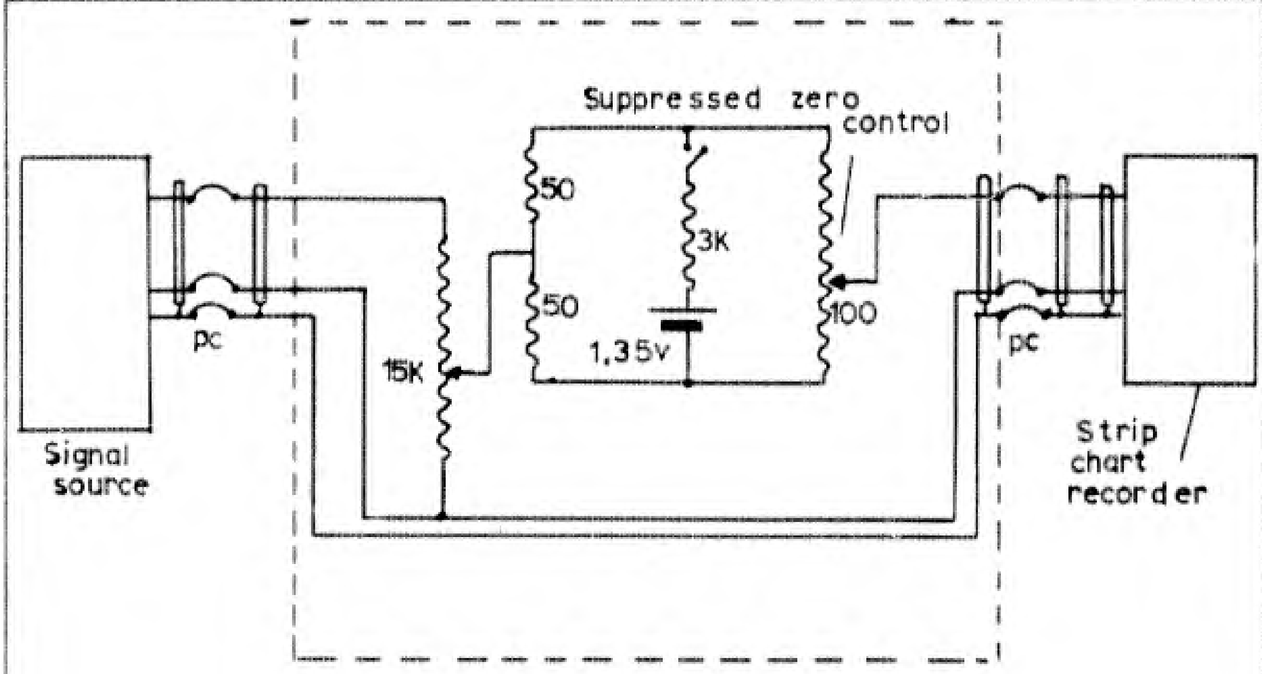
(2) R1 and R2 - IRC type 8000 ten-turn potentiometer

Fig. C-9 Signal Conditioner for Single Resistive Element



Note: (1) Connection made at transducer
(2) 0.1 / resistors, wire wound

Fig. C-11 Voltage Measurement Circuit



Potentiometers - IRC type 8000 ten-turn

Fig. C-12 Recorder Control Unit

Attachment 1

Transducer Calibration Procedure

Suggested calibration procedures are offered for the more frequently used transducers.

Strain Gauge Transducers

The transducer to be calibrated is carefully balanced at zero load, to the zero of a millivolt potentiometer, by an external balancing circuit. This circuit is patterned after that shown in Fig. C-5. The calibration load is applied in five to seven equal steps until 100% load is reached and the millivolt output recorded at each step. The load is then decreased by the same equal steps to zero load. This information defines the linearity and hysteresis of the transducer.

The transducer, electrically balanced at zero load, is shunted by a precision calibration resistor. The values of these resistors are given in Fig. C-5 (Rc). The millivolt output for each value of (Rc), calibration resistance, is plotted on the millivolt - load plot obtained previously. From this information, the load equivalent of the calibration resistor is established. This final relationship between calibration resistor and load constitutes the transducer calibration (Ref 14:2).

An alternate procedure that is often used is to apply the shunting resistance to the balanced transducer and gradually apply the calibrated load until the transducer is again balanced. This will produce the required relationship directly, providing that the load may be continuously applied rather than in discrete steps.

Potentiometric Transducers

The transducer is calibrated by applying a reference input load, e.g., pressure, and the voltage ratio output measured. This voltage ratio is the quotient of the output voltage divided by the input voltage. This information is used to determine the value of the stimulus for each voltage ratio step generated by the calibration circuit of the signal conditioner shown in Fig. C-11.

Thermocouples

The only calibration required for thermocouple circuits is to ensure that the signal conditioning circuitry (Fig. C-8) is providing the correct temperature simulation. In some installations, it may be possible to check the measurement by applying a known temperature to the measuring junction. This, however, is awkward and subject to error.

Appendix D

Visit Report

Subject	Visit to Rocket Test Facilities.
Purpose	To gain information on testing techniques and measurement methods used in rocket research. Visit made in support of the thesis to be written by F/L Fretts.
Visiting Personnel	F/L D. A. Fretts (RCAF) GAW 65 AFIT, W-PAFB.

Installations Visited

14-15	Sept 64	Edwards Rocket Test Site, California
15-17	Sept 64	Jet Propulsion Laboratory, Edwards and Pasadena, California
18	Sept 64	Rocketdyne, Canoga Park, California
21 & 23	Sept 64	United Technology Center, Sunnyvale, California
22	Sept 64	Lockheed Space Systems, Sunnyvale, California
24-25	Sept 64	Aerojet Corporation, Sacramento, California

Edwards Rocket Test Site

Personnel seen:

Lt Wm. Gamble	USAF Project Office
Mr. J. B. Lake	Instrumentation Staff
Mr. W. A. Wright	Instrumentation Staff
Mr. J. B. Davies	Instrumentation Staff

General. The first day of the visit was spent in discussion concerning the AFIT Propulsion Laboratory requirement and the measurement techniques employed at Edwards Rocket Test Site. Since the main activity at this site consists of work on massive liquid and solid engines with no application or experience on gaseous propellants, the discussions centered around general measurement instrumentation techniques and design criteria.

