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FINAL REPORT

PROPELLANT LEAKAGE
DETECTION SYSTEM

CONTRACT NO.
NAS 9-6649

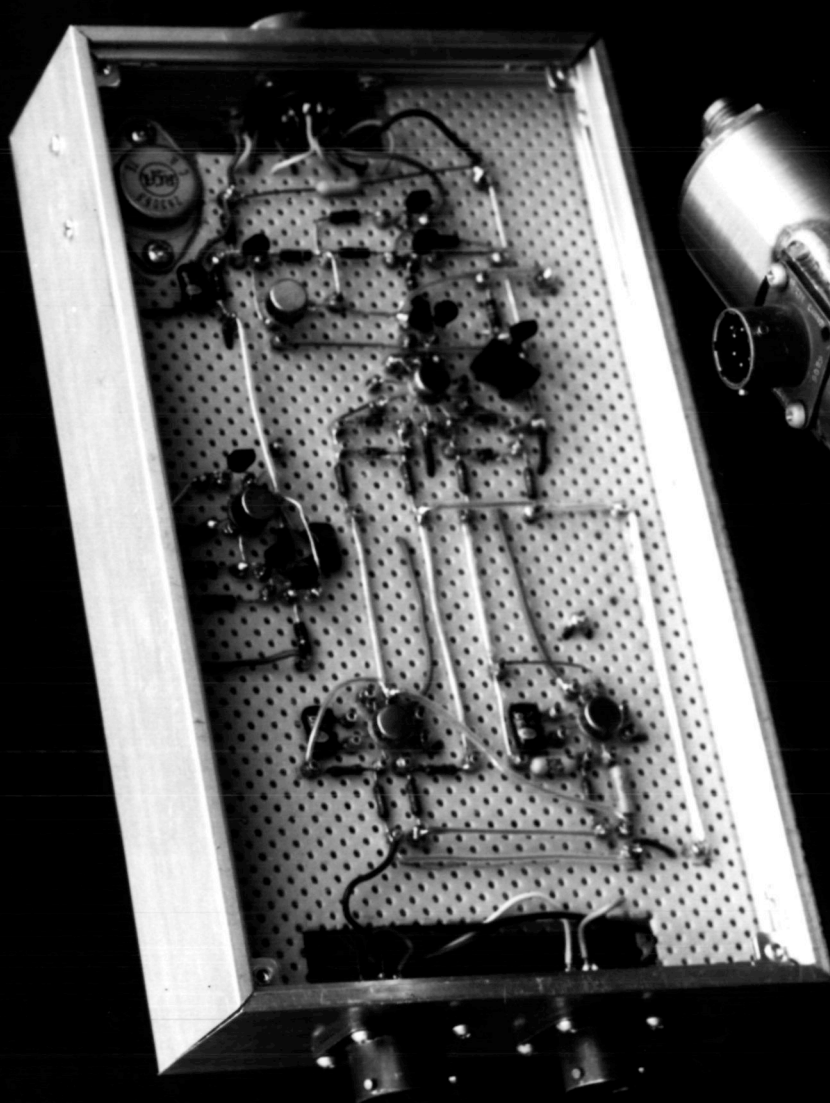
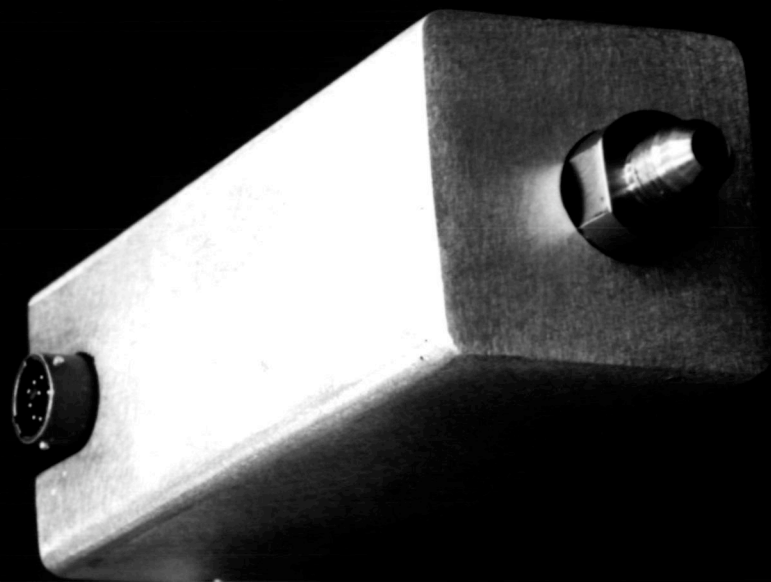
PREPARED FOR:

NATIONAL AERONAUTICS &
SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

PREPARED BY:

SPACELABS, INC.
14630 TITUS STREET
VAN NUYS, CALIFORNIA

8 APRIL 1968



PHOTOGRAPHY BY
Jack McMaster
ORDER BY
THIS No.

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FOREWORD

This report documents the development of the Spacelabs, Inc., Propellant Leakage Detection System. It was prepared under NASA Contract No. NAS 9-6649.

SUMMARY

A prototype Propellant Leakage Detection System (PLDS) has been developed by Spacelabs, Inc., for use in spaceflight propulsion systems. The PLDS is capable of measuring propellant leaks of extremely small magnitude in addition to monitoring propellant flowrates during RCS operation or a catastrophic failure, such as a valve malfunction or line rupture. This system was developed under Contract NAS 9-6649 and was delivered to NASA/MSC in April 1968. Both low flow and high flow sensors are housed in a single meter. The low flow and high flow sensor combination covers the range of 30 cc/hour to 0.88 lbs/second of N_2O_4 and 40 cc/hour to 0.44 lbs/second of UDMH. The primary functions of the unit are leakage detection and an alarm signal output by the low flow sensor, and a mixture ratio limit indicator by the high flow sensor. However, both sensors may be used for continuous flowmetering, but care must be taken to observe saturation flowrates, i. e., that flow where switching from low flow to high flow is required to provide the highest resolution. The electronic package provides power and signal conditioning for the sensors.

The experimental program was concerned primarily with removal of 1-g gravitational field and temperature effects. It was observed that there were variations in output that were attributed to scaling and manufacturing factors. Elimination of temperature effects could not be accomplished utilizing existing techniques. A number of possible solutions are presented in this report in addition to the approach used during the development period. Following an extensive experimental program, a variable power with constant temperature

difference technique in addition to variable sensor housing geometry resulted in a meter that would meet all conditions set forth in the specification with the exception of the temperature compensation.

TABLE OF CONTENTS

	<u>Page</u>
1 INTRODUCTION	1-1
2 OBJECTIVES OF THE PROGRAM	
A. Reaction Control System Characteristics	2-1
B. RCS Failure Modes to be Detected	2-2
C. Propellant Leakage Detection System Characteristics	2-3
D. Environment	2-4
3 LEAK METER DEVELOPMENT PROGRAM	3-1
4 DESIGN OF THE FINAL HARDWARE	
A. Sensor Design	4-1
B. Leakage Warning System	4-3
C. Ratio Computer	4-4
5 EVALUATION TESTS	5-1
6 CONCLUSIONS AND RECOMMENDATIONS	6-1
APPENDIX A	
APPENDIX B	
APPENDIX C	

LIST OF ILLUSTRATIONS

Figure

- | | |
|----|---|
| 1 | Schematic of Typical Reaction Control System |
| 2 | Three Probe Heater-Sensor |
| 3 | Three Probe Heater-Sensor |
| 4 | Three Probe Heater-Sensor Electrical System |
| 5 | Three Probe Heater-Sensor Test Results |
| 6 | " " " " " " |
| 7 | " " " " " " |
| 8 | " " " " " " |
| 9 | Schematic of Three Probe Heater-Sensor System |
| 10 | Three Probe Heater-Sensor Test Results |
| 11 | " " " " " " |
| 12 | " " " " " " |
| 13 | " " " " " " |
| 14 | " " " " " " |
| 15 | " " " " " " |
| 16 | Schematic of Three Probe Heater-Sensor |
| 17 | Thermal Differential System (Constant Power) |
| 18 | Cross Flow System |
| 19 | Coaxial Flow System |
| 20 | Schematic of Self-Heated Body Electronic System |
| 21 | Cross Flow System Test Results |
| 22 | Cross Flow System Test Results |
| 23 | Coaxial Flow System Test Results |
| 24 | Coaxial Flow System Test Results |
| 25 | Schematic of Folded Flow Path System |

Figure

26	Folded Flow Path System Test Results
27	Comparison of Configurations
28	Power Requirements
29	Cross Flow Sensor Test Results
30	Cross Flow Sensor Test Results
31	Annular Cylindrical Sensor
32	Cross Flow Sensor Test Results
33	Cross Flow Sensor Temperature Effect
34	Cross Flow Sensor Temperature Compensation at no Flow
35	Flowmeter Temperature Test Setup
36	Schematic of Heater Amplifier with Compensation
37	Cylindrical Sensor
38	Flowsensor for Oxidizer
39	Flowsensor for Fuel
40	Tube Assembly
41	End Fitting
42	End Fitting
43	Tube Assembly
44	Housing
45	Housing
46	Detector Body
47	End, Upstream
48	End, Downstream
49	Housing Weldment
50	Detector Housing
51	Detector Cover

Figure

52	Probe Inserts
53	Schematic, Flowmeter Amplifier (Constant-Temperature)
54	Schematic, % Ratio - Out of Limit Detector
55	Schematic, Leakage Warning System
56	Flowrate vs. Output Voltage at Different Fluid Temperatures for N_2O_4
57	" " " " " "
58	" " " " " "
59	Flowrate vs. Output Voltage at Different Fluid Temperatures for UDMH Low Flow Sensor
60	" " " " " "
61	" " " " " "
62	" " " " " "
63	Flowrate vs. Output Voltage at Different Fluid Temperatures for UDMH High Flow Sensor
64	Effects of Orientation on the Output of the Low Flow Sensor
65	Effects of Orientation on the Output of the High Flow Sensor
B-1	Natural Convection Around Horizontal and Vertical Cylinders
B-2	Isotherms Around a Horizontal Tube in Free-Convection Flow
B-3	Heat Transfer Coefficient vs. Flowrate Based on Ulsamer Equation
B-4	" " " " " "
B-5	" " " " " "
B-6	" " " " " "
B-7	" " " " " "
B-8	Schematic of Transient Response System
B-9	Transient Response System

SECTION 1

INTRODUCTION

Spaceflight propulsion systems require monitoring of the propellant flow. A propellant leak of very small magnitude could exhaust a reaction control system propellant supply during extended space missions. A failure such as a line rupture or a valve malfunction, could result in the loss of a significant quantity of propellant in a matter of seconds. Furthermore, a catastrophic failure could occur due to injection valve leakage allowing propellant accumulation in the combustion chamber. An effective leakage detection or propellant monitoring system would indicate any of these conditions requiring immediate attention and thus prevent those failures that might cause a mission to be aborted. A further desirable characteristic of a propellant monitoring system is the ability to detect abnormal mixture ratio conditions during operation of the reaction control system.

A problem arises from the corrosive nature of the propellants. The choice of flow device is based on flowmeter materials compatibility, contamination, sensitivity, and the flowmeter principle of operation.

Flowrates encountered in the reaction control system, from leakage rates to engine operation, require a rangeability of better than 70,000:1. This range exceeds by far the range of conventional flow measuring techniques. In order to cover this range with high sensitivity and accuracy, an electrothermal device with two probes was required.

The problems of propellant monitoring for a reaction control system led to a program directed at development of a Propellant Leakage Detection System

with removal of 1-g field and temperature effects as primary design goals. This program was undertaken under Contract No. NAS 9-6649 between the NASA/Manned Spacecraft Center and Spacelabs, Inc. The objectives of the program are set forth in Section II. The development program is outlined in Section III. The design and fabrication of the final hardware is described in Section IV. The results of evaluation tests of the prototype hardware are presented in Section V. Section VI summarizes the findings of the program and presents recommendations for future activities.

SECTION 2

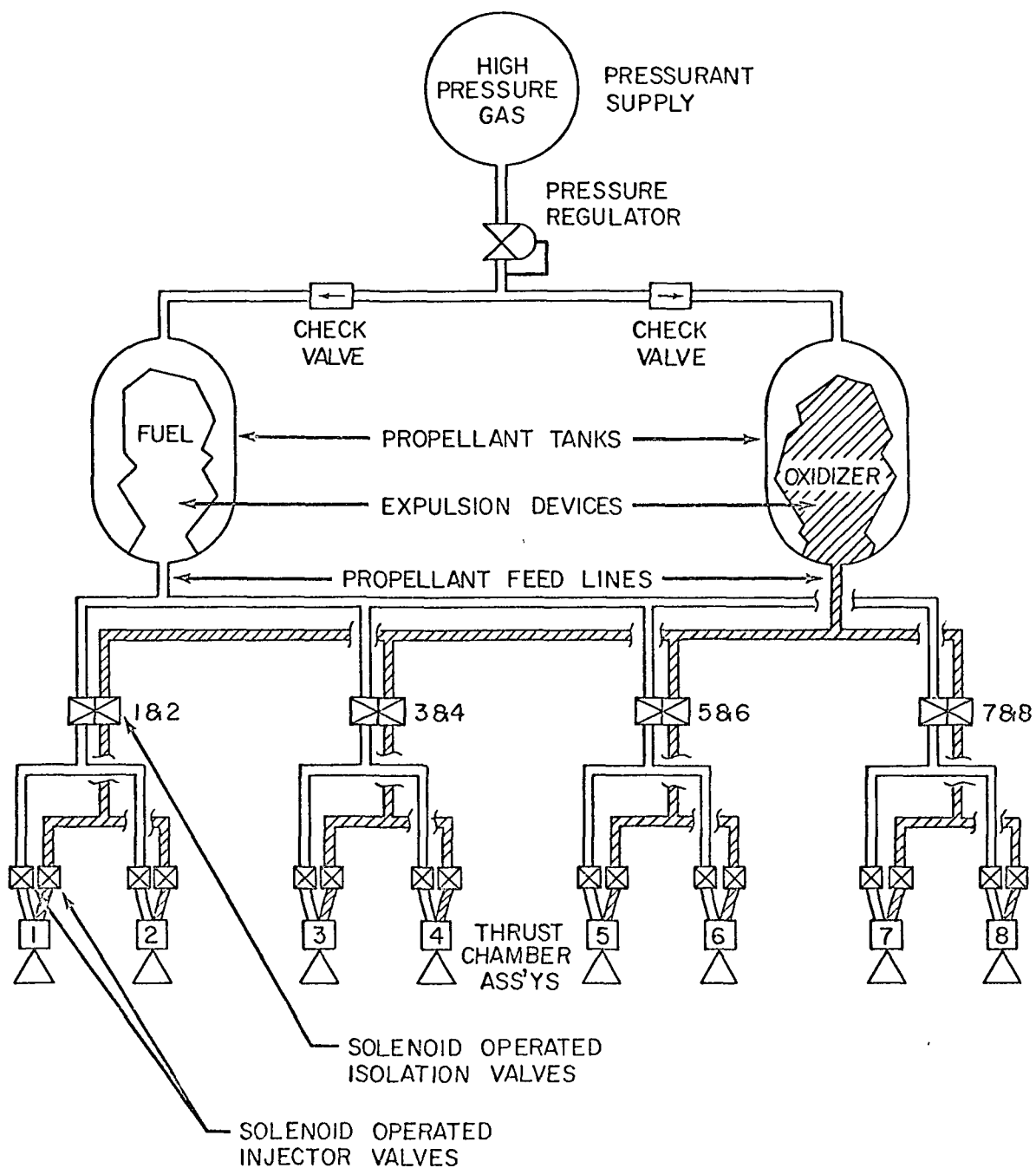
OBJECTIVES OF THE PROGRAM

The primary objective of the program was to develop an effective Propellant Leakage Detection System capable of measuring propellant leaks of minute magnitude in addition to monitoring propellant flowrates under normal RCS operation. The program was aimed at the elimination of temperature and 1-g gravitational field effects to the extent of generating sufficient knowledge to enable design and fabrication of a full-scale flight system. The prototype system was to include a leakage detection system, warning devices when minimum rates were exceeded, control electronics, and a mixture ratio limit monitor. The system requirements are presented in Exhibit A of Contract No. NAS 9-6649, and are summarized below.

A. Reaction Control System Characteristics

A typical reaction control system is shown in Figure 1. It consists of a propellant and pressurant supply system, a propellant feed system, a number of rocket motor assemblies and a propellant monitoring system. The propellants are nitrogen tetroxide as the oxidizer and members of the hydrazine family as fuels. The latter group includes such propellants as hydrazine, monomethyl hydrazine (MMH), unsymmetrical dimethyl hydrazine (UDMH) and Aerozine.

The operating pressure level of the system ranges from 100 to 300 psi. Normal operating temperatures are between 20°F and 105°F where the limits are controlled by the freezing point on the low end and the vapor pressure consideration on the high end. RCS operating flowrates range from 0.22 lbs/sec



SCHEMATIC OF TYPICAL REACTION CONTROL SYSTEM

FIGURE 1

to 0.88 lbs/sec of oxidizer and 0.11 lbs/sec to 0.44 lbs/sec of fuel. The nominal mixture ratio is 2:0. Line sizes vary from the propellant tanks to the thrust chamber inlets. The delivered prototypes were fabricated to adapt to the engine inlets per NASA request.

Two modes of thrust chamber operation are used. In the steady mode main stage durations of up to 10 minutes exist. In the pulse mode, the engine operates in pulses as short as 20 milliseconds.

B. RCS Failure Modes to be Detected

(1) The modes of failure most likely resulting in leakage rates requiring immediate attention would be a line rupture or a single thrust chamber valve failing in the open condition. To detect a leak of this magnitude before a significant amount of propellant is lost requires a system which could be operated continuously as long as the RCS is active and give an immediate warning in the event a leakage signal is received. Since a thrust chamber valve (either fuel or oxidizer) failing open would cause a propellant flowrate similar in magnitude to normal usage rate, some method of further establishing the existence of a true leak must be used.

(2) Small leakage rates could result from imperfect seating of a thrust chamber valve or defective assembly of propellant lines, fittings, or system components. This mode of failure does not always require immediate attention from a propellant loss standpoint; however, the existence and magnitude of such a leak may be of major importance when considering a mission abort before reaching the point of no return. In addition, an

accumulation of propellants in the chamber resulting from a valve leak could result in a catastrophic failure. Detection of small leakage rates through the thrust chamber valves will require continuous operation; however, detection of small leakage rates resulting from defective assembly of propellant lines, fittings, or system components will be required only during specific periods when at least one of the two redundant reaction control systems can be placed inactive.

C. Propellant Leakage Detection System Characteristics

The performance requirements for the Propellant Leakage Detection System include low flow leakage detection, high flow leakage detection, flow monitoring, and mixture ratio monitoring.

Low Flow System

For continuous operation, the system must indicate the presence of any leakage rate between the threshold of the low flow system and the threshold of the high flow system. The threshold of the low flow system is 30 cc/hour for the fuel and 40 cc/hour for the oxidizer.

High Flow System

The high flow warning system is also intended for continuous operation. It is to provide a warning in the event of a malfunction which requires immediate attention. When the RCS is not operating, such a malfunction is defined as a leakage rate exceeding 1350 cc/hour of fuel or 1700 cc/hour of oxidizer. It must respond to such a leak before 66 cc of fuel or 75 cc of oxidizer have passed the detector. The high flow system should also provide an alarm when the RCS is operating and the mixture ratio differs by more than 50 percent from a normal 2.0. The power used by the high flow system is not to exceed 3.2 watts.

General Characteristics

The PLDS must be integrated into the propellant lines of the reaction control system so as to cause no interference with normal operation.

The materials of the PLDS sensors must be compatible with the propellants. The flow sensing elements must introduce a pressure drop less than 1% of system operating pressure at the maximum expected flowrates. The system must provide high reliability and must be fail-safe with respect to the reaction control system. No failure in the PLDS can compromise the reliability of the reaction control system.

D. Environment

The PLDS must operate in the same environment as the RCS. The environmental requirements for the system are presented in Appendix A. These include acceleration up to 8.5 g's, shock up to 15 g's, random and sinusoidal vibration, and normal radiation requirements for interplanetary space travel. The environmental factors outlined in Appendix A do not form specific requirements for the breadboard hardware which was delivered under the present program. Testing was limited to successfully demonstrating the feasibility of future development of qualified hardware.

SECTION 3

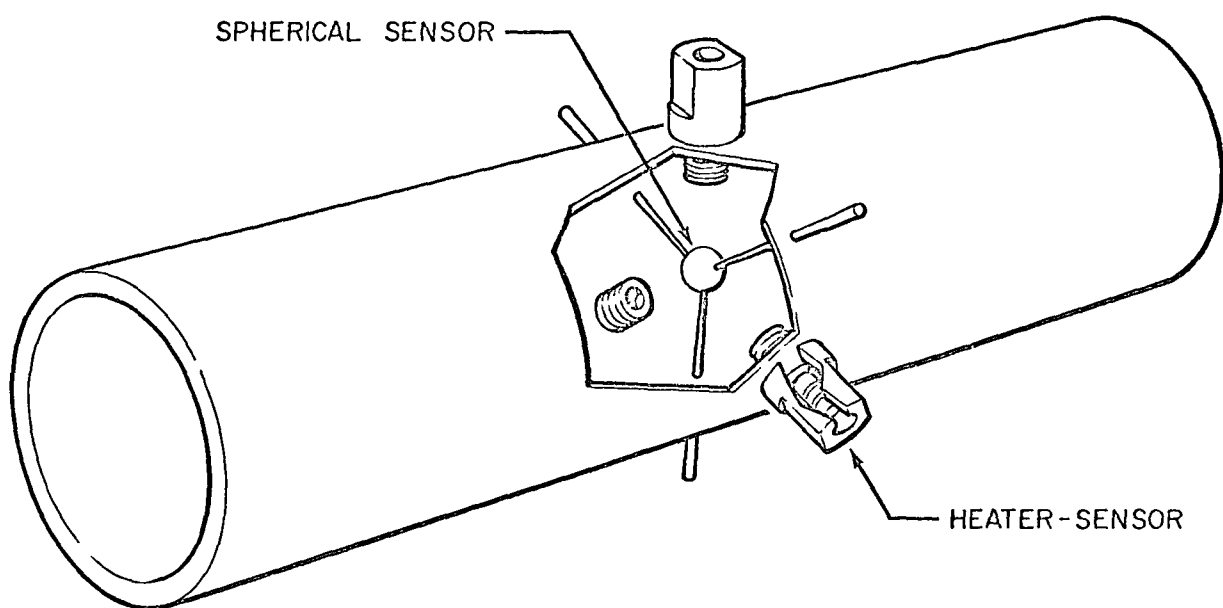
LEAK METER DEVELOPMENT PROGRAM

Following contract award, the program was initiated with a review of the former Leakage Detection Program (NAS 9-3427) and an evaluation of the data that resulted from that program. As a result of this review, a number of problem areas were defined and investigations were initiated.

The initial efforts were directed at solving the problems encountered in the low flow detection. At the minute flowrates being measured near the threshold of leakage detection, the forced convection heat transfer coefficient is an order of magnitude less than the heat transfer coefficient for natural convection. To obtain an indication of leakage flowrates that is repeatable requires that the changes in natural heat transfer coefficient as a function of temperature and orientation are minimized. This was verified by experimental data obtained during the former program which indicated the PLDS configuration used then to be very sensitive to orientation.

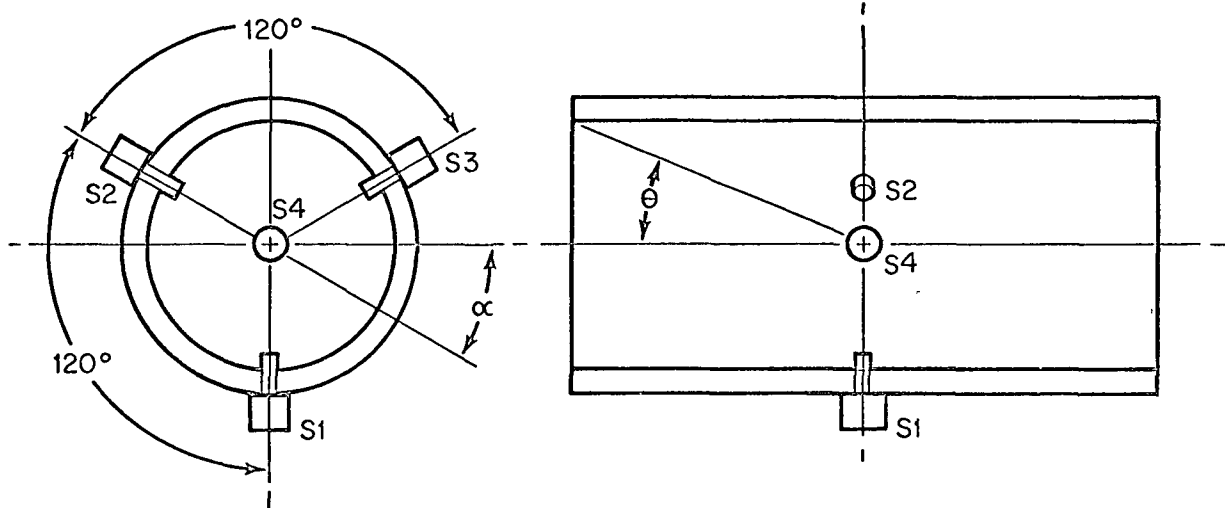
Before defining a configuration, a flow study was conducted where dye was injected into the fluid so that the natural convection phenomena could be observed. The result of this study was a three-probe heater-sensor arrangement equally spaced around the periphery and a spherical sensor located in the geometric center of the heater sensor probes (Figure 2).

Figure 3 references the changes in orientation to which the unit was subjected. A simplified electrical schematic is shown in Figure 4. Tests were conducted to determine the relative change in natural convection heat transfer coefficient and to establish a temperature field at the axis with changes in orientation. The results of the tests were corrected to zero degree orientation and are shown in Figure 5 and 6. These results warranted



THREE PROBE HEATER-SENSOR

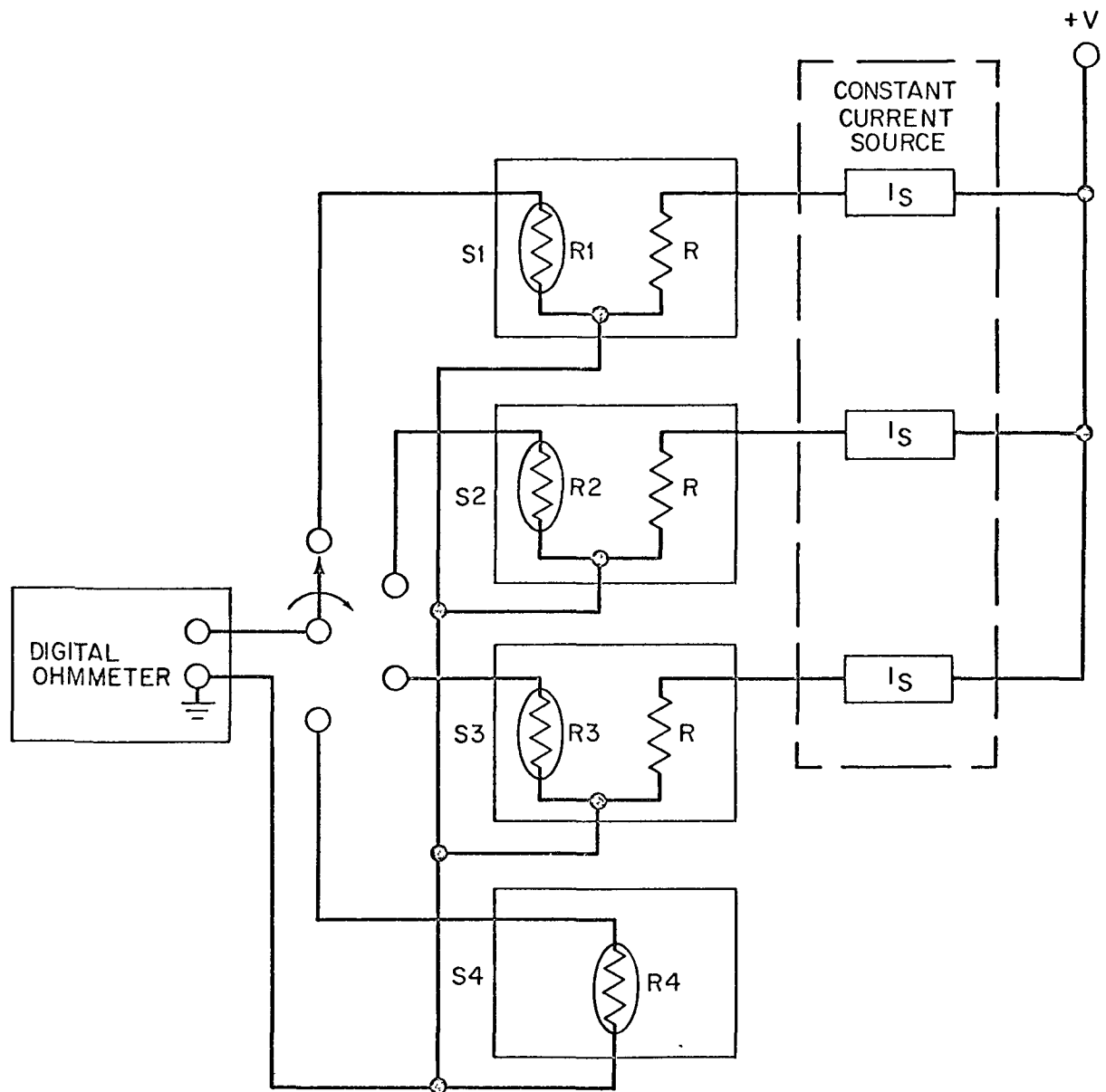
FIGURE 2



α = ROTATIONAL ANGLE
 θ = TILT ANGLE

THREE PROBE HEATER-SENSOR

FIGURE 3

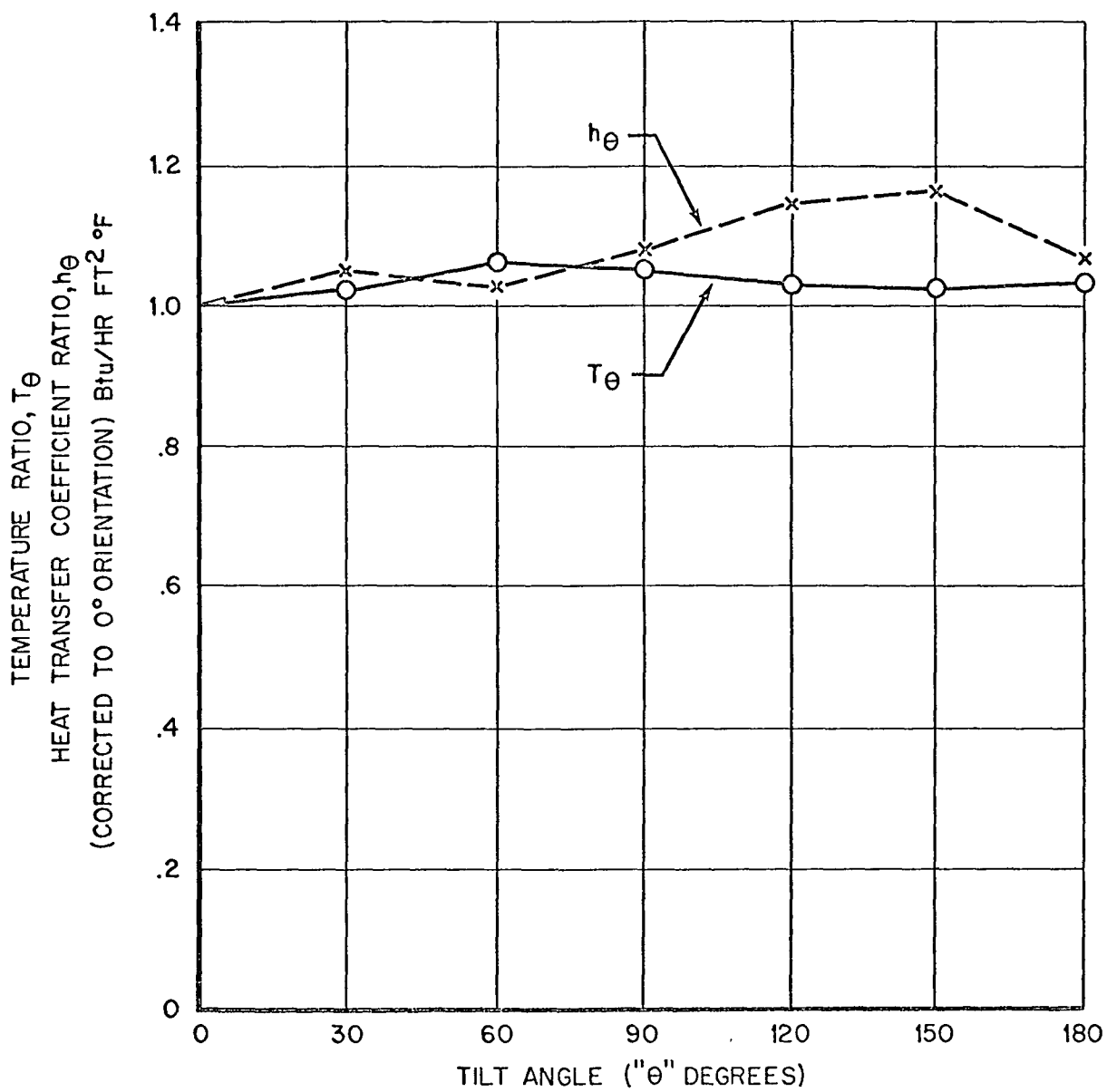


R = HEATER RESISTORS

R1, R2, R3 & R4 ARE THERMISTORS USED TO GIVE ABSOLUTE TEMPERATURE

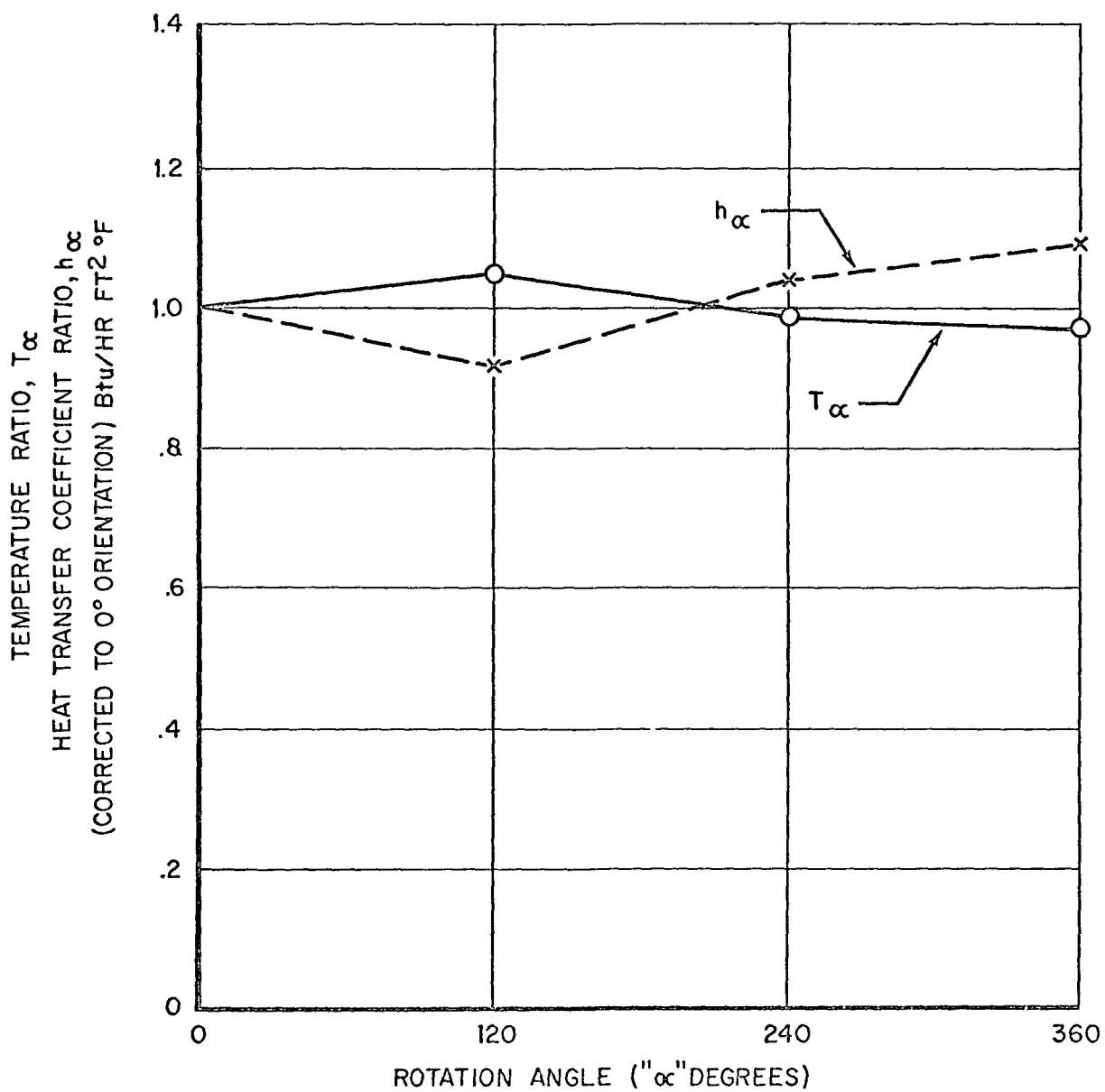
THREE PROBE HEATER-SENSOR ELECTRICAL SYSTEM

FIGURE 4



THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 5



THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 6

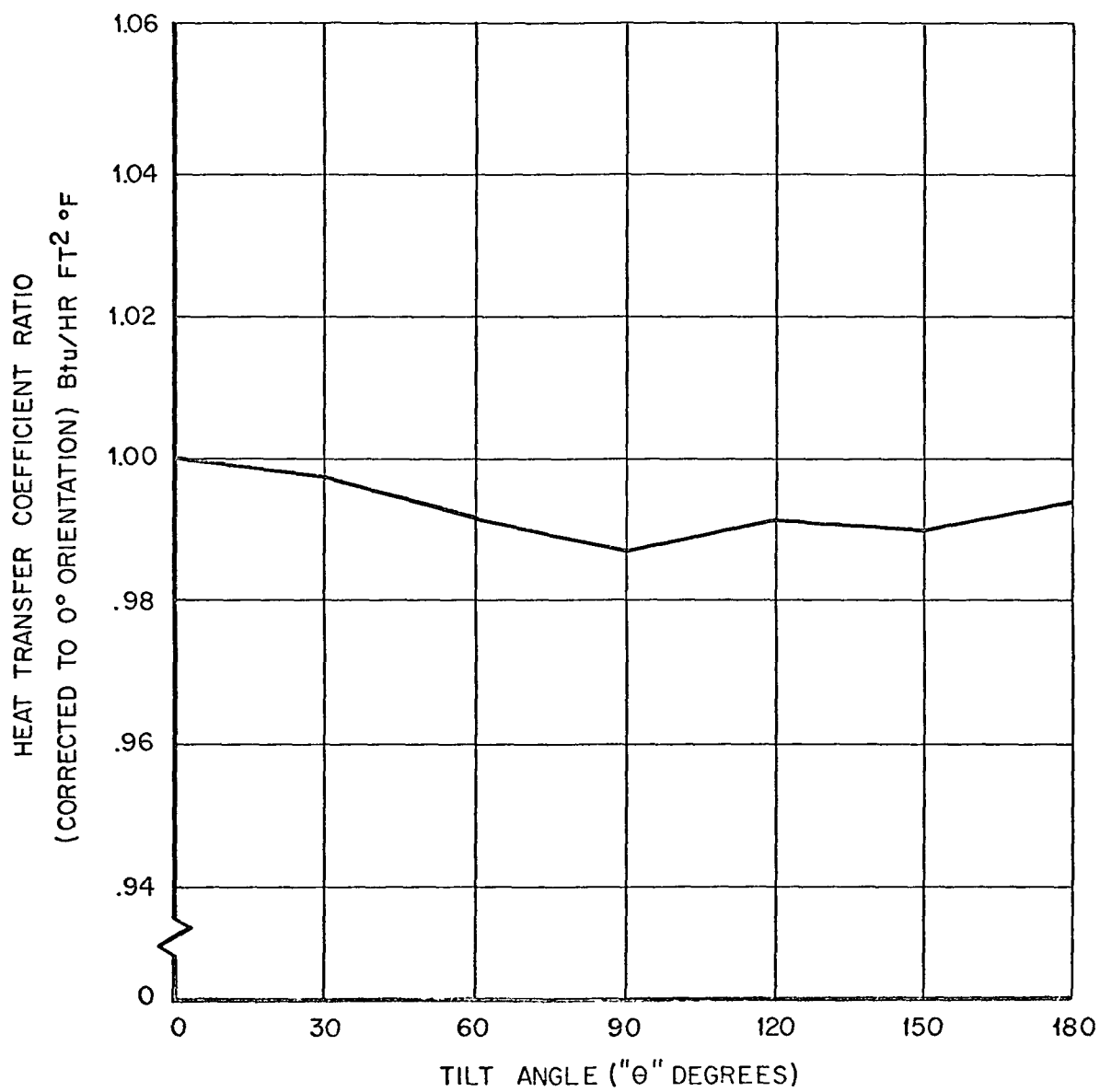
manufacture of an improved model constructed of stainless steel and with the capability of varying probe depth into the fluid stream. Data obtained for the individual corrected heat transfer coefficients indicated that the best results would be obtained if the electrical signal proportional to the individual heat transfer coefficients was averaged. The orientation test was repeated with the improved model and the results showed a marked improvement over the initial model (Figures 7 and 8).

To determine the effects of increased sensitivity of the electronic system on the average heat transfer coefficient, a modified version with better than twice the sensitivity was assembled (Figure 9). The equations establishing the sensitivity of the two systems are derived in Appendix B.

The orientation effect tests were repeated with the more sensitive electronic system. In addition to the orientation changes, various combinations of probe immersion depth and heater power tests were conducted. The results are shown in Figures 10 through 13. The results indicate no predictable trends in the change in heat transfer coefficient with orientation. There is, however, a definite decrease in the temperature at the axis with changes in tilt angle when less power is dissipated in the fluid or when the probe immersion depth is decreased. This change was attributed to the rate of heat transfer from the support.