Transducers. Experience at Edwards Rocket Test Site has proven that the unbonded strain gauge pressure transducers frequently fail on sudden relaxation of pressure and are vibration sensitive. A bonded strain gauge transducer, manufactured by Taber, which operates on the proving ring principle has proven to be entirely satisfactory for all gas and liquid pressure measurements. This transducer has a flat frequency response up to about 100 cps and is relatively insensitive to vibration. The Taber transducer has a diaphragm that can be readily replaced by the user and is considered to be a very rugged, reliable transducer. High frequency pressure measurements are made with a Kistler quartz crystal pressure pickup or the Photocon capacitive pickup. These signals are recorded on oscilloscope or on magnetic tape, according to application.

Temperature Measurement. Thermocouples, both locally manufactured and vendor supported, are used for metal and fluid temperatures. For critical temperatures of cryogenic materials, the resistance type temperature probe is necessary. Thin film thermocouple junctions (Nanmac Corporation) are used to measure motor wall temperature; however, these must be used with a high impedance amplifier because of uncertain and changing junction resistance.

Thermocouple reference junctions, supplied by Pace or Research, Inc., are used in all thermocouple circuits. These junctions operate at 150°F. Thermocouple calibration is accomplished by applying precision voltages across a resistor in series with the thermocouple.

Instrumentation System. The Edwards instrumentation system is discussed in detail in Rocketdyne Report R-5298 performed under contract AF04 (611)-8167, dated August 1963. A copy of this report was loaned to this officer by Lt Gamble.

Thrust Measurement. Several small stands were seen which are used to measure the thrust of short duration, low thrust engines. These were double flexure types with virtually zero restoring force. A modified Kistler pressure transducer was used as a load cell to read the short duration (10 millisecond) impulses. This stand was being calibrated by the use of a shock tube. A small piston attached to the stand was placed in the end of a shock tube and shock reflections of suitable duration and amplitude used to provide the standardizing impulse.

No large thrust stands were inspected; however, brief discussions were held on the subject. All stands use a flexure suspension, and the thrust is recorded on flexure isolated axial load cells. Rocketdyne Technical Reports 60-48 and 61-16 entitled,"Dynamic Response of Large Liquid Engines, Supports and Thrust Measurements", discuss the problems being encountered and the possible use of analog computing elements to improve instrumentation response.

Transparent Rocket Motor. A rocket motor, recently illustrated in Aviation Week, with Plexiglass side wall is used for combustion instability studies. The motor is considered to be two dimensional, i.e., of constant internal width, and the height conforming to typical chamber and nozzle configuration. The motor inspected was approximately 4 in. in width and the height at the throat, about 4 in., i.e., throat area about 16 sq. in. The side wall was made up of two layers of common Plexiglass, an inner expendable layer 0.5 in. thick, and supported by a 2.0 in. layer of Plexiglass. This outer sheet of Plexiglass was supported by steel ribs at 5 in. intervals. Pressure transducers were installed in the contoured surface to correlate pressure recordings, with instability phenomena photographed by high speed framing and streak cameras. This motor had operated reliably up to a chamber pressure of 300 psi and runs of one to three seconds duration. Mild and acceptable errosion is evident on the inner Plexiglass surface in the chamber and nozzle entrance. More severe errosion is noted in the throat and nozzle exit. Instabilities were triggered by firing a blasting detonator or grenade cartridge into the chamber from the contoured wall.

Test Injector. A novel injector was used with the transparent two dimensional engine. A series of dovetail grooves were cut in the surface of the injector; these grooves are alternately supplied with fuel and oxidizer from the injector manifolds. A slim plate, machined to match the dovetail groove could be readily slid into place. This plate was drilled to provide the appropriate injector pattern. This method permitted modifications to be made without necessitating fabrication of a complete injector.

Equipment. Some surplus instrumentation equipment is available at Edwards Rocket Test Site. This equipment is listed for disposal within the USAF after Edwards AFB organizations have screened the lists.

Lt Gamble recommends that Mr. Sundahl of the Edwards Rocket Facility be contacted concerning surplus test instrumentation equipment.

Jet Propulsion Laboratory, North Edwards Test Station

Personnel seen:

Mr. S. Rogero

General. This visit consisted of a brief tour of the several test stands at the Jet Propulsion Laboratory (JPL) Edwards Test Station and a discussion on use and calibration of pressure transducers.

Pressure Measurements. Mr. Rogero recommends the use of the Taber pressure transducers with a built-in shunt calibration resistor. He has found these to be of excellent accuracy and durability and can withstand considerable abuse. JPL have done some detailed investigations on pressure measurement techniques. These include the use of a small orifice at the end of the pressure line remote from the transducer to improve response and to provide critical damping for the transducer and connecting tube system. A copy of these findings was given to this officer. Mr. Rogero urges that connecting lines be kept as short as possible between the pick-up point and the transducer and flexible lines be used for vibration isolation. He also suggested that vibration isolation of the Taber transducer was unnecessary for small engine tests.

All pressure transducers are calibrated on a precision dead-weight tester at 30 to 90 day intervals, or on demand. Calibration consists of a pressure-millivolt run to establish transducer hysteresis and linearity and of a shunt resistor value versus pressure for system calibrations.

High frequency pressure measurements are made with Kistler and Photocon transducers. JPL Technical Report 32-624 discusses these measurements in detail. The water-cooled Photocon transducer is used by JPL for rough combustion cutoff systems.

Shocktube Measurements. The Kistler flush mounted transducer is used for pressure measurements in shock tube studies. Shock propagation velocity is measured by the use of platinum thin film probes mounted in the shock tube.

Data Recording System. Signal lines originate at the test stand instrumentation junction box and are terminated in the recording room on an AMP patchboard. From this board, signals are patched to a DC amplifier prior to recording on oscillograph and magnetic tape. For accurate monitoring of test functions, data is displayed in actual engineering units on a digital voltmeter. JPL Project Engineers find such displays very valuable for monitoring test runs.