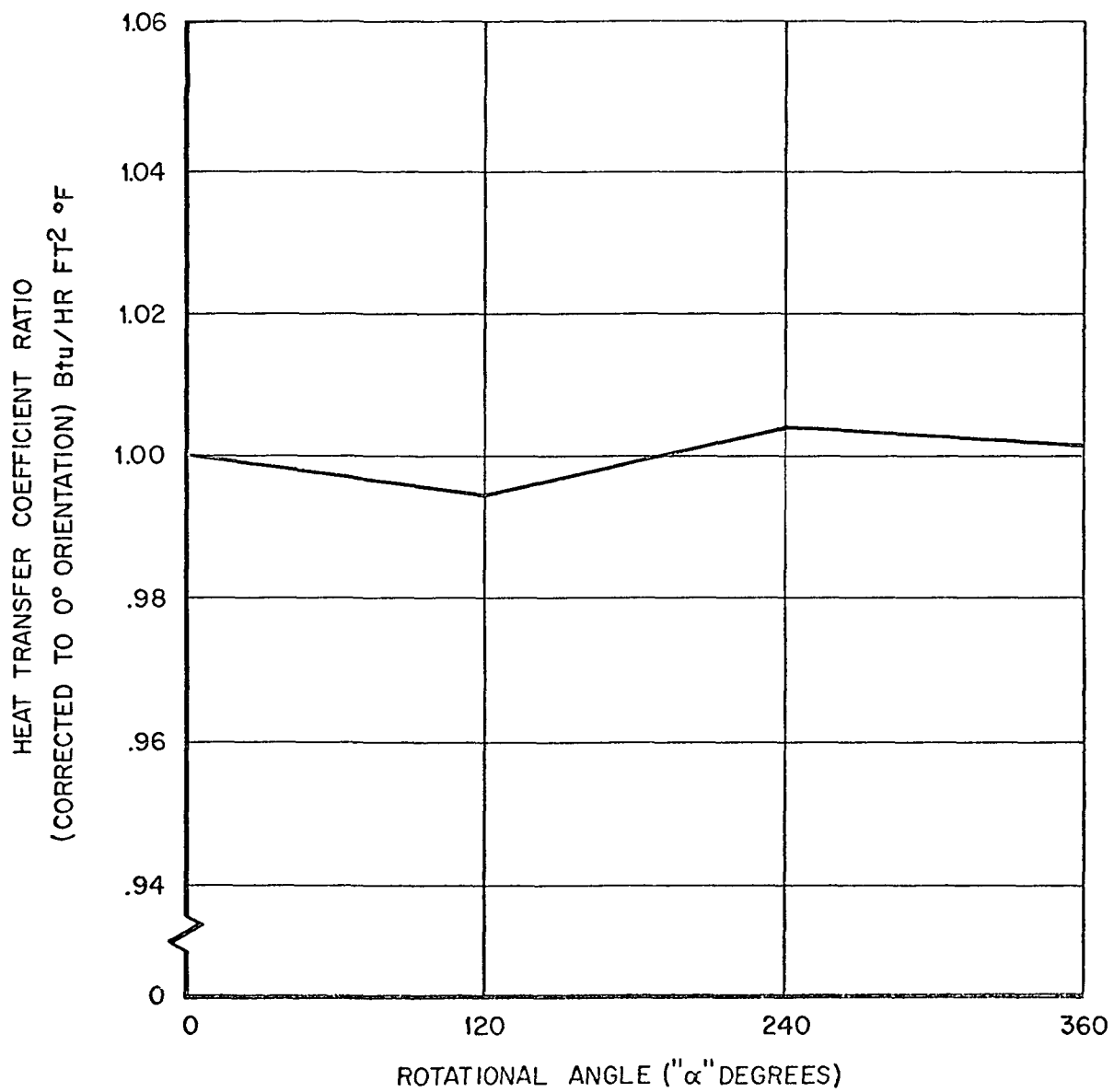
This was verified experimentally by thermally insulating the heater sensor probes from the flowmeter housing with teflon sleeves. The results are shown in Figures 14 and 15, and there is an improvement over the non-insulated probes.

To further improve its symmetry two more sensors were added, bringing the total to three (Figure 16). Using the constant temperature differential



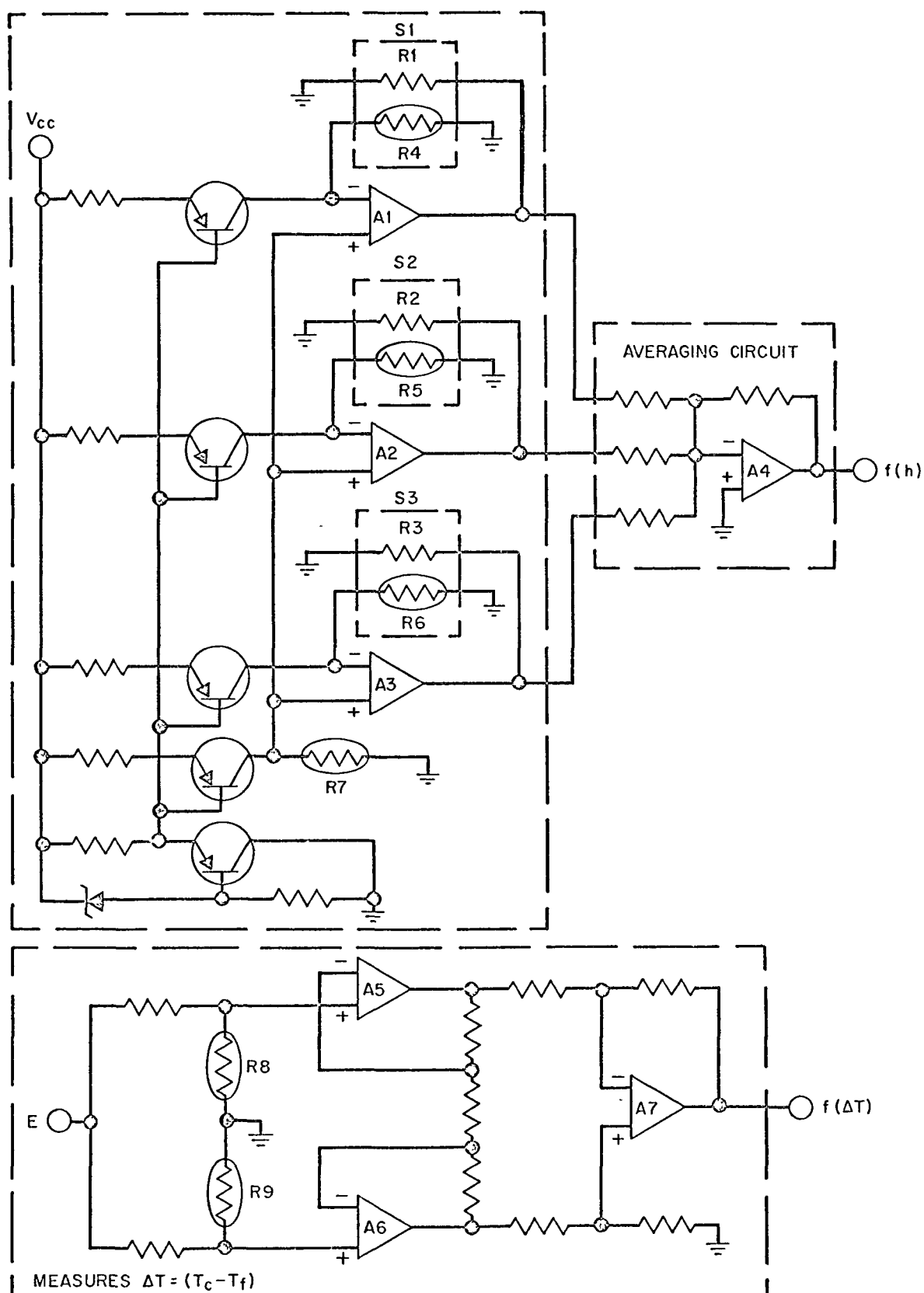
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 7



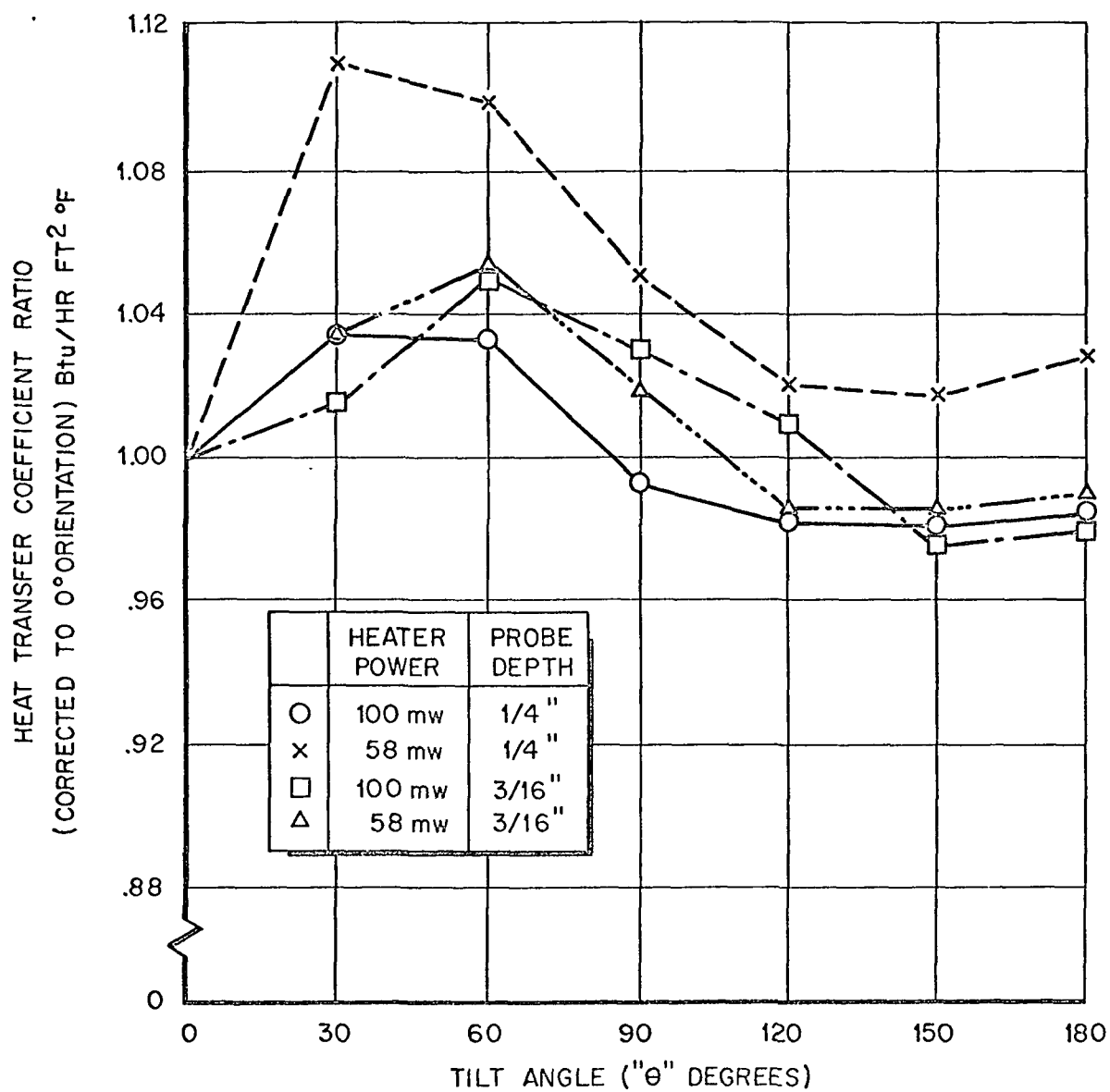
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 8



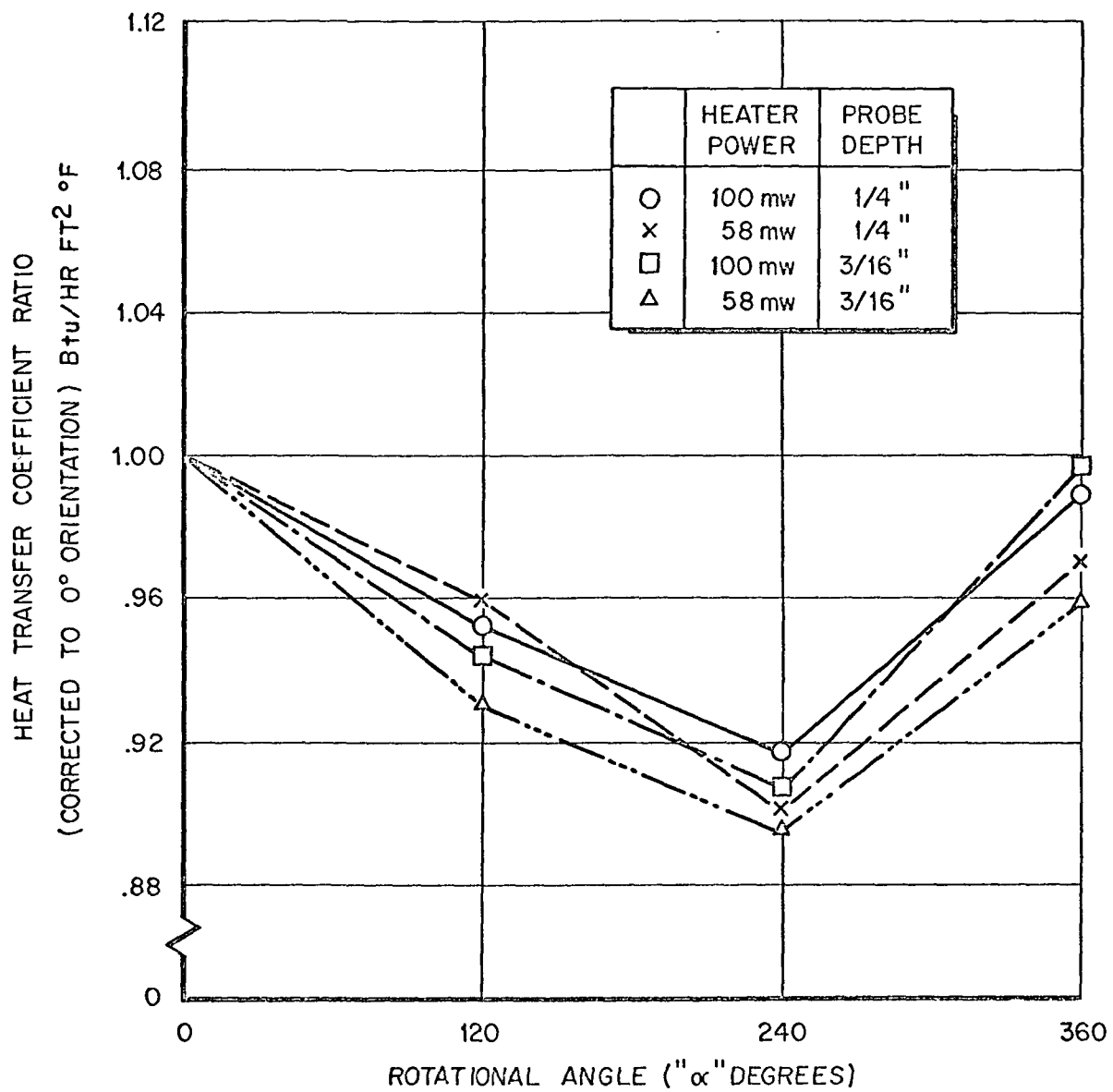
SCHEMATIC OF THREE PROBE HEATER-SENSOR SYSTEM

FIGURE 9



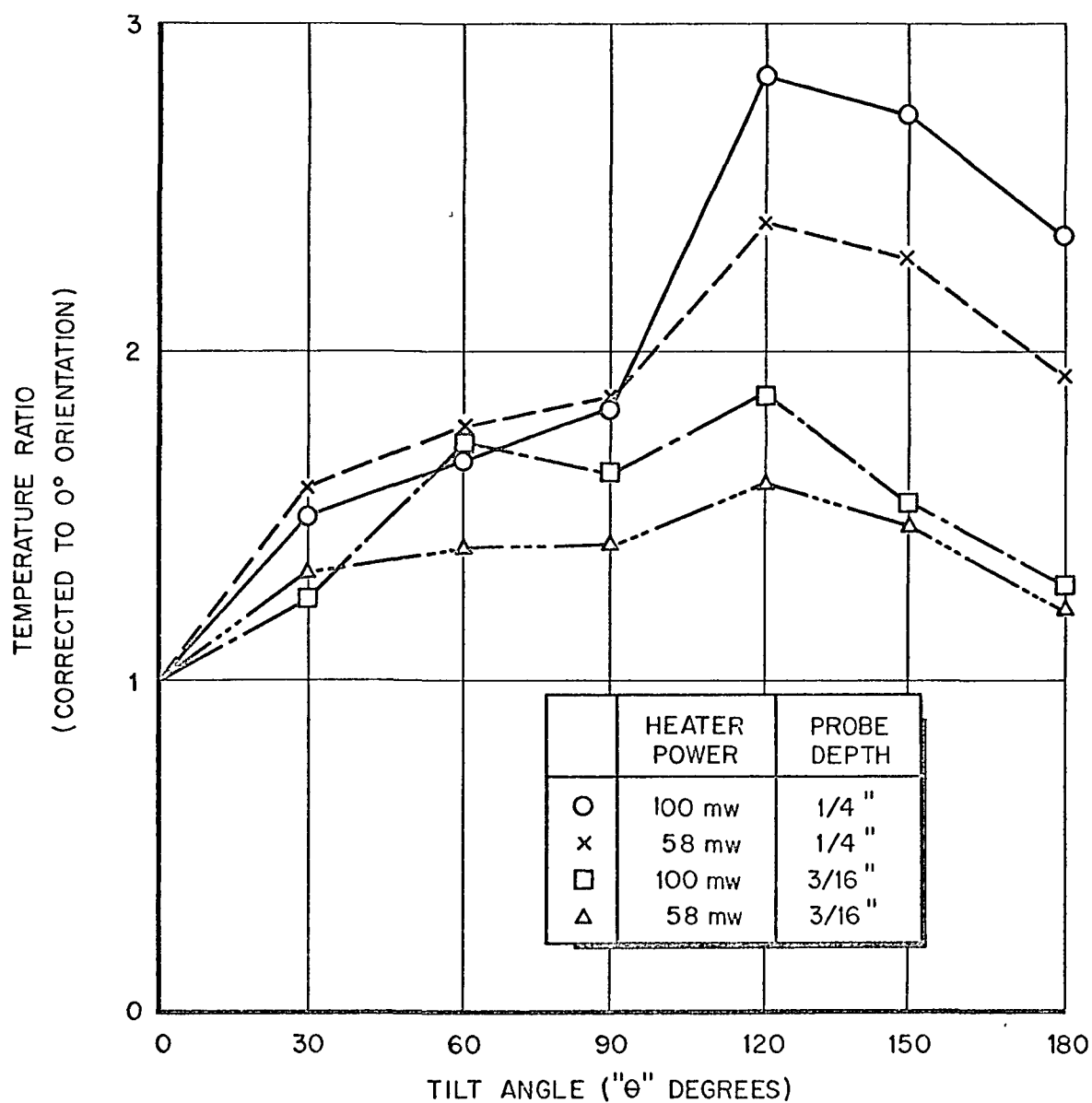
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 10



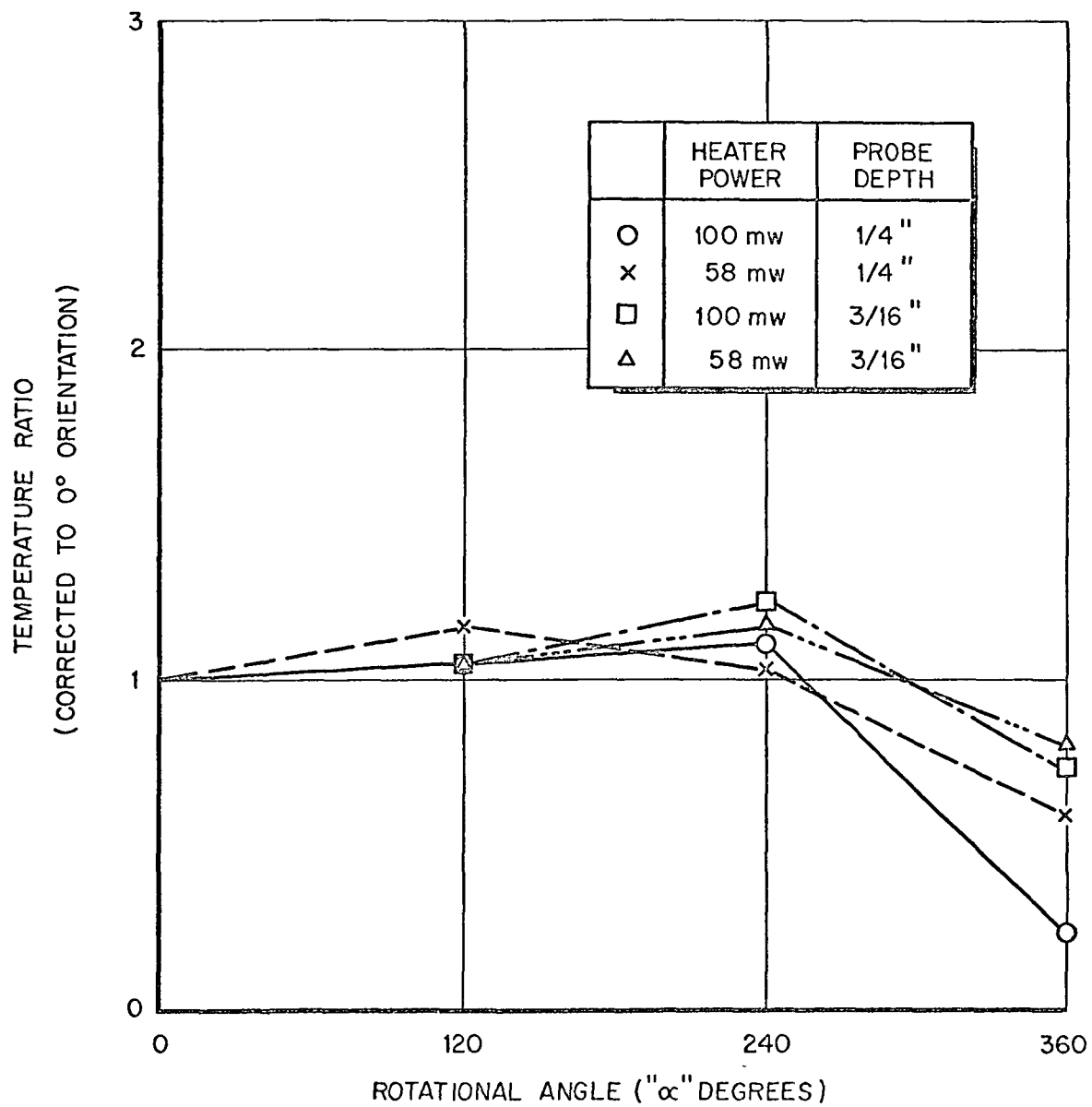
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 11



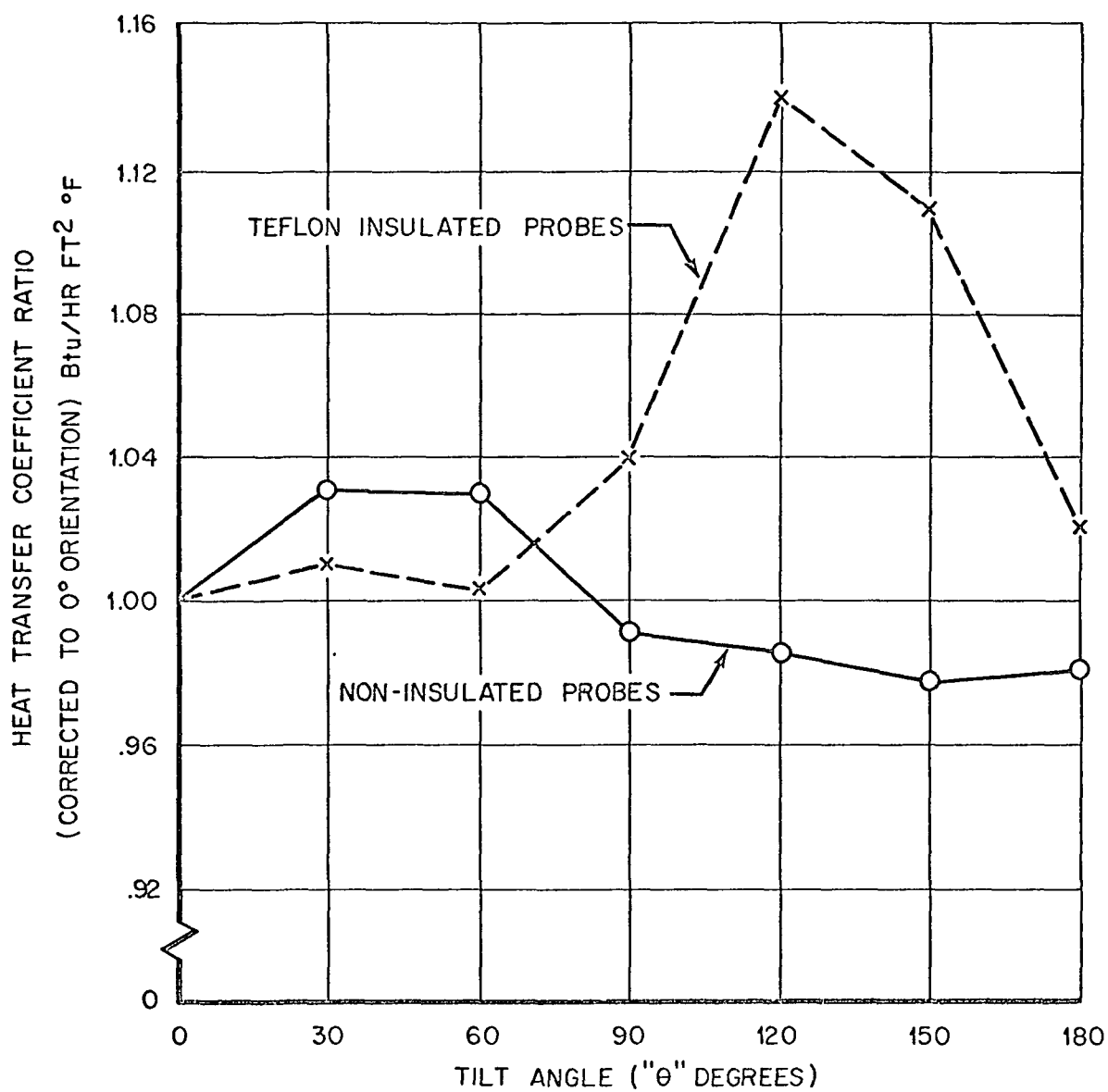
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 12



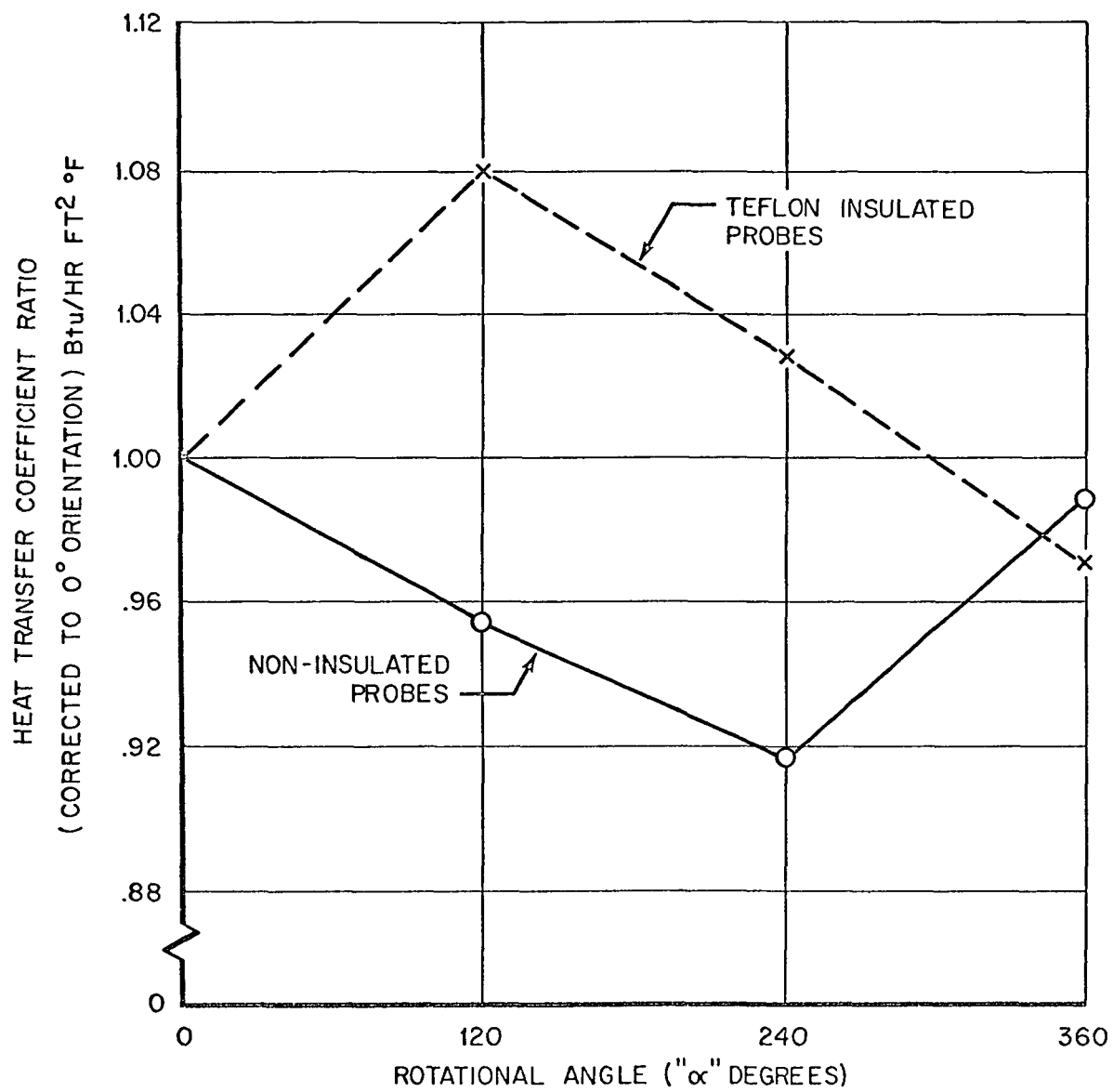
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 13



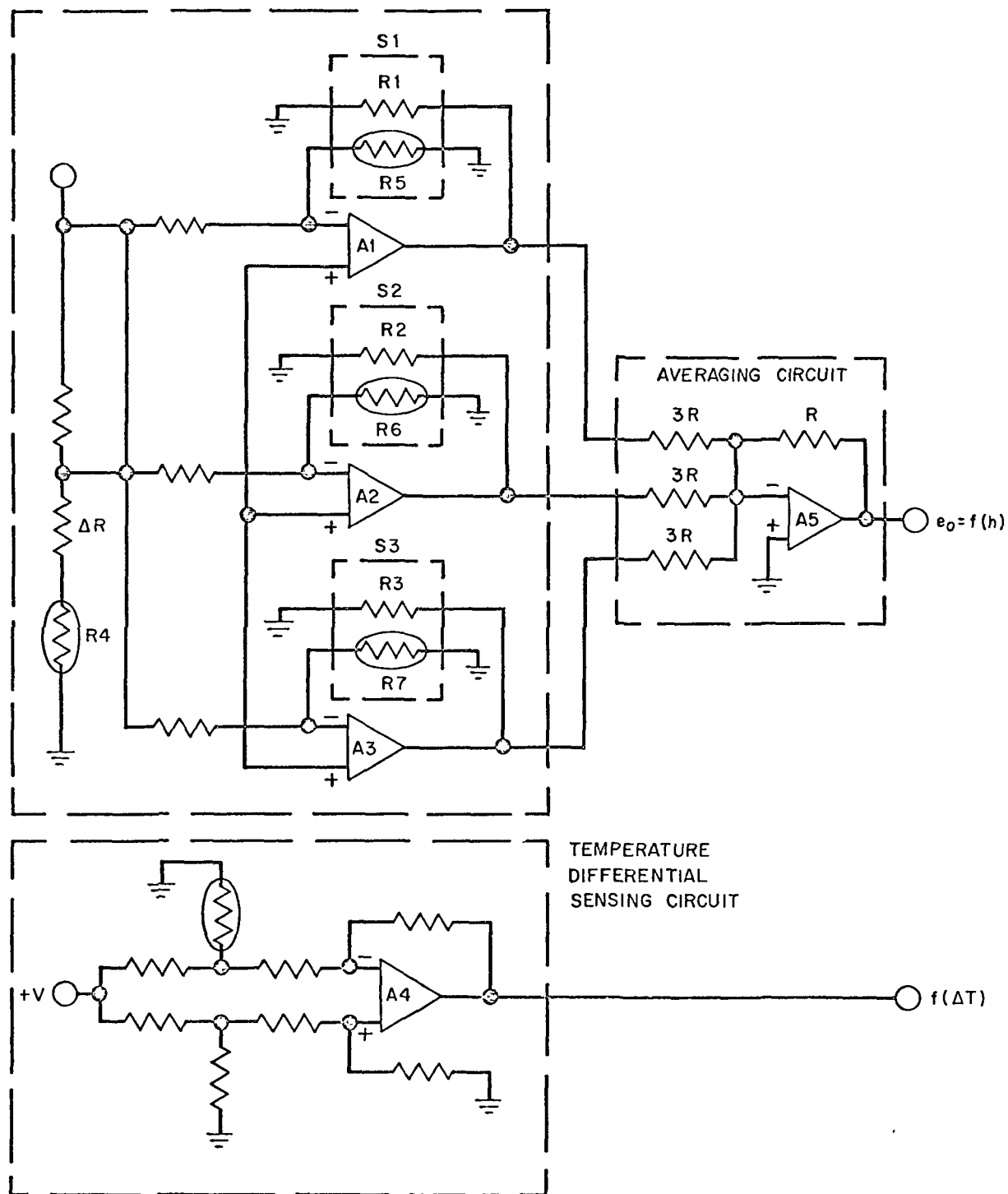
THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 14



THREE PROBE HEATER-SENSOR TEST RESULTS

FIGURE 15



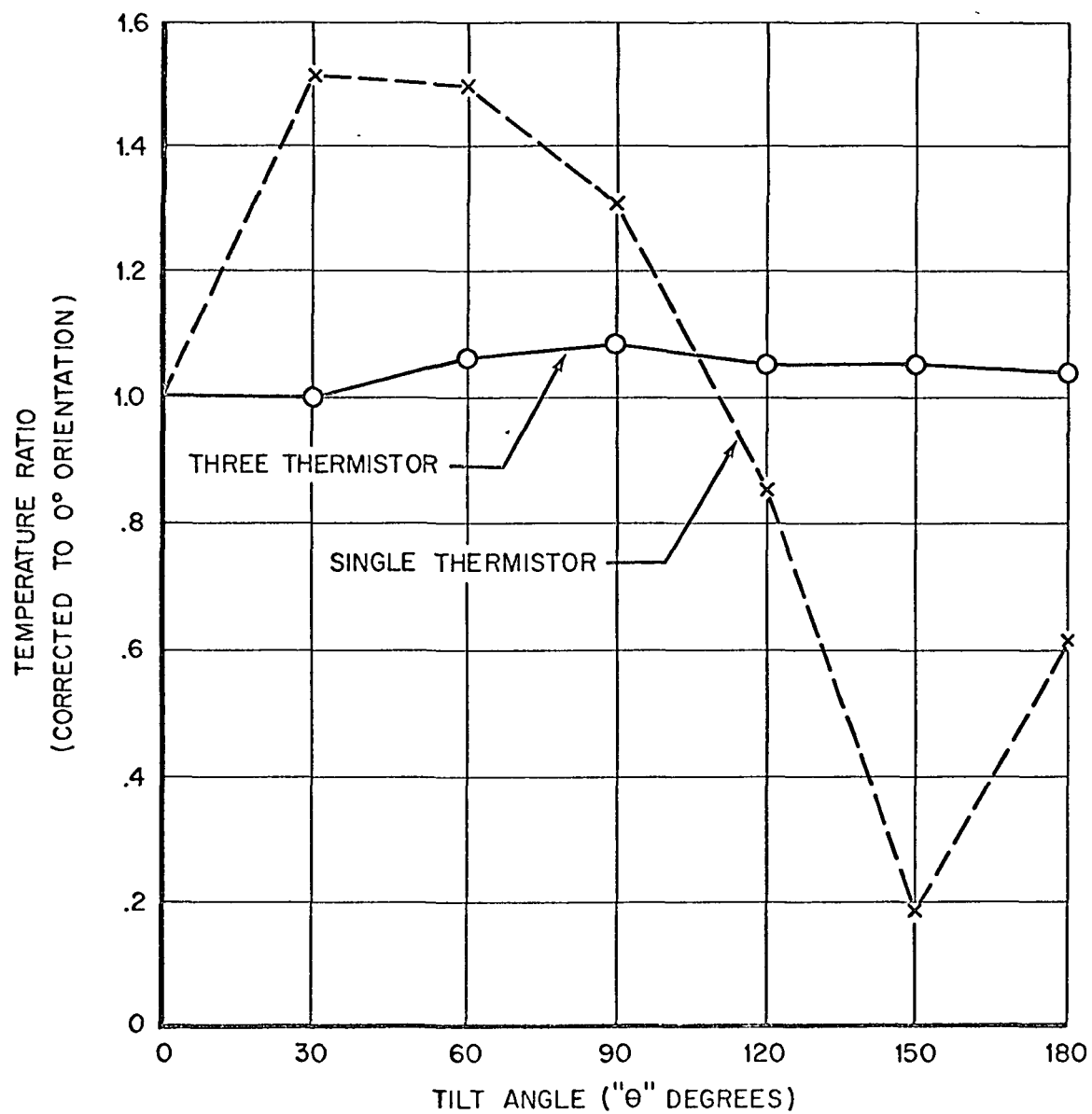
S1, S2 & S3 ARE HEATER-SENSOR PROBES
 R1 - R3 ARE HEATERS
 R4 - R7 ARE TEMPERATURE-SENSITIVE RESISTORS

SCHEMATIC OF THREE PROBE HEATER-SENSOR

FIGURE 16

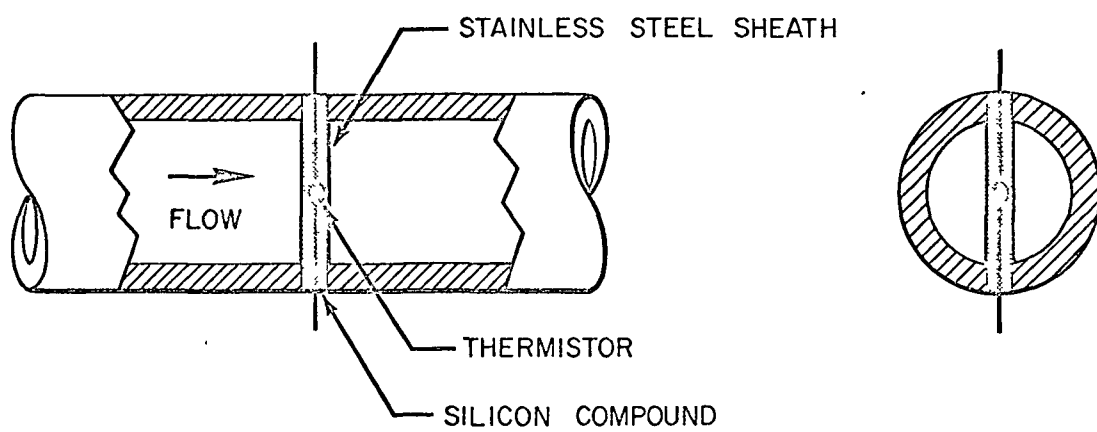
technique, the tilt angle was varied through 90° and the data is presented in Figure 17.

From the changes in the temperature field with orientation, it was assumed that the large deviation was probably due to the randomness of the flow pattern. A flow pattern study was conducted which verified the validity of the assumption. Dye was injected into the stream and the patterns were observed for flowrates similar to those existing in the propellant leak detector. The dye was of identical specific gravity as the fluid. It was observed that the velocity profile in the tube was not fully developed, and that it appeared as filament flow. The center of the filament was found to be travelling about six times faster than the average velocity calculated from the continuity equation. The filament was very temperature-sensitive and would shift with even the smallest temperature change. The results of this study led to the criteria of using a single self-heated sensor and measuring input power as a function of flowrate. This was based on the fact that if a separate heater and sensor were used, not all fluid that was heated would necessarily be sensed by a downstream sensor due to the random flow. Two such systems were evaluated: one a cross-flow sensor (Figure 18) and the other a coaxial flow sensor (Figure 19) where the cylindrical sheath is parallel to the direction of flow. The latter was of particular interest as it was felt that it would be very insensitive to orientation, because of the geometry and location of the sensing portion. However, testing indicated that this unit was not quite as satisfactory as the cross-flow unit, though both units were found to be suitable for flow measurement (Figures 21 through 24). The electronics was identical for both systems and is shown in Figure 20. During the testing of these two units, the fluid temperature was very closely controlled.