Measurement of Rocket Chamber Pressure. Two Taber pressure transducers are mounted opposite each other on the chamber of the flight rocket. This pressure readout, accurately calibrated to 0.1% is integrated to give total motor impulse in flight. JPL finds this method more reliable than attempting to measure actual thrust for motor cutoff calculations.

Jet Propulsion Laboratory, Pasadena

Personnel seen:

Mr. D. Griffen	Instrumentation Section
Mr. C. M. Berdahl	Chief Instrumentation Section
Mr. K. Morgan	Propulsion Section

<u>General</u>. The morning of 16 Sept was spent in general discussions with Mr. Griffen and Mr. Berdahl concerning the AFIT requirement. JPL concede that no suitable or acceptable mass flow meter for gases is available at this time. Their opinion is shared by NBS and the University of Colorado, agencies that are considered to be leaders in flow measurements. Many transducers have been tried, but none found satisfactory.

Gas measurements at JPL are made with a rotometer, or with turbine meters such as the Potter Volumetric flow meter. These methods are perfectly satisfactory for steady state measurements on runs of 5 to 30 minutes duration but have limitations for short tuns or variable flow rates.

JPL suggests that a heat exchanger and turbine flow meter in series would constitute the best method for steady state mass flow measurements.

<u>Heat Transfer</u>. A heat transfer apparatus was inspected which illustrated some of JPL measurement techniques. The basic system was a segmented nozzle through which hot gases were flowing continuously. The nozzle was segmented into slices approximately 1/2 inch thick. Through each segment, a separate flow of cooling water was circulated, and the ΔT of the water measured at each segment. A pressure tap was installed in each segment to measure gas pressure at that station. The flow rate of the hot gas and cooling water was carefully measured and controlled. Thus, at each of the 30 to 40 stations, gas pressure, ΔT of the coolant chamber and surface temperature were measured. Pressures were measured on a manometer board and photographed for each datapoint. The thermocouple outputs were sequentially sampled by an electronic commutator, amplified, and converted to a frequency through a voltage to frequency converter. These temperature functions are scaled

to engineering units and printed out on a tape printer that prints function number and temperature for each data channel as it is sampled. The sampling rate is approximately five functions per second.

A motor driven total temperature probe is inserted into the nozzle test section and its position as a percentage of travel is recorded vs temperature on an XY recorder. Three such probes were installed in the system at the time of the visit.

Pressure Measuring System. To replace the manometer board previously discussed, JPL were fabricating a pneumatic scanner. This system permitted one pressure transducer to sequentially scan 10 pressure points. The apparatus under construction could sample 80 pressure points with 8 pressure transducers. The output of these transducers was amplified, converted to a frequency, and recorded on printed tape along with the parameter number. In addition, this signal is routed through cables several thousand feet in length to a central data recording facility for direct recording on magnetic tape and/or computer analysis. The particular advantage of the local printout of test data in engineering units is that the test engineer monitoring the steady run can quickly analyze his system and apply corrections immediately.

Plasma Jet Facility. An experimental Argon plasma engine was being run in one of the laboratories visited. This work was being supervised by a JPL scientist engaged in doctorate studies at Cal. Tech. The flow of the Argon gas was measured with a Brooks rotameter and the temperature measured in a manner described previously. Shadowgraph and spectroscopic techniques were used for the plume analysis.

Thrust Measurement. Lengthy discussions were held with Mr. Morgan on the subject of multicomponent thrust stands. Drawings of a single component and six component stands were secured.

Highlights of the discussion are as follows:

(1) Consider only flexure suspension of thrust stand.

(2) Do not attempt to make a load cell or to apply strain gauges for precision load measurements. Considerable time and effort is expended in fabrication such instruments, and the frequent result is a non-linear transducer with appreciable hysteresis.

(3) Mr. Morgan recommends the use of Baldwin Lima Hamilton (BLH) load cells equipped with flexures to ensure that loads are applied in the axial direction only. BLH cells have excellent accuracy and linearity.

(4) Load cells have a significant temperature coefficient even though they are supposed to be temperature compensated. This amounts to 1 to 3 μv/deg F; therefore, a calibration against temperature is required for accurate work.

(5) By means of suspension bias, the load cell should be preloaded so that a measurement is not made through a zero load. Electrical shunt calibration is still valid in the presence of a preload.

(6) The flexure system, less load cell linkage should have very low natural frequency, i.e., the spring constant is vanishingly small. However, with the load cell connecting the system to the solid stand, a high frequency is desired (at least 60 to 100 cps). This requires a load cell with a very high spring constant. (Typical deflections for a load cell are in the order of 0.01 in. for full load).

(7) In a single component thrust stand, extreme care must be exercised to ensure that thrust axis and the axis of the load cell are coincident. Mr. Morgan urges alignment flats to be placed on all test motors to aid in the alignment.

(8) The only practical means of calibrating a six-component thrust stand is to apply calibrated loads to the stand with the test motor in place. For one-component stands a second reference load cell may be used and the load applied with a hydraulic jack.

(9) A rather complex computer program is necessary to analyze the output of a six component stand because of residual crosstalk between transducers and flexures.

(10) Reaction from propellant feed lines can be minimized in one component stands by looping flexible feed lines in a plane normal to measurement axis. The actual effect of line pressurization can be measured by pressurizing the lines with the aid of a valve at the motor or by flowing an equivalent mass rate of acceptable gas.

Thermocouples. A lengthy discussion was held with Mr. Griffen concerning the fabrication of thermocouples. He stated that unless great care is taken, thermocouple junction errors as high as 5% may be encountered. They insist that for accurate measurements, the thermocouple must not be taken for granted.

Mr. Griffen recommends Thermo-Electric Ceramo cable for fabrication of thermocouples. Two pertinent references were quoted: NBS Circular 561 and ISA Recommended Parctices RP 1.1-7.

Design Considerations. Mr. Griffen made several pertinent recommendations concerning the design of the AFIT facility. These were:

(1) Take extreme care in the design of system electrical ground circuits and cable shields.

(2) The use of a patch board system for transducer, signal conditioning units, and recorder selection gives excellent system flexibility.

(3) The installation of wiring and racks for the total system even though some components would not be purchased until later. This would avoid errors, confusion, and also reduce noise and crosstalk problems.