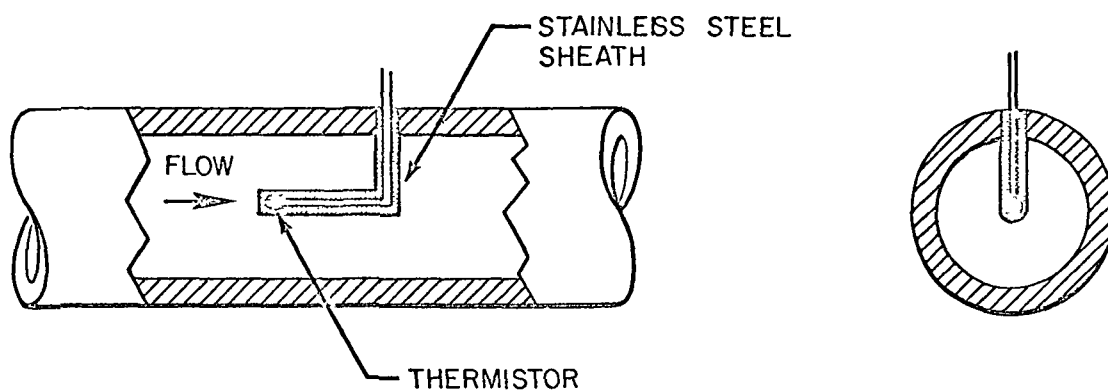
THERMAL DIFFERENTIAL SYSTEM
(CONSTANT POWER)

FIGURE 17



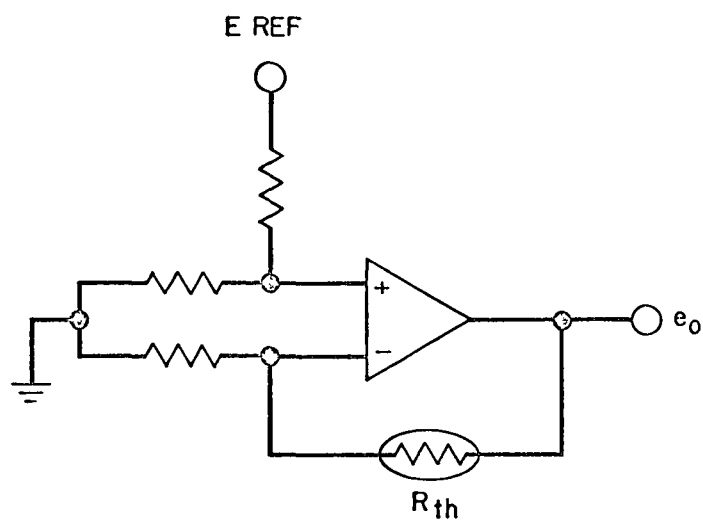
CROSS FLOW SYSTEM

FIGURE 18



COAXIAL FLOW SYSTEM

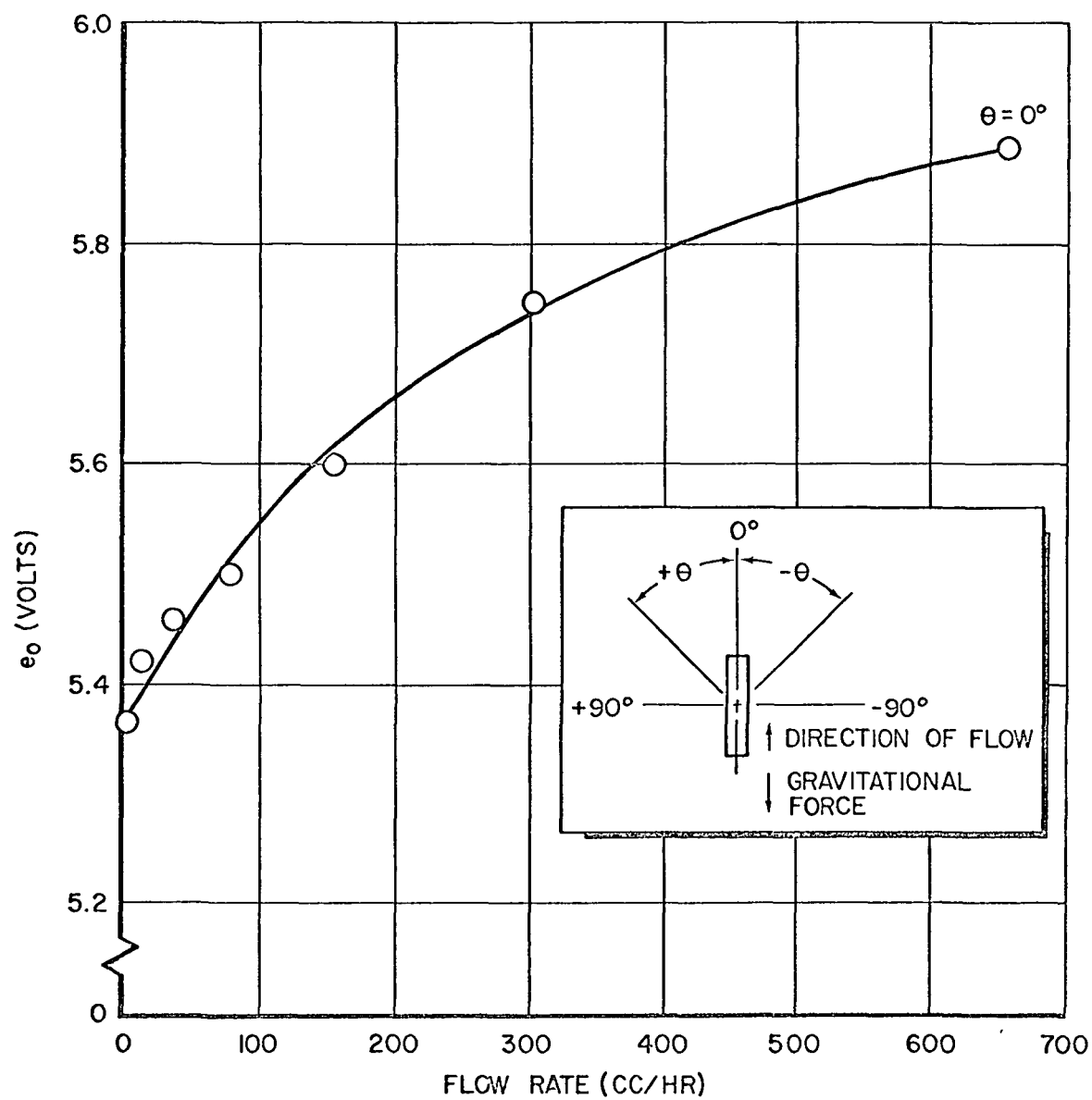
FIGURE 19



R_{th} = SELF HEATED THERMISTOR

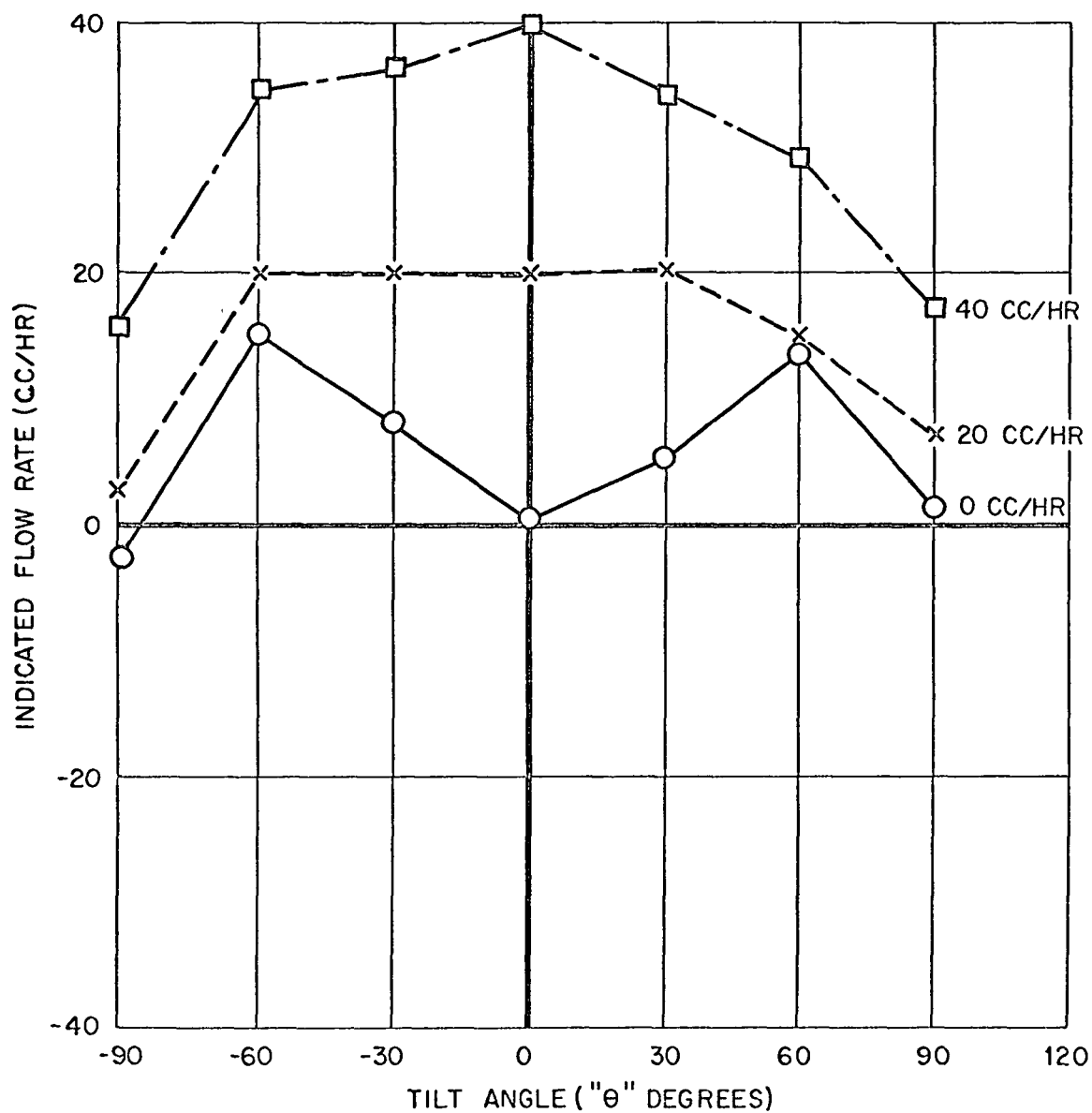
SCHEMATIC OF SELF-HEATED BODY ELECTRONIC SYSTEM

FIGURE 20



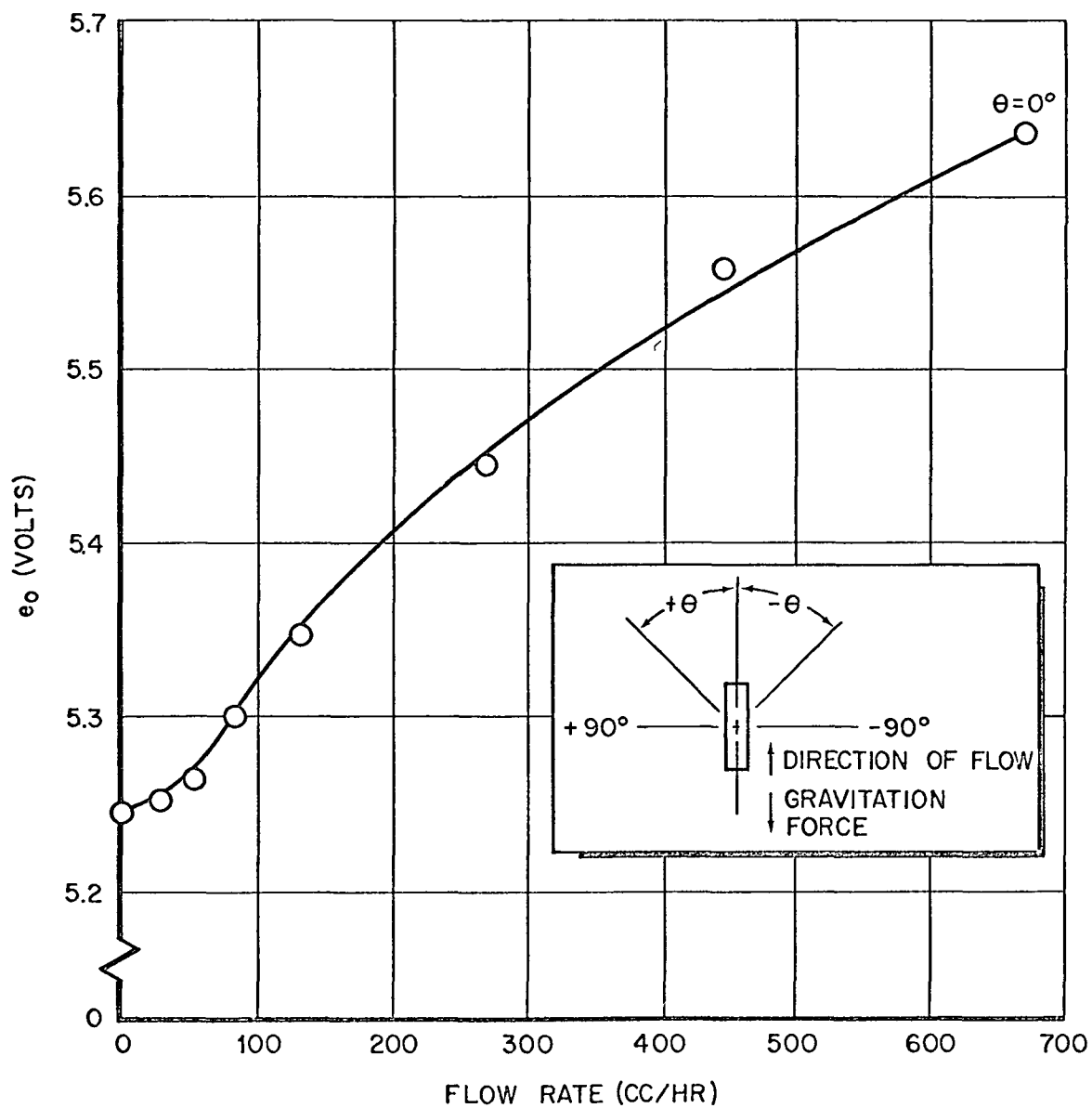
CROSS FLOW SYSTEM TEST RESULTS

FIGURE 21



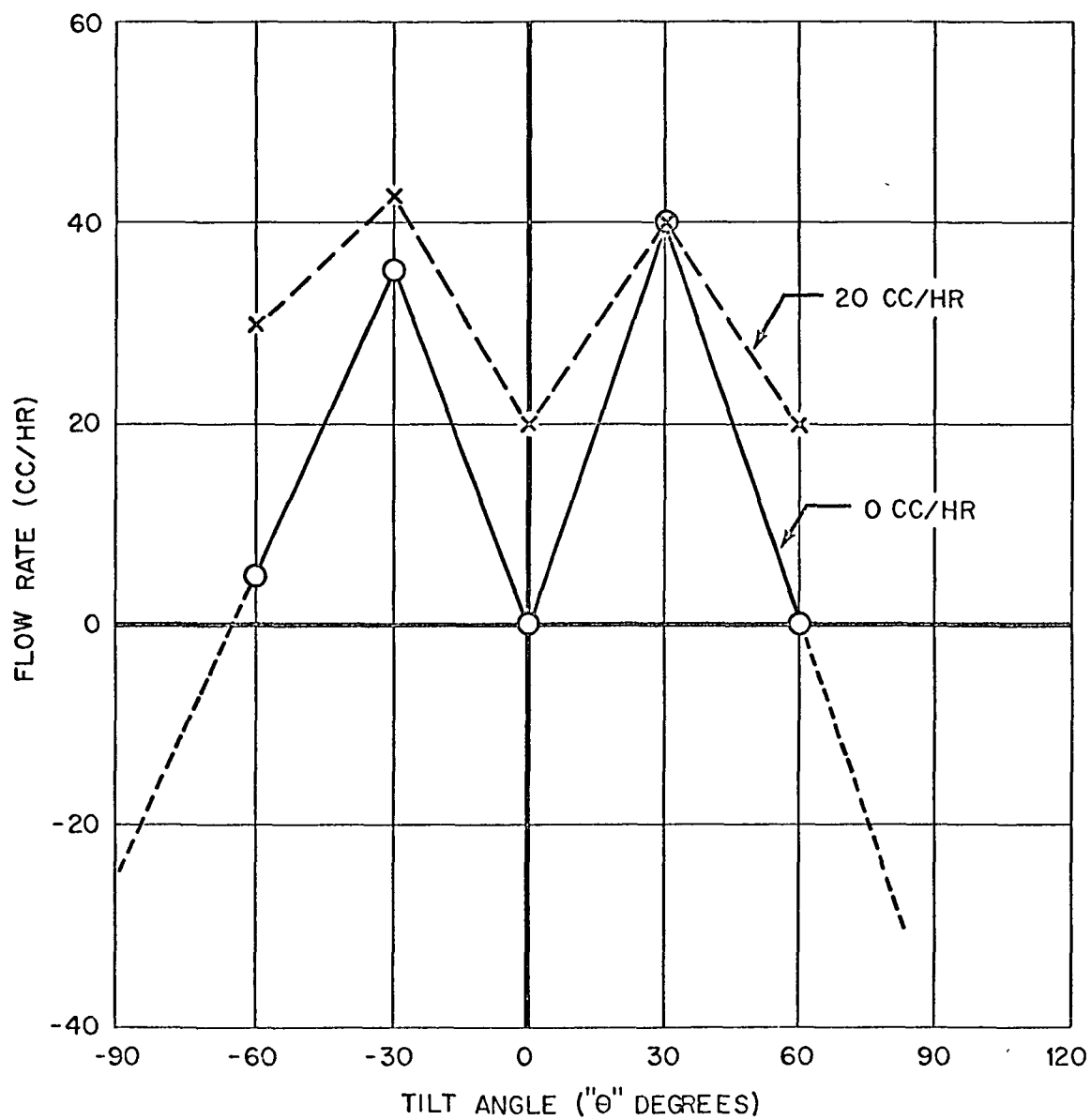
CROSS FLOW SYSTEM TEST RESULTS

FIGURE 22



COAXIAL FLOW SYSTEM TEST RESULTS

FIGURE 23

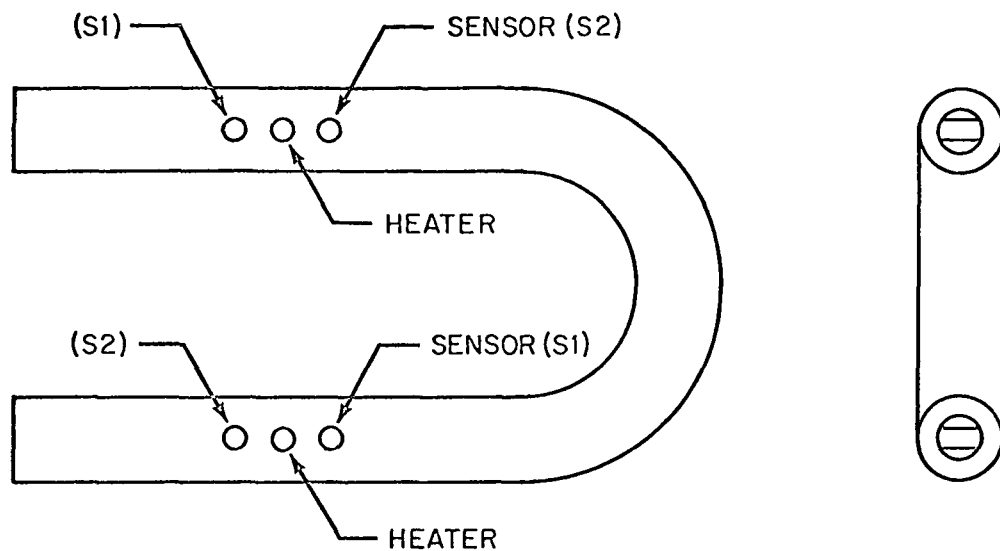


COAXIAL FLOW SYSTEM TEST RESULTS

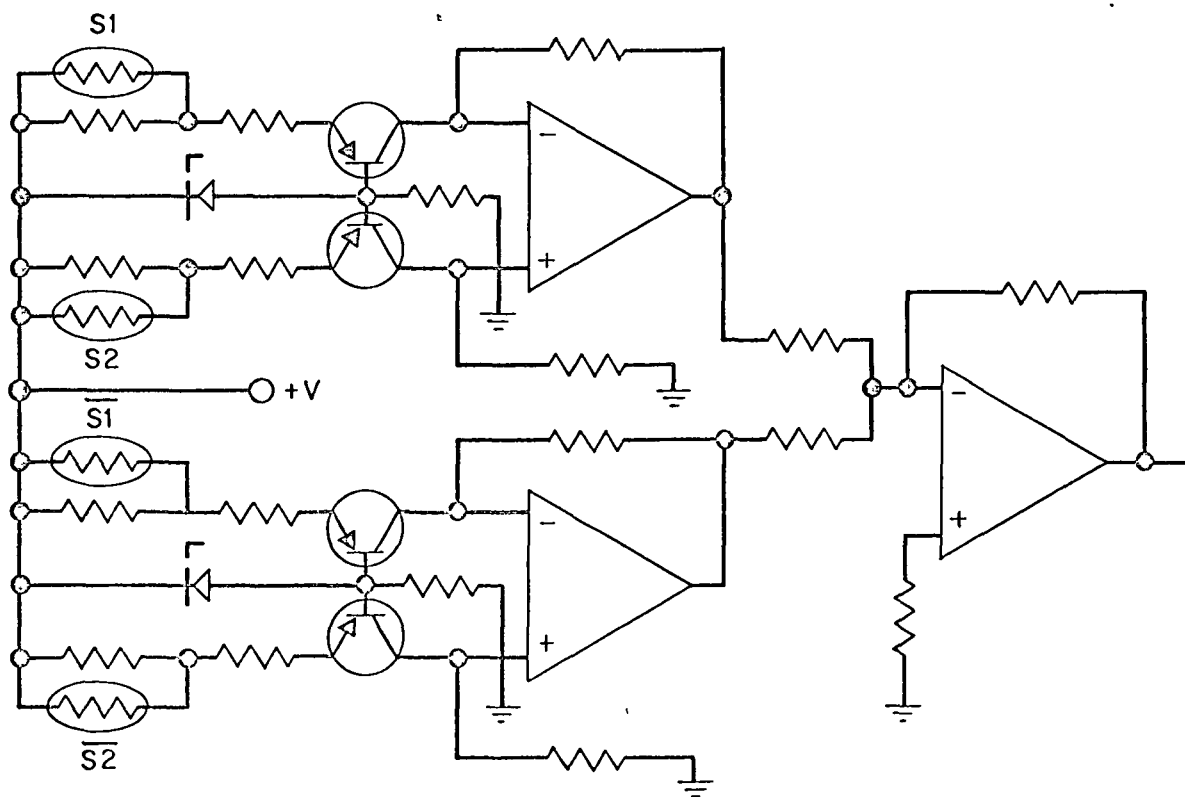
FIGURE 24

Prior to finalizing the configuration of the leak detector a folded flow path device was tested (Figure 25). It was found to be very insensitive to flow (Figure 26) and showed no improvement over the other devices with orientation changes. The results of the evaluation (Figure 27) led to the decision of using the cross-flow system to measure low flow rates. This method, due to the simplicity of the electronics, requires the lowest power of the system evaluated (Figure 28).

The next step in the program was to check the cross-flow device under high flow conditions. It was found that in the high flow region the system saturated due to the convective heat transfer coefficient becoming very much larger than the conductivity of the sensor and its housing (Figure 29). Since the conductivity in this case may be considered fixed because of the limited material selection, the only other variable affecting the problem was the convective heat transfer coefficient. There are basically two methods of changing the latter: one, change the flow area so that the heat transfer coefficient is decreased as affected by the change in Reynolds Number (Appendix B), and the other to create a sensor shape such that the flow pattern changes with a resulting change in heat transfer coefficient. The latter method was approached first. A large variety of shapes were tested, one of which, an aerodynamic shape, showed great promise (Figure 30). This model consisted of three parts: the sensing tube to which a fairing and trailing edge were attached; the latter two were made of wood. A single stainless unit did not repeat the performance of its model predecessor. The other type of sensor tested was an annular cylindrical sensor, where two tubes were placed concentrically, with different hole patterns in the outer tube (Figure 31). One of these configurations had by far the largest dynamic range (Figure 32), but was built with non-compatible material. The other units offered no improvement over the single cross tube.

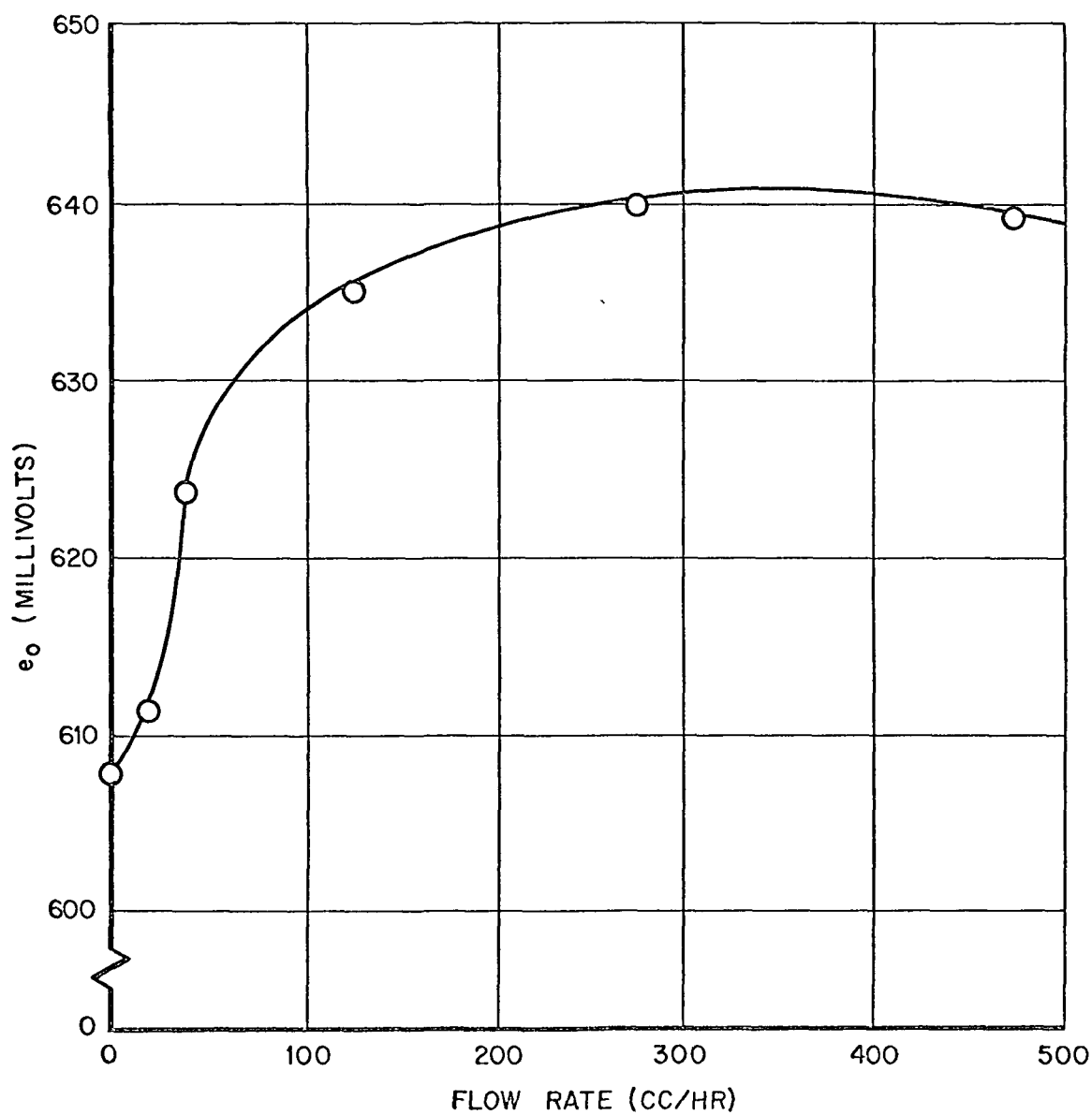


FOLDED FLOW PATH



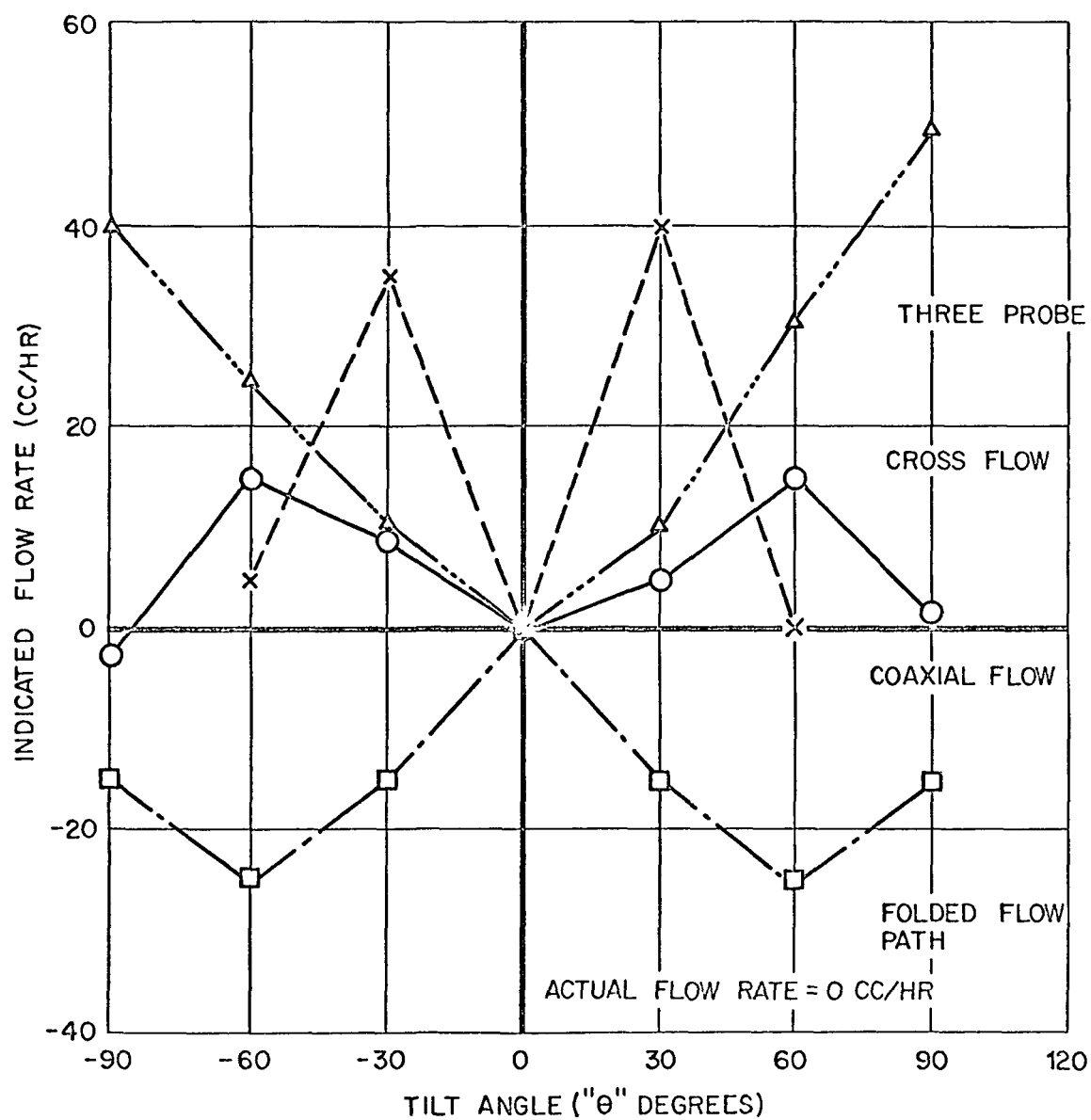
SCHEMATIC OF FOLDED FLOW PATH SYSTEM

FIGURE 25



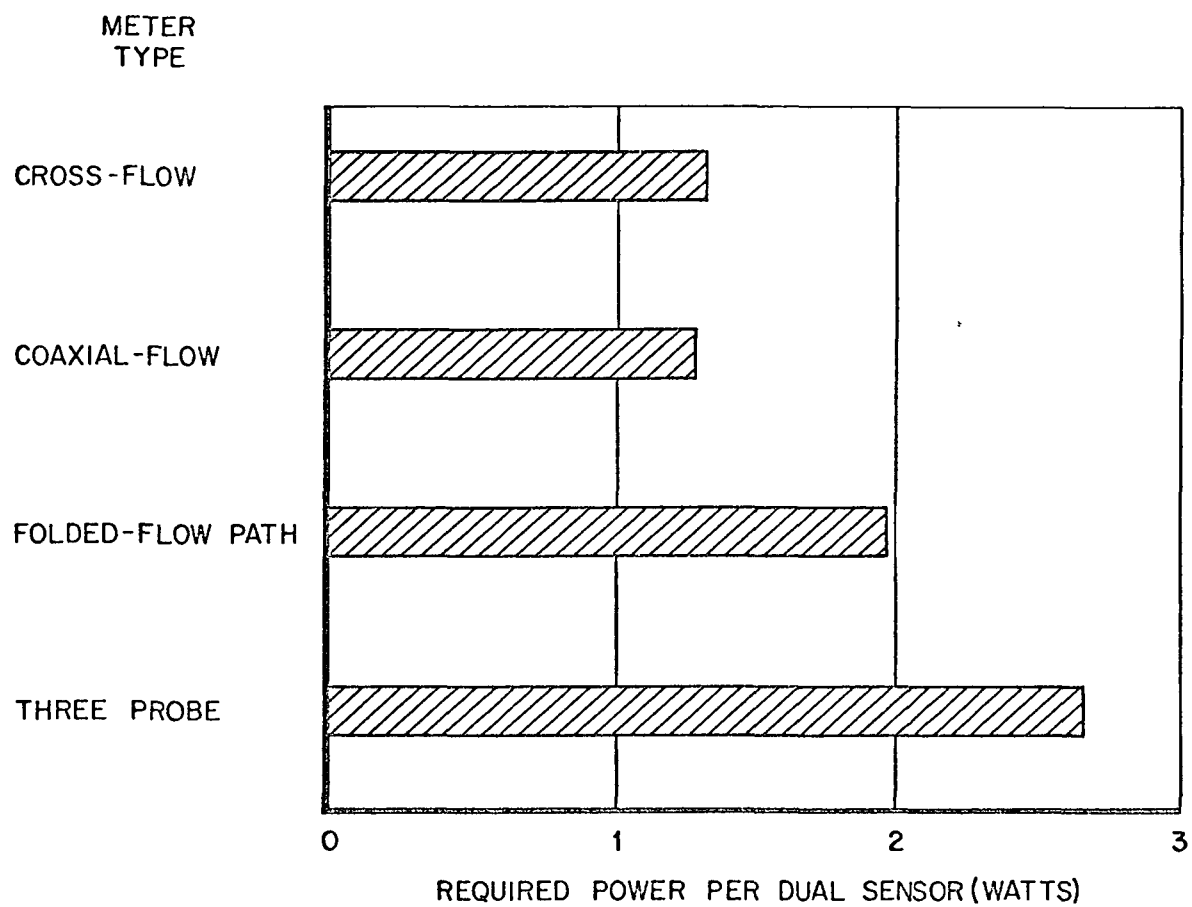
FOLDED FLOW PATH SYSTEM TEST RESULTS

FIGURE 26



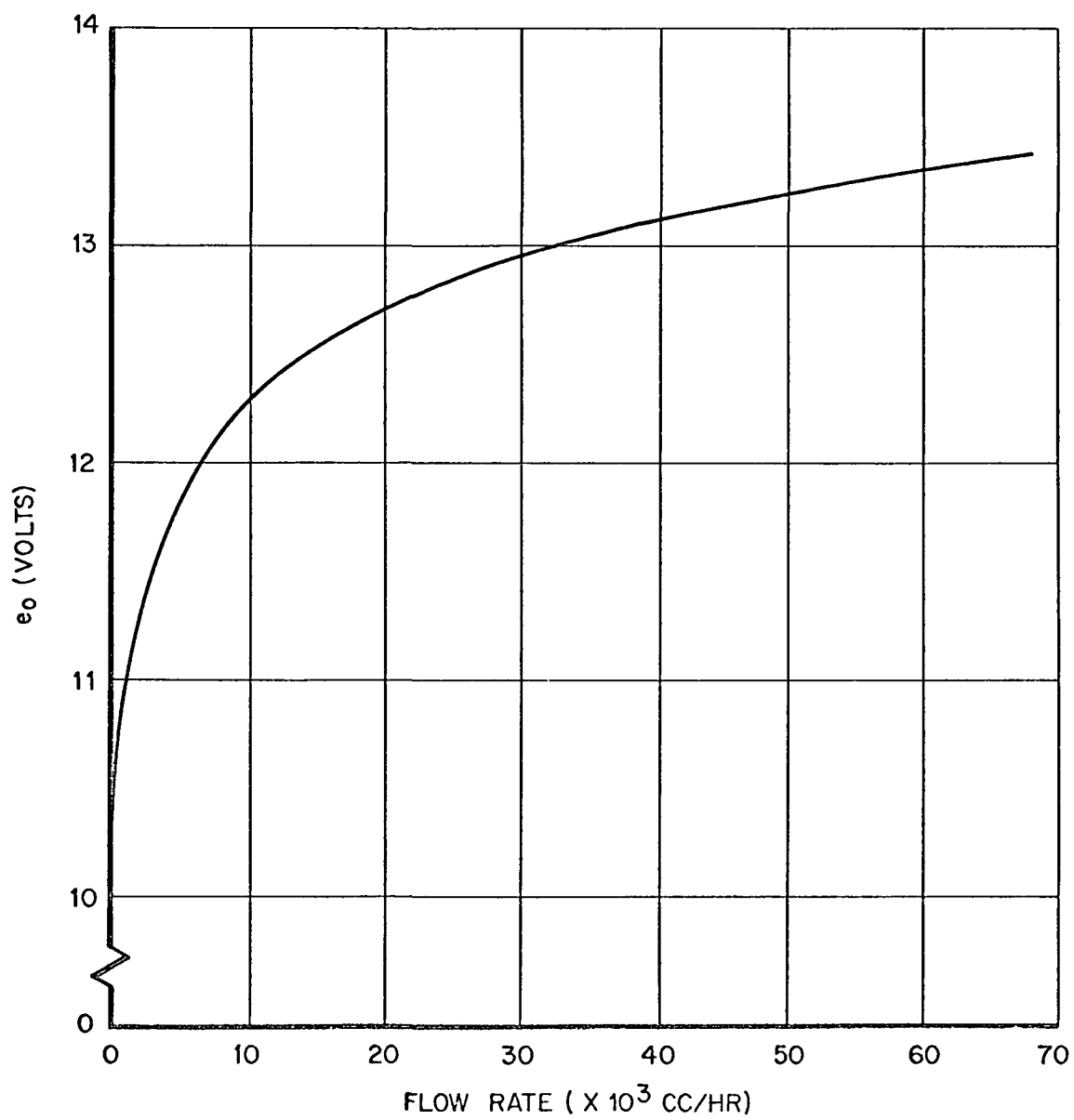
COMPARISON OF CONFIGURATIONS

FIGURE 27



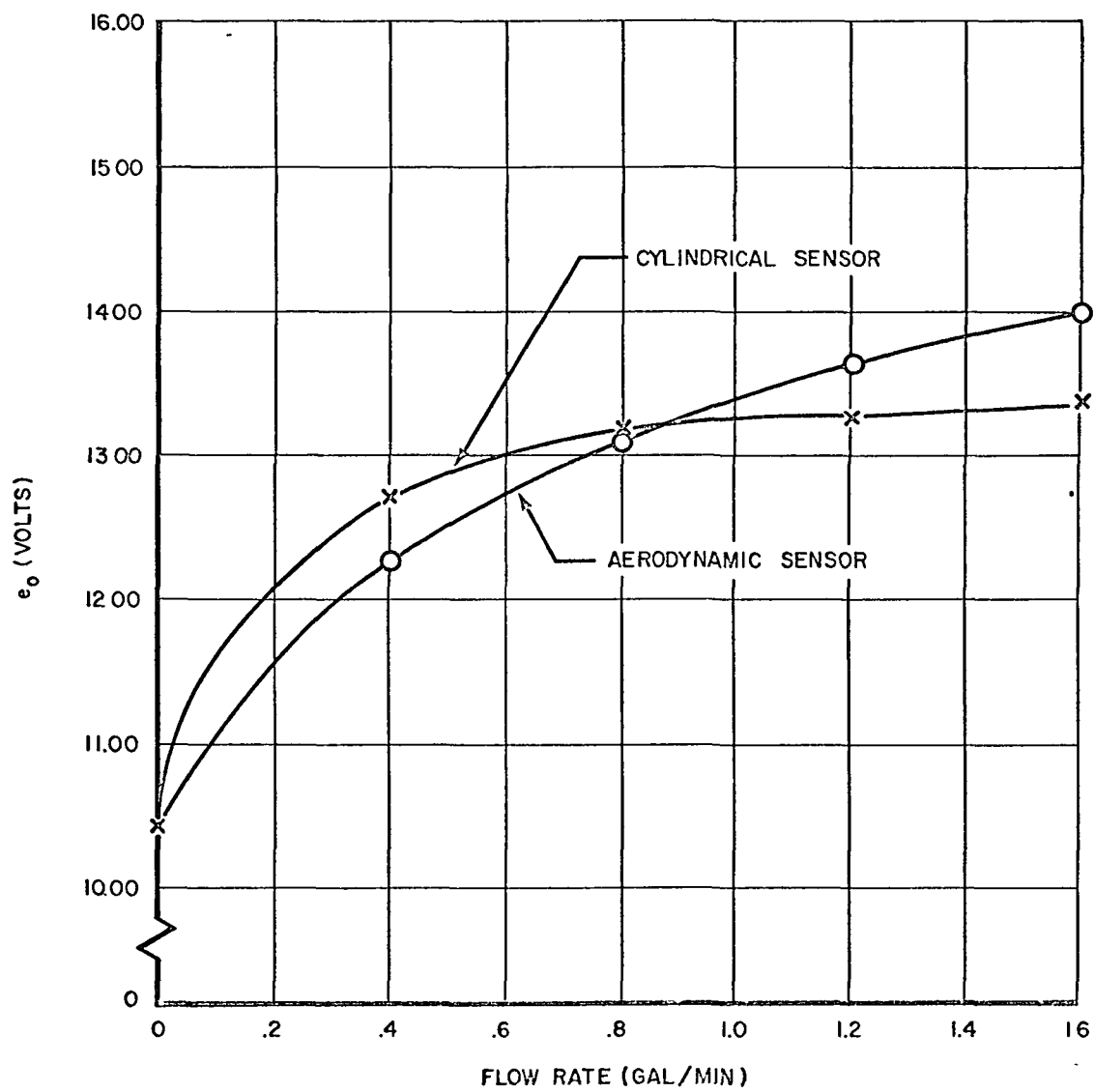
POWER REQUIREMENTS

FIGURE 28



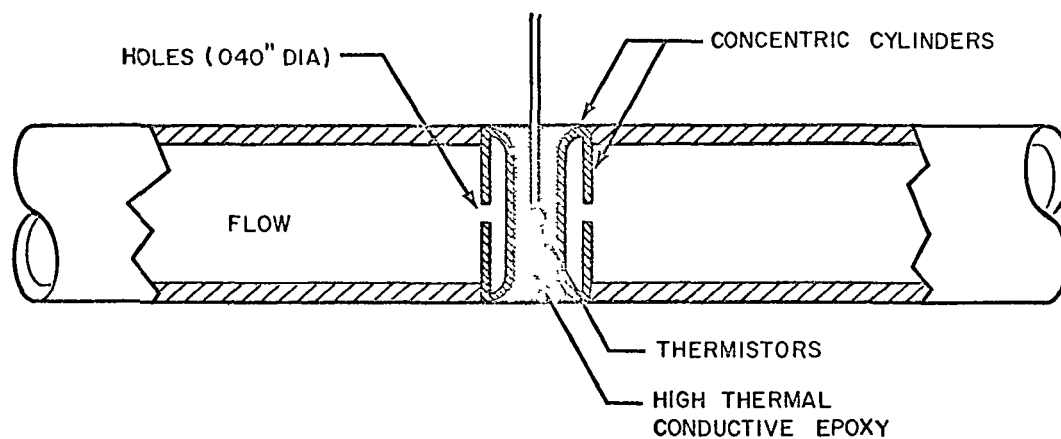
CROSS FLOW SENSOR TEST RESULTS

FIGURE 29

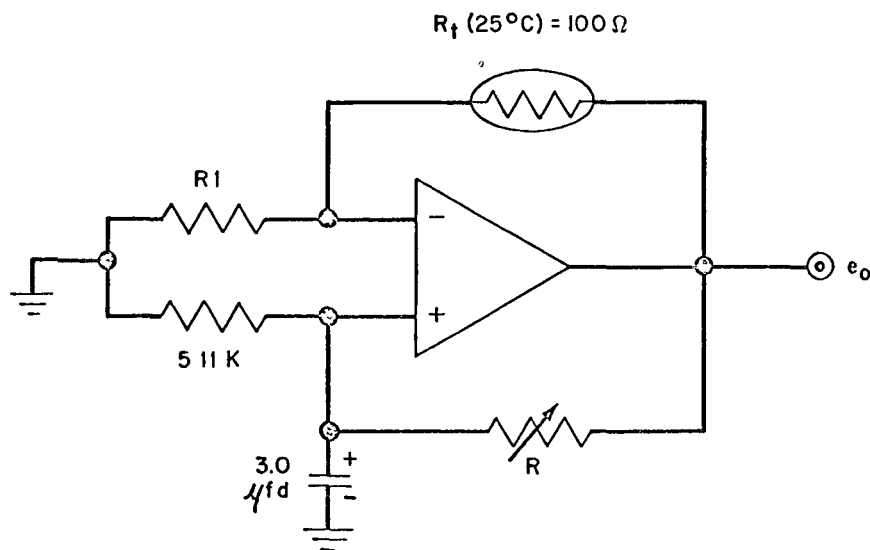


CROSS FLOW SENSOR TEST RESULTS

FIGURE 30

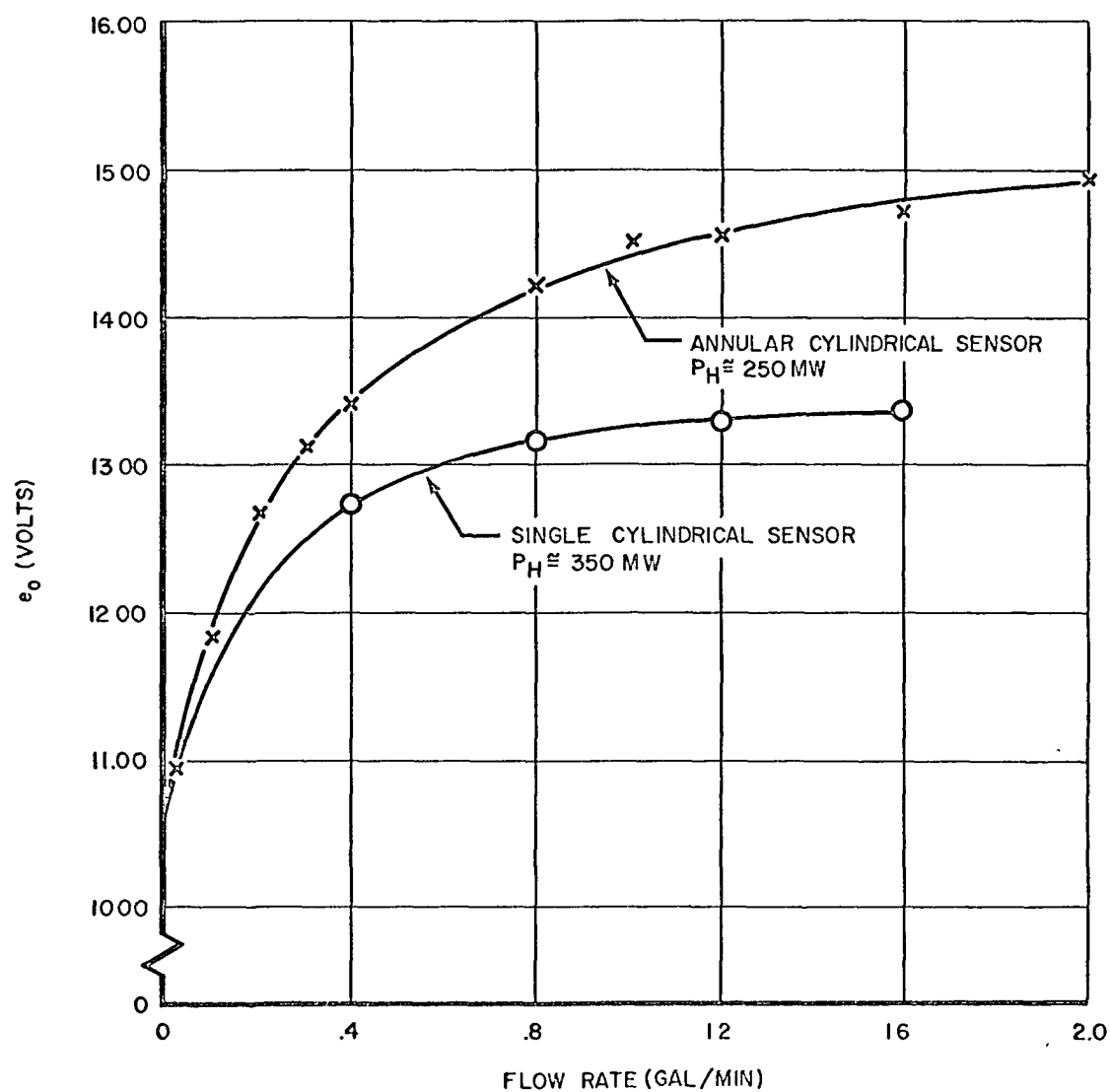


a. ANNULAR CYLINDRICAL SENSOR



b. TEST CIRCUIT

FIGURE 31

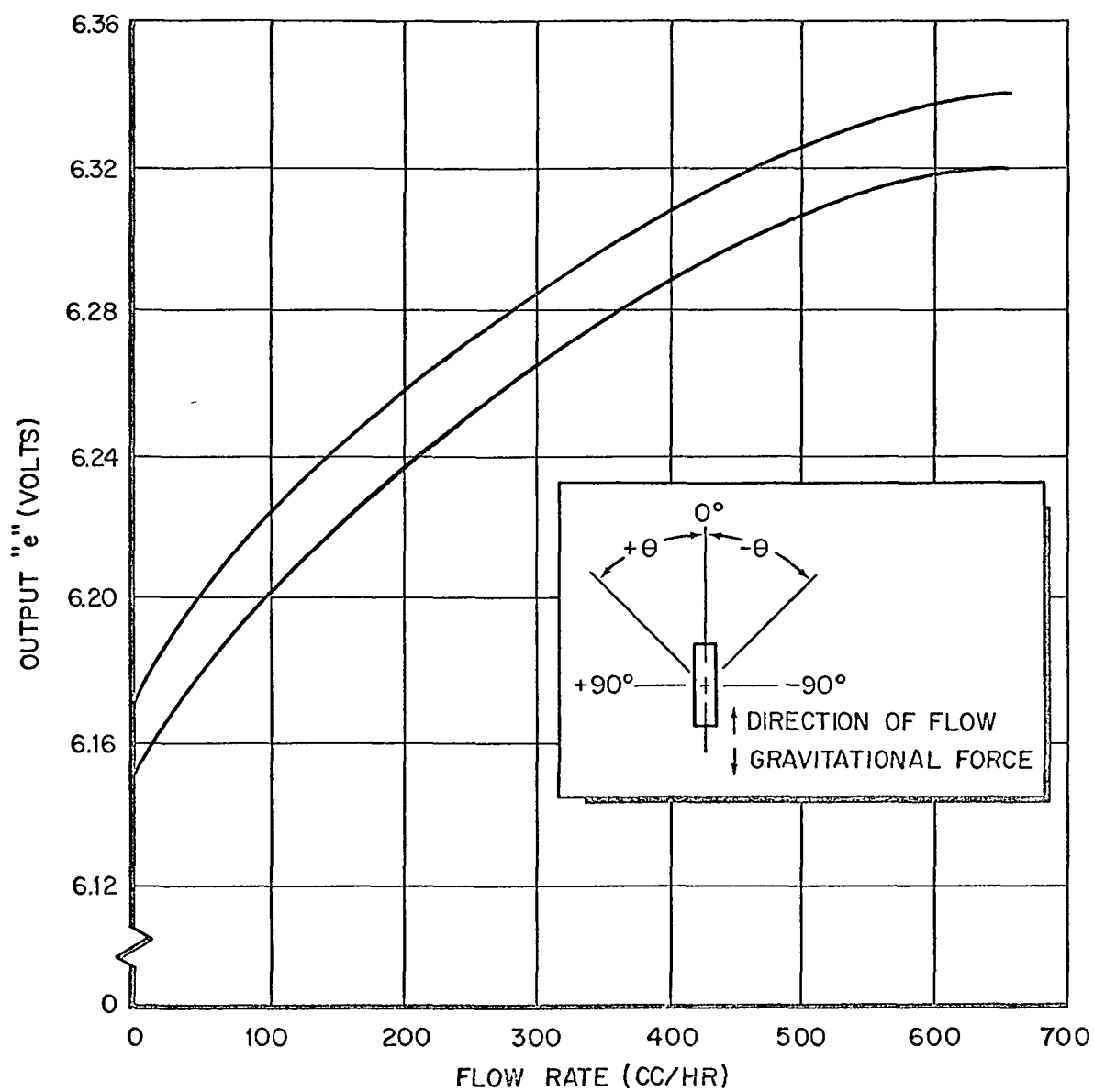


CROSS FLOW SENSOR TEST RESULTS

FIGURE 32

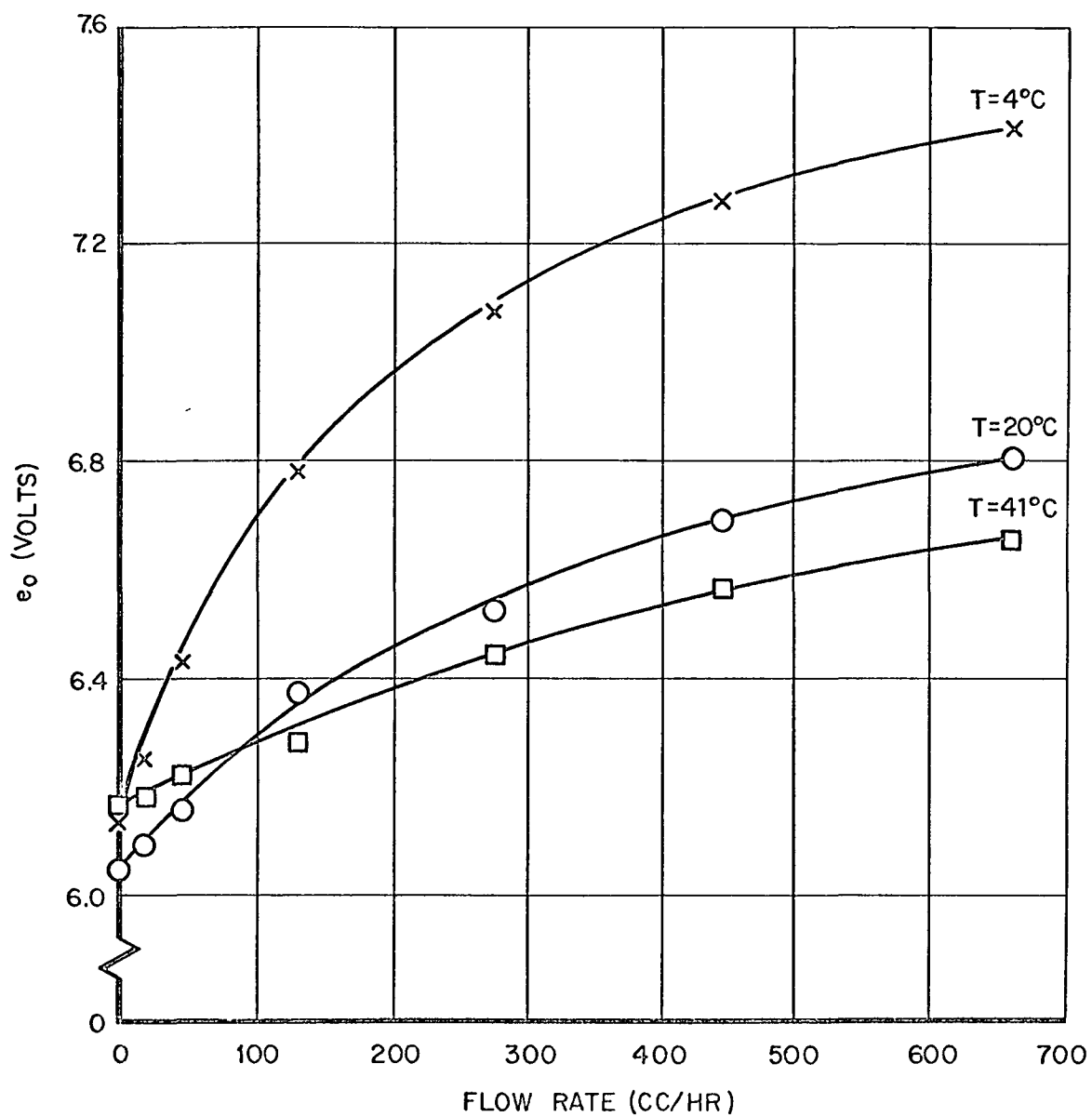
No explicit explanation for these variations can be offered at this time; however, it was felt that such variables as material, fastening technique and tolerances on machined parts drastically changed the sensor output. Prior to a production phase such scaling and manufacturing factors should be evaluated.

No attempts of temperature compensation were made until a configuration was defined. With the cross-flow system the effects of temperature change on the output voltage were investigated. The ambient temperature was increased by 0.3°F which resulted in as much as 25 cc/hr equivalent flow indication under no-flow conditions (Figure 33). The results of the first attempt to temperature compensate under zero flow conditions are shown in Figure 34. The results indicate a larger deviation at the lower temperature from nominal than the higher temperature. This can be attributed to the thermal properties of water. The test setup and