Rocketdyne, Canoga Park, California

Personnel seen:

Mr. R. Rice	Customer Relations
Mr. W. B. Mechling	Customer Relations
Mr. R. Nelson	Santa Susana Facility
Mr. J. J. Enloe	Santa Susana Facility
Mr. R. W. Roberts	Santa Susana Facility

General. The one-day visit was spent in discussions and a tour of the experimental facilities at Rocketdyne's Santa Susana Test Site. These discussions confirmed that no suitable mass flow metering device existed and that turbine volumetric meters for gas systems were acceptable for steady state measurements only. Rocketdyne engineering staff suggested the use of Taber transducers and oscillograph recorders for pressure measurements from dc to approximately 100 cps. The Dynisco transducer with suitable amplifier for oscillograph recording is suitable to above 1000 cps. The Kistler quartz transducer is recommended for very high frequency pressure measurements up to about 10,000 cps.

Rocketdyne makes extensive use of the Rosemount temperature probes, particularly for cryogenic temperature measurements.

Measurement Techniques. Rocketdyne measurement techniques are discussed in a report given to this officer by Mr. Nelson.

Hydrogen-Oxygen Engines. Some test work is in progress in which gaseous hydrogen and liquid oxygen is used. The hydrogen is cooled prior to injection. Gas flow rates are measured by recording the differential pressure across a metering orifice. Rocketdyne carefully filters any gases used in this motor by means of a Linde molecular sieve. A pure hydrogen-oxygen plume should be colorless. The presence of any color indicates impurities in the hydrogen or oxygen supply. The Linde sieve removes most of these impurities.

Transparent Rocket Motor Test. Rocketdyne is performing combustion instability studies on large rocket engines by means of a full scale, two-dimensional model of the test engine. The third dimension is approximately two inches. One wall of the engine is made up of a layer of two inch Plexiglass. This Plexiglass side wall is in turn supported by a heavy steel grid. Conventional pressure and temperature measurements are made on the contoured surfaces of the chamber, and the flame patterns photographed by high speed framing cameras and streak cameras. Dr. Levine of Rocketdyne has recently written a paper describing this technique. A copy of this paper was secured.

Experimental Engines. Rocketdyne makes use of Atlas vernier engines for many of their experimental studies. They find that these are readily modified to test configurations and save them considerable time and money. A variety of small vernier engines in the USAF and Rocketdyne inventory are suitable for laboratory test purposes.

Data Recording. Input data channels, e.g., pressure, temperature, strain, etc., are patched through an AMP patch board to signal conditioning amplifiers, to oscillograph or chart recorders, and to a Beckman digitizing system for transmission over telephone lines to the Canoga Park data reduction facility. This system permits the test engineer to have reduced data available within a few minutes of the test. The oscillograph output is used for preliminary analysis and on the spot trouble shooting.

The accuracy of data produced by an oscillograph instrumentation system was the subject of a brief discussion. The generally accepted criteria is that a good self-calibrating signal conditioning system, using the output from well calibrated transducers can normally be expected to produce a 2% data. With extreme care, this could be reduced to 1% depending on the type of measurement.

A report written by Mr. Enloe will be mailed to this officer. This will describe, in detail, the signal conditioning techniques used by Rocketdyne at a newly constructed facility at the Edwards Rocket Site.

Safety. Because of the temperate climate in California, most test stands are in the open air and have little or no overhead cover. Rocketdyne is very cautious about the accumulation of explosive or toxic materials. After each test, the stand is deluged to cool and flush the area. Explosion proof fans are located in each test bay to prevent gas accumulation. Vents from tanks, etc., are carried to the top of the test stand before release to the atmosphere. Rocketdyne considers entrapment of gases in clothing and hard hats a potential hazard.

United Technology Center, Sunnyvale

Personnel seen:

Dr. E. Aultman	Vice President
Dr. E. A. Weilmunster	Staff Scientist
Mr. A. L. Holtzman	Test Engineer
Mr. K. Hindersinn	Test Engineer

General. The visit to United Technology Center (UTC) was arranged and conducted by Dr. E. A. Weilmunster, staff scientist to the company president. The visit consisted of a tour of the Sunnyvale facility and the Coyote Canyon Test Site, plus detailed discussions with personnel in charge of various test and experimental facilities.

Operational Gaseous Propellant Test Cell. Mr. Holtzman demonstrated an operational gaseous propellant rocket test cell. This system was the only such system encountered during the two-week visit. Mr. Holtzman's system was simple, flexible, reliable, and closely approximates the AFIT requirement. The system uses two pressure regulators in series. The first, at the bottle farm, is a welding type regulator or Grove dome regulator which is set to a nominal pressure for a test run. The second electrically loaded dome regulator is precisely set prior to the start of a test run. Flow control is achieved by passing the gases through a Liston Cavitating Orifice and thence to the injector. The property of this orifice is that there a direct relationship between mass flow (at a given gas temperature) and the upstream pressure. Mr. Holtzman claims better than two percent accuracy for this type of flow control system. To vary a flow rate during a run, a valve selection can be made so that the gas is routed through a different sized orifice.

Mr. Holtzman's test engines are ignited by means of a miniature spark plug located near the injector face and powered by a Model T Ford ignition coil. An ingenious sequencer controls engine start, run, shutoff, and purge as well as recording instruments. This officer was provided with photographs and schematics of this sequencer.

Ballistic Analyzer. Total impulse and mass of propellants consumed during a test run is measured and calculated by a ballistic analyzer. Signals representing propellant flow rates and engine thrust are converted to frequencies proportional to the function. The thrust and fuel flows are integrated on electronic counters which are gated by a pressure switch on the engine chamber. This apparatus provides an accurate measure of impulse and total fuel consummation immediately upon termination of the test run.

Shock Tube Applications. UTC uses a shock tube to subject samples of solid propellants to heat pulses for the determination of ignition and measure ignition delays. Wave velocity is measured by means of locally fabricated thin film platinum temperature gauges. This film is applied by painting a mixture of metallic platinum suspended in an organic fluid (Liquid Brite 05X) on the glass face of the temperature probe. Vacuum depositing or sputtering is recommended for more uniform film thickness.