electronics are shown in Figures 35 and 36, respectively. Additional tests indicated that the temperature effects could not be eliminated utilizing existing techniques. The factors affecting the output change making temperature compensation extremely difficult are the non-linearity of sensing devices, the variation of fluid properties, the various modes of heat transfer based on geometry of the sensors and flowmeter housing. This is not to say that it is impossible to temperature compensate. Data indicates a number of possible solutions, though time did not permit a thorough investigation into these methods. The methods are described in Section 6 of this report.



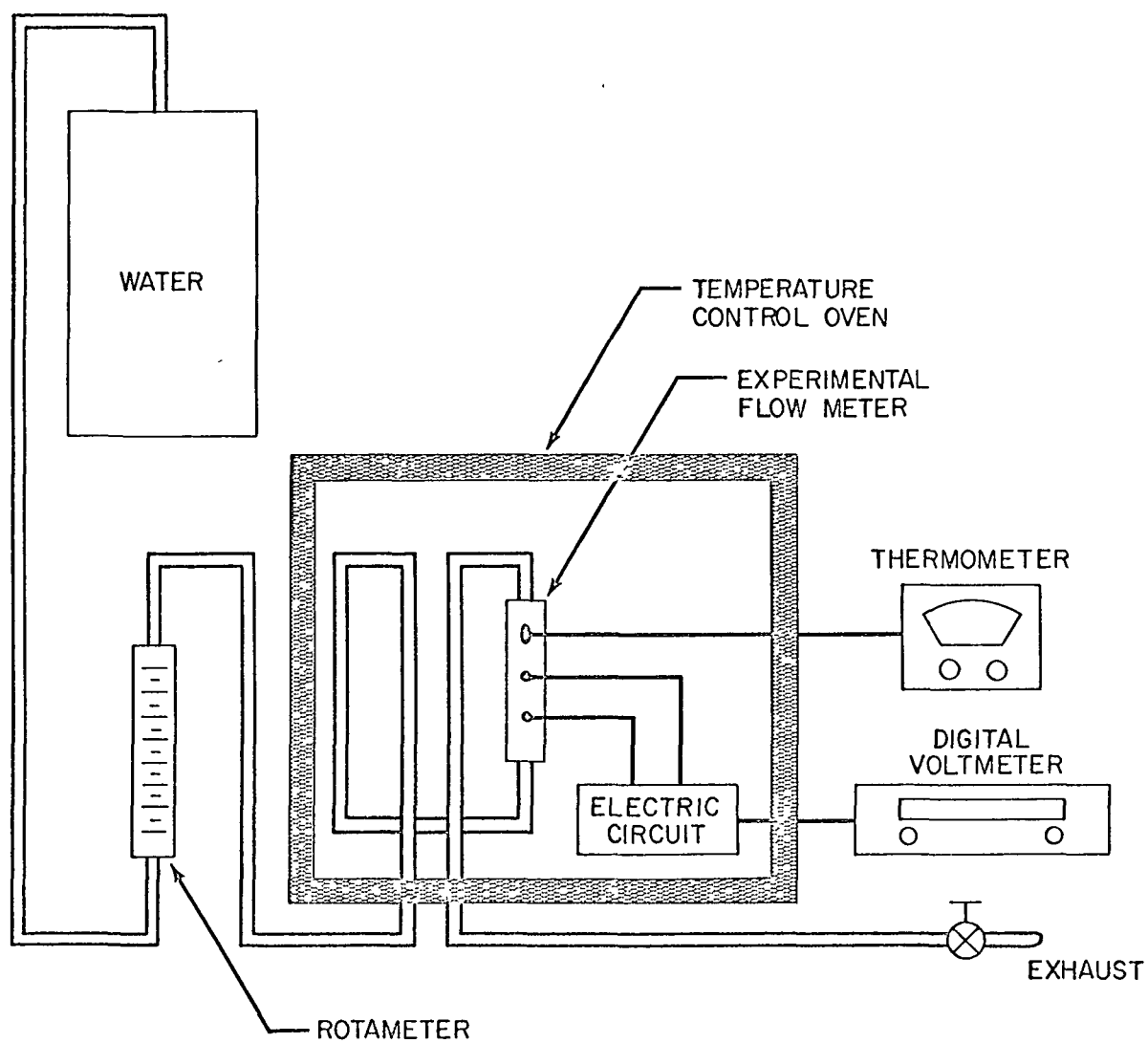
CROSS FLOW SENSOR TEMPERATURE EFFECT

FIGURE 33



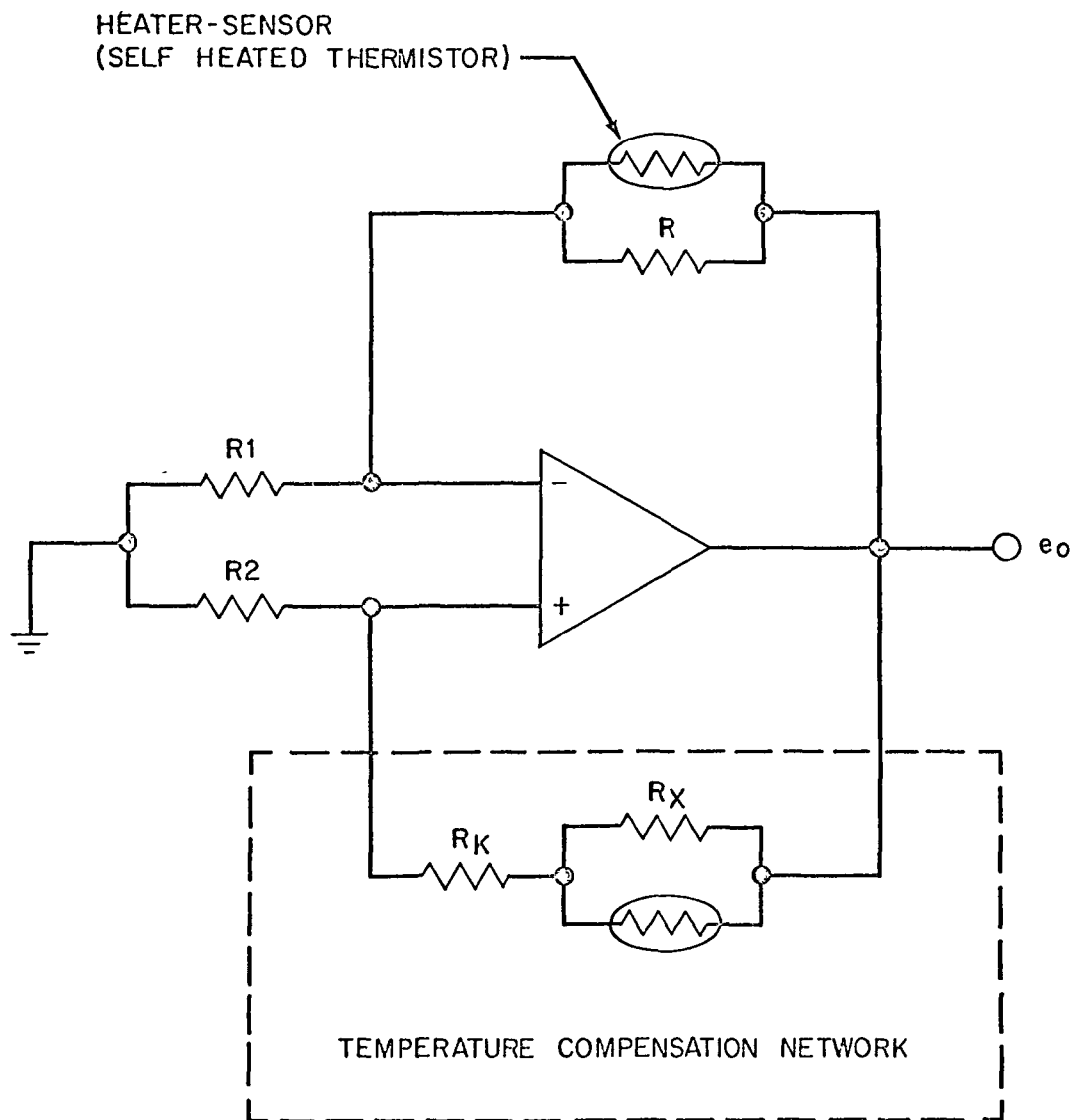
CROSS FLOW SENSOR TEMPERATURE
COMPENSATION AT NO FLOW

FIGURE 34



FLOW METER TEMPERATURE TEST SET-UP

FIGURE 35



SCHEMATIC OF HEATER AMPLIFIER WITH COMPENSATION

FIGURE 36

SECTION 4

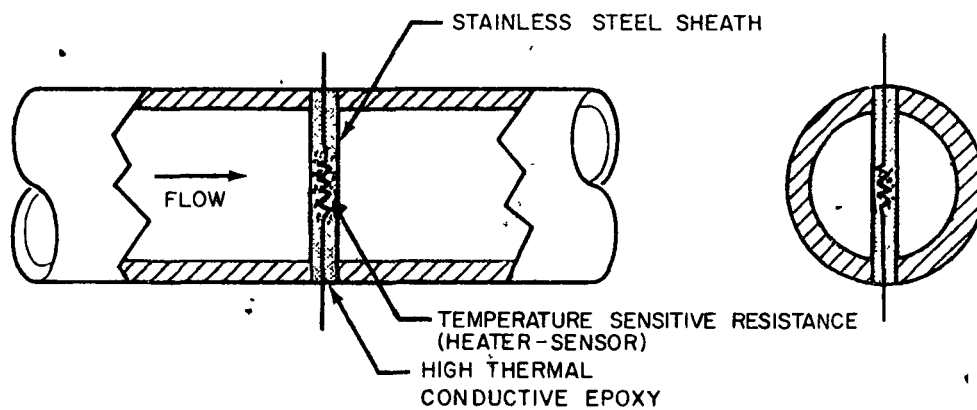
DESIGN OF THE FINAL HARDWARE

A. Sensor Design

One of the major objectives of the experimental program was the development of a flow measuring technique in which all the sensor components could be enclosed by stainless steel in a single package. The delivered hardware was designed to take advantage of this facet of the experimental program. The transducers are completely different in configuration but the sensor housings (except for length) are identical - a single thin-wall stainless steel tube (Figures 37, 38, and 39). The unit is a welded assembly and has been leak checked with a mass spectrometer to preclude any possible leakage that could result in failure of the unit with possible catastrophic results.