Burning Rate Measurement. To measure burning rate of solid propellants, UTC bury a Plexiglass light pipe in the propellant. When the flame front reaches the end of the light pipe, the light is detected by a transistorized photo sensor and is suitably recorded. This method is used to measure burning rate of a grain within the rocket motor.

Hydrid Engine. Dr. Weilmunster demonstrated a hybrid rocket motor which delivered approximately four pounds thrust. This was a demonstration model of a motor currently being investigated at UTC. The system uses a solid Plexiglass internally burning grain and gaseous oxygen. A steel nozzle and injector terminated a hollow Plexiglass cylinder which is about eight inches in length, one and one quarter inches external diameter, with internal bore of one quarter inch. No outer case is used on the grain; consequently, the internal burning of the grain may be viewed while the engine is running. The Plexiglass tube is both motor case and fuel. Burning is terminated before the wall burns through. Nominal running time on a grain is about one minute. Ignition is accomplished by spark ignition of a short pulse of propane, followed immediately by the gaseous oxygen delivered from a small high pressure bottle and controlled by a welding type gas regulator. Dr. Weilmunster demonstrates this motor on lecture tours and would accept an invitation from AFIT to demonstrate this fascinating rocket engine.

<u>Coyote Canyon Facility</u>. The last site visited at UTC was the Coyote Canyon Facility. Because of the limited time available, only the transducer calibration and data recording facilities were seen. Schematics of typical signal conditioning and recording systems were obtained.

<u>Lockheed Missile and Space Company</u>, <u>Sunnyvale</u>

Personnel contacted:

Mr. J. Graca	USAF Admin. Office
Mr. R. Knotts	Lockheed Training with Industry Officer
Mr. J. Engler	Propulsion Laboratory
Mr. W. Trask	Propulsion Laboratory

Mr. P. L. Peterson	Polaris Instrumentation
Mr. H. Hemesath	Santa Cruz Test Site

Instrumentation Techniques. Discussions were held on instrumentation techniques with Mr. Trask, Mr. Engle, and Mr. Peterson. Lockheed like the other companies recommended Taber pressure transducers and Baldwin Lima Hamilton load cells. They make high frequency pressure measurements and strain measurements on magnetic tape or oscillograph running at 160 inches per second.

Mr. Peterson demonstrated the instrumentation techniques for fabricating thermocouples. A water-gas, hydrogen-oxygen welder is used for welding junctions of the more difficult materials. Other junctions are formed by capacitor spark discharge welding technique.

Discussion - State of the Art. A very interesting discussion was held with Mr. Hemesath from the Santa Cruz Test Site. His first recommendation was that visits such as this had best be made to the Santa Cruz facility rather than the main plant at Sunnyvale; however, time precluded such a visit on this occasion.

He spoke of studies initiated on the infrared analysis of rocket plumes. He used a very simple device made by the Hammon Burner Co. of Oakland, California, as a flame source for these infrared studies. This burner is capable of producing accurately controlled flame temperatures and mixture ratios. He suggests that this would be an ideal injector for a gas-gas rocket motor.

Mr. Hemesath provided this visitor with a copy of a report entitled "Experiments with a Solid Propellant Acoustic Oscillator", with the suggestion that it would be an excellent starting point for an AFIT thesis.

Aerojet, Sacramento

Personnel seen:

Lt Col Dano	USAF Plant Representative
Mr. H. Dow	Manager, Measurement Engineer
Mr. A. B. Johnson	Measurement Engineer
Mr. R. Baumer	Measurement Engineer
Mr. G. Wallace	Measurement Engineer
Mr. L. Stone	Measurement Engineer
Mr. H. Friedland	Measurement Engineer
Mr. S. Takeda	Measurement Engineer

General. Lt Col Dano referred this visitor directly to Mr. Dow who made detailed visit arrangements for the two-day visit.

Tour of the Test Area. A tour of the test area included viewing a 1,000,000 pound thrust stand designed for use on the new generation engines. Elaborate, yet practical precautions were in evidence, such as fail-safe circuits, readily replaceable control and instrumentation elements, and associated cables.

The control rooms contain the instrumentation recording facilities for the local test area. Strain gauge and thermocouple data is amplified and recorded on a digital tape system as well as on an oscillograph. Strip chart recorders are used to display control functions and to monitor test sequences.

Thrust Measurements. A number of test stands for solid rocket motors were inspected. Their capacity ranged from 250 lbs thrust to 0.5 million lbs. All test stands use flexure suspension to support the test bed and motor; the heavier stands use flexure plates, while the lighter ones use rods. The more precise systems, 5% and better, featured a built-in calibration device. This calibration force was derived from deadweights or through reference load cells which were loaded by hydraulic jacks.

A lengthy discussion was held with Mr. Stone about design considerations for rocket thrust stands. He stated that care must be exercised in the design of a thrust stand in order to achieve the necessary frequency response and accuracy. Correctly designed flexures will permit the stand bias, or flexure restoring force, to be less than 1%. Although this bias does not constitute an error, it complicates the calibration process if it is to be assessed. Mr. Stone provided this officer with several reports and drawings on thrust stands which may be readily adapted to AFIT use.

Measurement Instrumentation. A discussion with Mr. Takeda, Mr. Wallace, and Mr. Freidland covered the areas of control and measurement instrumentation. Mr. Freidland proposed a flexible control system using variable delay relays and a Vector patchboard. Also noted as an excellent safety feature was a Plexiglass panel placed over a test cell control console to prevent accidental activation of switches during power-on checkout operations.

Aerojet has made use of a multi-holed averaging pitot-static system to measure mach numbers in lines where mass flow rates of gases were required. This system was applied to tubes approximately twelve inches in diameter. Reference was made to work being done by Mr. John Krupp, North American at Englewood and to Mr. Sorne of NASA.

Mr. Tokeda provided this visitor with equipment recommendations for signal conditioning systems as well as several very useful reports and drawings on the subject. Aerojet recommendations were in agreement with those given by other agencies visited on this tour.

<u>General Comments on this Visit</u>

In all cases, this officer was warmly received by genuinely interested and qualified personnel in responsible positions. They were interested in the AFIT facility and the work being done there. These persons gave much time and energy in ensuring that the visit was as successful as possible. They have offered continued assistance via telephone or letter communication. The visit has proven valuable to this officer and has placed at his disposal considerable information and many valuable contacts. The objectives of the visit were realized with the exception of finding the panacea for mass flow measurement of gases.

Appendix E

Implementation and Procurement Schedule

The system design offered in this report can be implemented in three phases. The first phase will incorporate some of the more critical features, while the second and third phases will complete the improvement program. This schedule lists, for each of the separate systems, the work and procurement required for that phase. Costs of major system components are listed; minor components and miscellaneous parts are not included. For such sub-assemblies that may be locally fabricated the estimated cost includes only those items that may have to be purchased and not those parts normally available from workshop stock.

Propulsion Feed System

Phase One. This phase involves modifying the system for electrical control of propellant flow. Components listed refer to those shown in Fig. A-1 and listed in Table A-5.

(1) For remote electrical operation of the existing Grove dome regulators, install valves V11 and valves V9 and associated plumbing. Approximate cost of valves, $150.

(2) Install solenoid valves V1 at the propellant manifold. Approximate cost of valves, $480.

(3) Install two test stand connection racks. On one, mount valves as recommended in Table A-5. The second may be a reduced capacity stand which uses 0.75 inch valves throughout. Approximate cost of recommended valves is $920 and about $800 if the 0.75 inch valves are used.

(4) Conversion to 1.0 inch outside diameter tubing should be commenced during this phase.

Phase Two. During this phase the system is converted to sonic choke flow metering as shown in Fig. A-1.

(1) Install valves V2 and V3 in each propellant circuit. Valve cost $760.

(2) Install variable and fixed sonic chokes. Approximate cost is $500 for each of the variable venturi and $100 for each fixed venturi, as supplied by the Fox Valve Company. Investigations should be made into the possibility of locally fabricating fixed chokes using the purchased item as a guide and as a calibration reference.

(3) Install precision gauges G3 and pneumatic transmitters. Approximate cost $312.

(4) Install burst diaphragm and pressure relief valves as applicable. Cost approximately $120.

(5) Install temperature and pressure transducers.

Phase Three. System schedule should be completed in this phase.

(1) Install recommended regulators R1 and R2 in the propellant lines. Approximate cost is $1600.

(2) Install regulator R4 in purge system. Approximate cost is $50.

(3) Install remaining items such as filters, small gauges, pressure switches, etc., to complete system. Approximate cost is $1000.

Propulsion Control System

A single phase construction program is suggested for this electrical control system. Two phases are listed to permit the cost to be spread and to avoid having the complete electrical system in operation before the propulsion feed system requires all the electrical circuits.

Phase One. The complete electrical system should be fabricated, less computing indicators, etc., and installed in the console cabinet. A temporary control panel should be installed which includes only the controls applicable to the operational configuration at the completion of phase one. Unused cables and switches, etc., should be stowed below the surface of the control panel. Since the system uses plug-in relays, only those required for the operation of the phase-one system need be purchased. The approximate cost for this phase is estimated at $400.

Phase Two. At this stage all of the electrically controlled components will be installed in the system allowing the complete electrical system to be placed in operation. The temporary control panel is replaced with the complete, final configuration panel including matrix board, illuminated panels, etc. The optional operator display functions (Fig. B-2) may be deferred until stage three; however, the mass flow computing panel should be included if possible. The cost of completing the control system will be about $400. The cost of the mass flow computer for two channels is estimated at $400, and the parameter display circuits may be built for approximately $110 per panel including operational amplifiers.

Phase Three. Those portions of the system not previously completed should be installed, thus completing the system as designed.

Safety

Because laboratory safety cannot be compromised, all of the test cell safety features listed in Appendix F must be installed during the first phase of the modification program. The major cost items will be the explosive gas detection apparatus at a cost of approximately $600 and the ventilators approximately $50 each.

Measurement Instrumentation System. Improved accuracy and reliability, in particular, an electrical calibration capability, is urgently required of the laboratory instrumentation system. Therefore, the basic minimum of the measurement instrumentation system must be implemented in the first phase.

Phase One.

(1) Purchase and install patch panel, rain tight wire ducts, terminal box, drop box, recommended instrumentation cables, and connectors (Ref. Appendix C).

(2) Install complete instrumentation system wiring as required in Fig. C-1 and C-3. The estimated cost is $900.

(3) Fabricate and install the following signal conditioning chassis.

(a) One, 10 channel strain gauge transducer bridge balance and calibrator chassis (Figs. C-5 and C-6). Approximate cost $200.

(b) One, 10 channel thermocouple control and calibrate chassis (Fig. C-8). Estimated cost $100.

(c) One, 12 channel attenuator and galvanometer control chassis (Fig. C-10). Estimated cost $150.

(4) Procure the following equipment:

(a) Transducer reference power supply - Harrison Laboratories Model 6201A power supply, cost $180.

(b) A reasonably accurate dead-weight tester, range 25 to 2500 psig. Available from Federal Stock.

(c) Kintel Model 202B microvoltmeter, Federal stock number 6625-720-3537.

(d) Resistor decade box to 99,999 ohms at 0.1% accuracy estimated cost, $75.

(e) Consolidated Electrodynamics galvanometers. The existing stock of 350 ohm impedance galvanometers is to be retained; the others may be used in exchange for the following:

8 ea. 7-341 at $180 ea.

8 ea. 7-346 at 180 ea.

8 ea. 7-315 at 180 ea.

2 ea. 7-362 at 165 ea.

(5) Procure the following pressure transducers:

(a) For installation in the propellant feed system, two Taber Teledyne pressure transducers Model 206, 0 - 750 psig, at $325 each.

(b) For chamber pressure and injector pressure measurements, four Taber Teledyne pressure transducers, Model 206, 0 - 500 psig, at $325 each.

(c) For lower pressure measurements, each two Taber Teledyne pressure transducers Model 217, 0 - 100 psig, at $350 each.

<u>Phase Two</u>.

(1) Fabricate and install additional signal conditioning chassis.

(a) One, 10 channel strain gauge transducer bridge balance and calibrate chassis.

(b) One, 10 channel thermocouple control and calibrate chassis.

(c) One, 10 channel voltage measurement chassis (Fig. C-11). Estimated cost $100.

(2) Procure the following equipment:

(a) Research Incorporated, Universal thermocouple reference junction. Cost $1060.

(b) Two each, Moseley strip chart recorders, Model 680-02 (with 1 millivolt span). Cost $825 each.

(c) One, BLH Electronics double bridge Universal 500 pound load cell, Model U3G2, catalog number 207797, at $510. One load cell required for each thrust stand.

(d) One, BLH Electronics single bridge Precision 500 pound load cell, Model C3P1, catalog number 206173, at $400. One required for laboratory calibration reference.

(e) Medium frequency range pressure transducer (up to about 4000 cps), two each, Consolidated Electrodynamics pressure transducers, Model 4-350-0001, 500 psi. Approximate cost $350.

(f) Good quality mercury manometer complete with pump. Equipment used to calibrate aircraft aneroid instruments would be suitable and is available from Federal stock.

(3) Fabricate 500 pound thrust stands as required, based on design given in Aerojet General drawing SRT-5828 and Engineering Report 3400:10-20, 7 August 1964 "Axial Force Measurement Accuracy of T-407729 Small Motor Test Fixture with T-430689 In-Place Calibrator", and the remarks on this subject given in Appendix D.

<u>Phase Three</u>.

(1) As required, fabricate additional signal chassis from circuits offered in Appendix C.

(2) Continue to build up transducer inventory based on types listed in phase one and phase two. Kistler and Photocon transducers are recommended for high frequency pressure measurements.

(3) Procure 36 channel Consolidated Electrodynamics oscillograph - 5-119 P4V-36, plus one standard and one exit slot magazine. Approximate cost $9000.

(4) As required, purchase Ampex FR 1300 Portable Tape Recorder. Approximate cost for 0.5 inch system with selection of plug-in units $12000.

Appendix F

Laboratory Safety

Introduction

This appendix summarizes the safety features included in the system design and lists additional safety features required for optimum safety. Also included are notes on the handling of gaseous oxygen.

In addition to these mechanical and electrical precautions, a simple set of safety rules for test cell operation are required. These may be derived from the system operating procedures given in Appendix G, these notes, and normal test cell safety rules.

Propulsion Feed System

The propulsion feed system as described in detail in Appendix A of this report includes the following safety features:

(1) Remote operation of all oxygen valves and regulators.

(2) Solenoid valves in propellant system are normally closed.

(3) Low pressure rated component protection is achieved by the use of blow-out diaphragms and pressure relief valves.

(4) Propellant gases are filtered prior to entry to the regulators and system tubing.

(5) Stainless steel components are used wherever possible in the system.

(6) A separate purge valve in series with a check valve is used to purge the propellant lines. Purge and propellant valves are located as close as possible to the test stand to minimize operating time constants.

(7) The complete propellant system is capable of being manually vented and purged for maintenance or servicing purposes.

Propulsion Control System

The electrical control system has a number of safety features which ensure optimum protection for personnel and equipment, as summarized below:

(1) Cable ducts from the control room to the test cell are pressurized to eliminate explosive gas concentration.

(2) A system of interlocks prevents the system from being "Armed" if these interlocks are not satisfied.

(3) Low pressure warning and cutoffs operate if gas supply is too low.

(4) A removable test stand safety and selector plug is used for operator protection.

(5) Key operating arming switch.

(6) Fail-safe electrical control.

(7) Emergency shutdown switch plus emergency power supply to operate normally closed purge and deluge valves.

(8) Flow chart type control panel with valve position indicators and system warning lights.

Test Cell

Because Building 79D was originally designed for liquid rocket tests, it is not completely suitable for operation with low density gaseous fuels such as hydrogen and methane. Ideally, for these propellants, an open test cell or a roll back roof is desired. Since this test cell does not have these features, there exists the probability of hydrogen gas accumulating in the roof structural members of the test cell. It is recommended that the following modifications be incorporated:

(1) A series of combustible gas detecting probes be installed in the roof structure and sequentially sampled by a single analyzer located in the control room. This detector would operate an alarm when the concentration reaches 10% of the lower explosive limit. The Houston Atlas Model 520 multiprobe detector is suggested for this application.

(2) Several roof ventilators be installed in the roof to draw off explosive mixtures.

(3) All electrical fixtures in the upper portion of the test cell be absolutely explosion proofed, this includes lights, heating fans, and door opening motors.

(4) Explosion proof fans be mounted in the test cell so as to aid in the dilution and removal of explosive mixtures.

(5) Gas storage bottles containing fuel and oxidizer, respectively, should be separated by a flame and fragmentation barrier such as a concrete block wall. This precaution is particularly applicable if trailers of high pressure gases are to be used.

(6) The test cell should be fitted with interlocks to ensure that access doors are closed and the main test cell door is open. In addition, interlocks should monitor the operation of ventilating fans, fire and explosive gas detectors.

Oxygen Handling

Gaseous oxygen must always be handled with extreme care. Components exposed to this gas must be absolutely clean and completely inert. For this reason, specially cleansed stainless steel components should be used wherever possible. Notwithstanding these precautions, accidents resulting in severe burns to personnel have been recorded. Most of these are "unexplained" usually occuring on operation of a manual valve on an oxygen line.

An oxygen safety memorandum, received from Aerojet General Corporation and conversations with experienced experimentors (see supplementary References), have produced the following recommendations concerning the handling of large quantities of gaseous oxygen:

(1) System components must be absolutely clean and inert in an oxygen atmosphere.

(2) Sudden opening or closing of a valve in a line carrying a high flow of oxygen is to be avoided, in particular, opening a valve that will admit oxygen into a large volume at low pressure. Most recorded oxygen valve fires have occured under these circumstances.

(3) If the precautions in (2) cannot be adhered to as is the case in most systems, then arrangements must be made to operate these valves remotely so that no injury will result from such fires. Hand operated valves, in particular, a valve between the main supply manifold and the system feed lines should be operated by means of an extension handle through a flame shield oriented to protect the operator from the flames which would originate from a valve fire.

(4) While the Aerojet spokesman could cite no instance of a "K" bottle burning, he recommended that the manifold to which a series of these bottles would be attached should be of small volume so

that a small flow of gas would be required to pressurize the manifold. To allow for the possibility of a valve fire at a "K" bottle, the use of fire proof or flame retardant gloves is recommended.

(5) Flame shields should be located around possible sources of oxygen flames, i.e., valves, regulators, etc., to deflect the flame from fuel carrying components. Ample deluge plus the flame shield may well prevent the fire from burning through a fuel line. This is on the presumption, of course, that the oxygen supply can be quickly shut off by remote control.

Appendix G

Operating Procedure for Propulsion Feed and Control System

General. A tentative operating procedure has been drafted to aid the understanding of the system operation and to serve as a guide for the preparation of the finalized system check list. This will outline the procedure for the firing of a simple rocket engine.

Log Book. A log book should be placed in the laboratory control room; in this book an operating log will be maintained on a suitable pro forma. Entries will include settings of pressure switches, relief valves, hand loaded regulators, throat area of sonic metering chokes, filter data, engine running time, etc.

Preliminary Calculations. The basic operating parameters for an engine run are established by the test operator. These are engine chamber pressure and the propellant mass flow rates required for the test. From a series of previously prepared curves, or from Eq (1), the necessary sonic choke throat area and inlet pressures are established. Also required is an estimated value of system purge pressure.

Propulsion Feed and Control System Preparation. It is assumed that the necessary adjustments and pressure settings on the relief valves, pressure switches, and blow-out diaphragms have been made. The following steps are performed by the system operator:

(1) With "Arm" key and safety plug in his possession, the operator performs the following:

(a) Inspect test cell, noting pressure gauge readings, position of vent valves, manifold valves, etc.

(b) Check test engine, open hand valves of propellant and purge lines, check security of all fittings and connections.

(c) Check security of electrical connections including instrumentation cables, etc.

(d) Using gloves, open valves of propellant supply "K" bottles.

(e) Open main nitrogen supply valve. Confirm that the pressure setting on regulator R4 is at the recommended value (approximately 1000 psi). Set purge pressure regulator to the required system purge pressure

(f) Confirm that pressure settings on propellant regulators R1 are suitable for the test, i.e., about 100 to 120 psi greater than the maximum pressure required from regulator R2.

(g) Set required throat area on variable area sonic chokes.

(h) Check status of doors, ventilators, fans, and other test cell safety features.

(2) Apply 28 volt power (S6), confirm Emergency shutdown switch (S3) is closed, select Ready switch to manual. Check voltage of emergency power supply, and confirm a low battery charging rate.

(3) Vent low pressure portion of propellant lines to atmosphere by operating valve control switches SV2 and SV11 (vent) for both propellant lines.

(4) Turn on instrumentation system reference power supplies. After 10 minutes warm up to allow circuit stabilization, the balance controls associated with force and pressure transducers are used to accurately "zero" each data channel at zero load. Note: vent valves actuated in step three are still open. After

transducers and signal conditioning circuits are balanced, a step calibration is applied to each of the data channels in use and recorded on the oscillograph.

(5) Close vent valves opened in step three.

(6) Select Ready switch S1 to "sequencer". Patch matrix pin board to required test configuration (Ref. Fig. B-1).

(7) Turn test cell status light to red.

(8) Open main propellant valves V1, confirm the green light on pressure warning indicators.

(9) Using load-vent switch SV11, charge control regulator R2 to pressure (displayed on G3) required to deliver desired propellant mass flow rates.

(10) Insert safety plug in test stand socket corresponding to the test stand in use. Confirm from log book time settings on delay relays K3, K4, K7, and K8. These relays are located beside the safety plug receptacles.

(11) Check malfunction light and check that all system interlocks are satisfied. Check position of interlock defeat switches S12 and S13.

(12) Confirm that instrumentation system is ready. Confirm sequencer switch (S10) is correctly set, i.e., all buttons up.

(13) With Arm key, operate Arm switch (S2).

Engine Run. For sequencer operation, as set up by the foregoing procedure, the system firing is as follows:

(1) Sound siren briefly.

(2) The push buttons on switch S10 are operated one at a time from top to bottom. A card holder, located beside sequencer switch S10 can be used to display the time schedule for the test.

(3) The last button(s) on the sequencer shut the engine down. Had the Ready switch (S1) been set to "Ready manual", the following steps would be executed to run the engine. Note that the sequencer as used above accomplishes the same procedure.

(1) Start recorders.

(2) Press igniter switch (S5).

(3) Open fuel and oxidizer start valves (SV2).

(4) Open fuel and oxidizer run valves (SV3).

(5) Close start valves (SV2).

(6) Open igniter switch (S5).

(7) Engine is now running.

(8) To stop engine, press Auto-Stop (S4) or operate purge switch (S7), close propellant valves in desired order (SV3), close purge switch (S7) after two seconds.

(9) Turn recorders off.

Shutdown. To shut the system down perform the following steps:

(1) Remove Arm key and safety plug.

(2) Select Ready manual (S1), open start valves (SV2), vent regulators R2 and lines (SV11) until exhausted.

(3) Close main propellant valves (SV1).

(4) Turn off Ready and Power switches (S1 and S6).

(5) Vent propellant lines (V7 and V8).

(6) Close "K" bottle valves, vent manifold, turn off nitrogen supply.

(7) Complete log book entries, stow Arm key and Safety plug in an assigned location. Secure the laboratory.

Emergency Shutdown. The Emergency shutdown (ESD) switch (S3) may be operated at any time during the test sequence. Actuation of this switch closes all propellant system valves at the same instant and starts the purge which continues as long as the ESD switch is open or until the system Ready switch (S1) is set to "off".

Vita

Douglas Allen Fretts was born on [redacted] son of Raymond Osbourne Fretts and Cecilia Fretts. He graduated from the Napanee Collegiate in June 1947. He alternately attended Queen's University, Kingston, Ontario, from September 1947 to May 1952. In October 1952 he joined the Royal Canadian Air Force and after completion of his training as a Technical Armanent Officer, was assigned to the Central Experimental and Proving Establishment. His degree of Bachelor of Arts (Physics), which was completed by correspondence, was awarded in May 1959. Prior to his coming to the Air Force Institute of Technology, he served as Laboratory Facility Officer at the Air Armanent Evaluation Detachment of the Central Experimental and Proving Establishment, Cold Lake, Alberta.

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