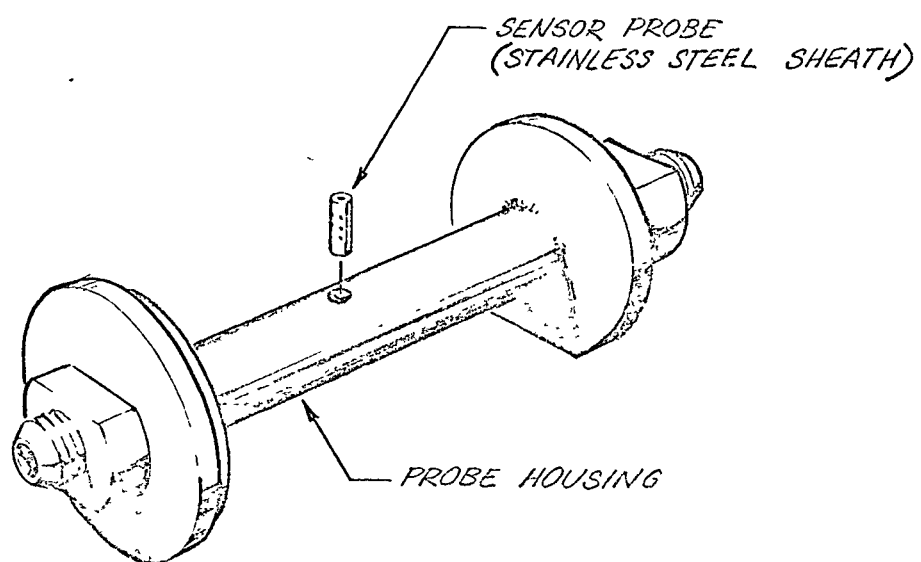
The designs for the transducers are shown in Figures 40 through 45 for the oxidizer and Figures 46 through 51 for the fuel. The transducers consist of an inner tubing assembly and an outer housing with the electronic components installed in the annulus. The transducers for the oxidizer consist of a 0.430 inch inner tube in which a single heater sensor probe is mounted, which will cover the entire flow range. The transducer for the fuel consists of a variable area tube expanding from 0.430 inch ID to 1.005 inch ID with two sets of self-heated sensors. Considerable difficulty was encountered in welding in the cross-tubes. While cooling, the sensor tubes would cool much faster than the housing resulting in cracking of the thin-walled tubes. This was circumvented by inserting an aluminum slug in the sensor sheath while welding it to the housing.

The heater-sensor and fluid sensor assemblies were then prepared for insertion in the transducers. The heater-sensor and fluid sensor consists of an enamel



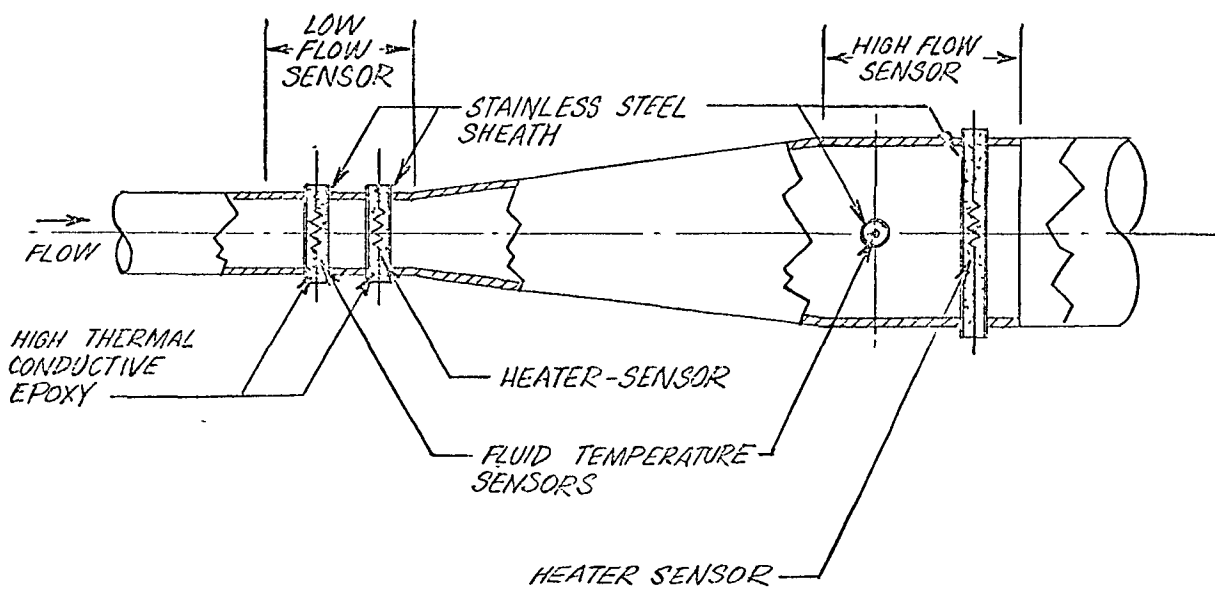
CYLINDRICAL SENSOR

FIGURE 37



FLOW/SENSOR FOR OXIDIZER

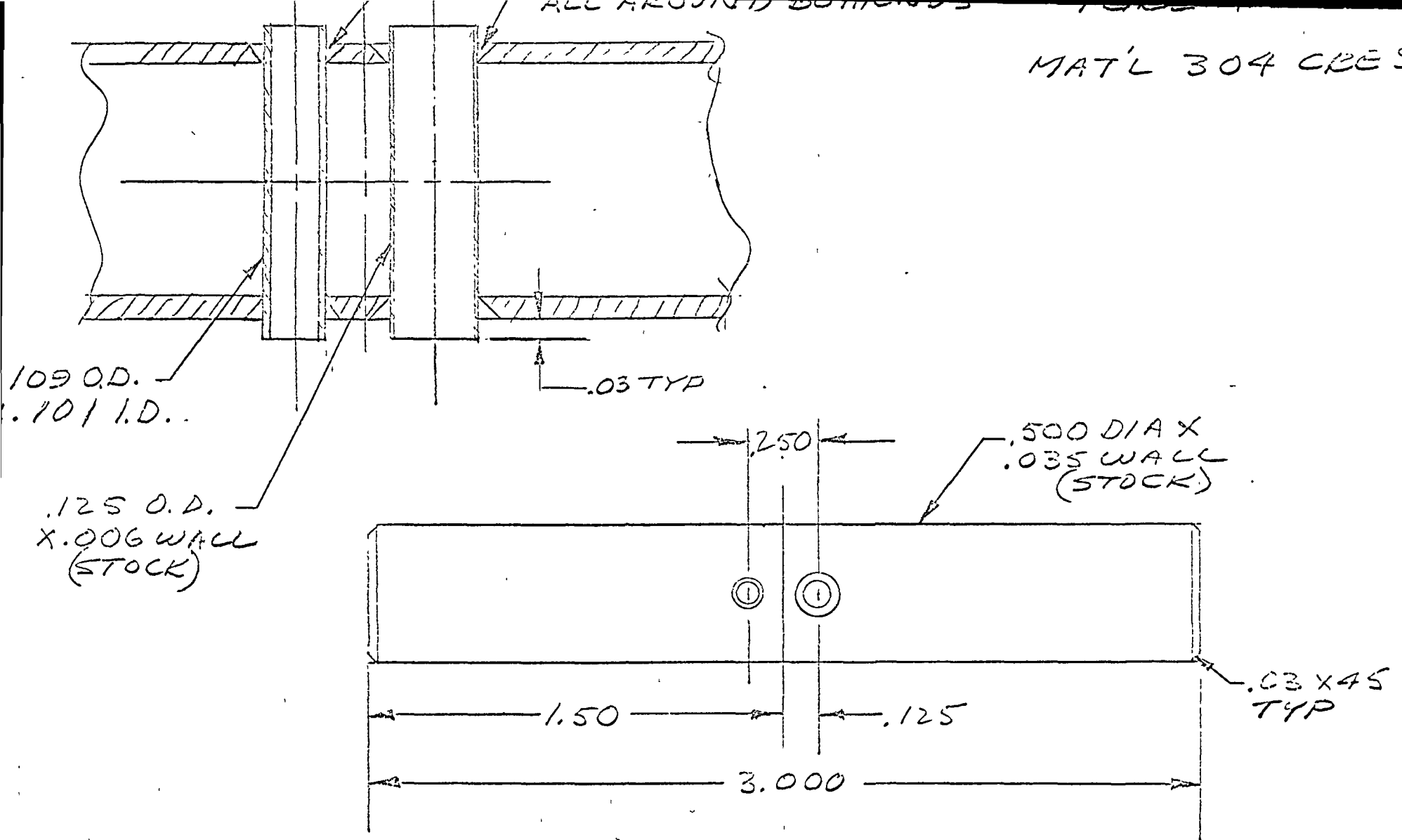
FIGURE 38



FLOWSENSOR FOR FUEL

FIGURE 39

MAT'L 304 CRES



SCALE 4/1

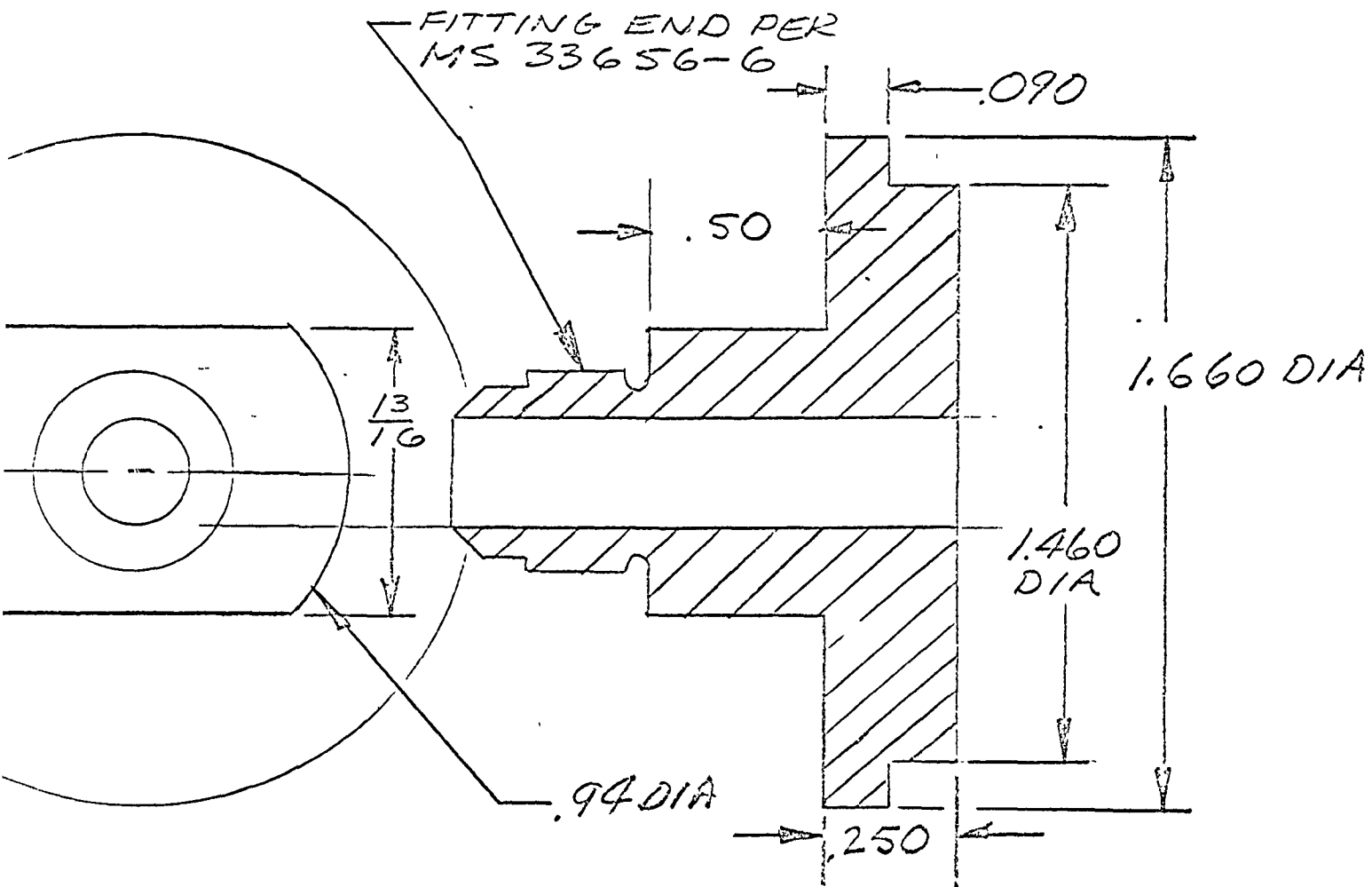


FIGURE 41

SK0000081B
END-LARGE
MAT'L 304 CRES

END STALL
MITL 304 CRES

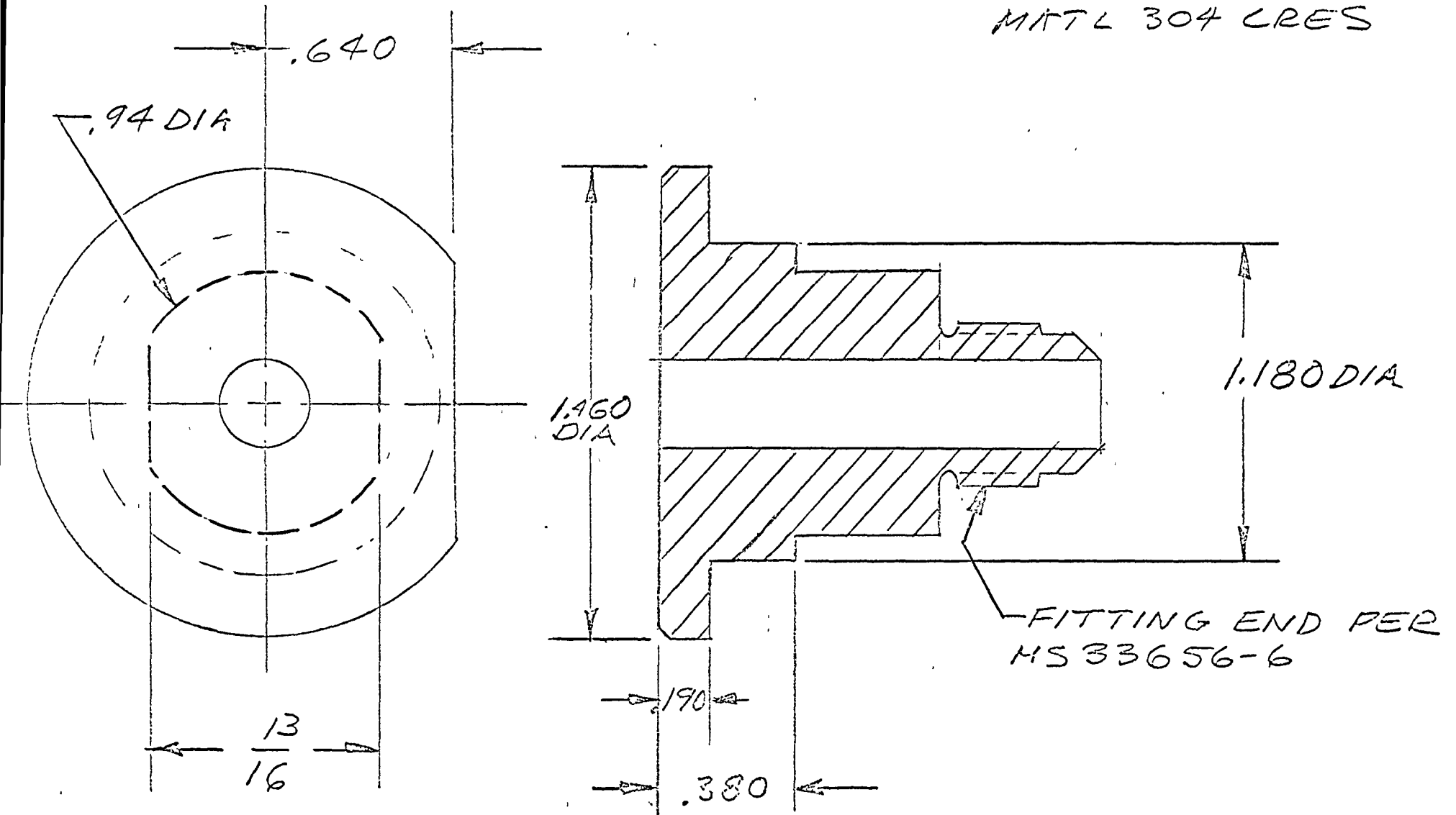


FIGURE 42

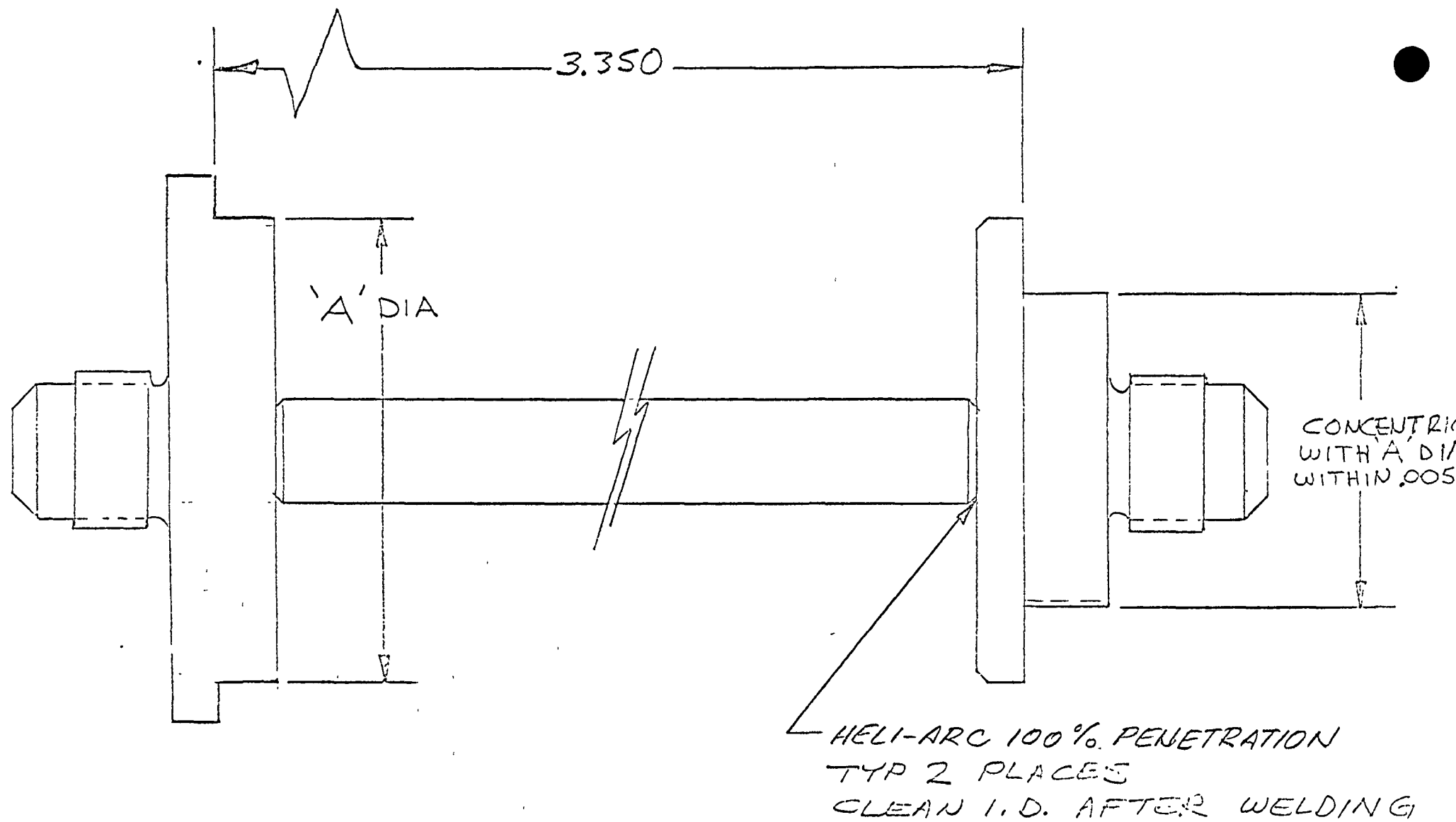


FIGURE 43

SK0000083A
TUBE ASSY
SCALE 2/1

SHEET 1 OF 2
HOUSING

MAT'L 303 CREEL
1/4 SCHEDULE 160 PIPE
(.250 WALL)

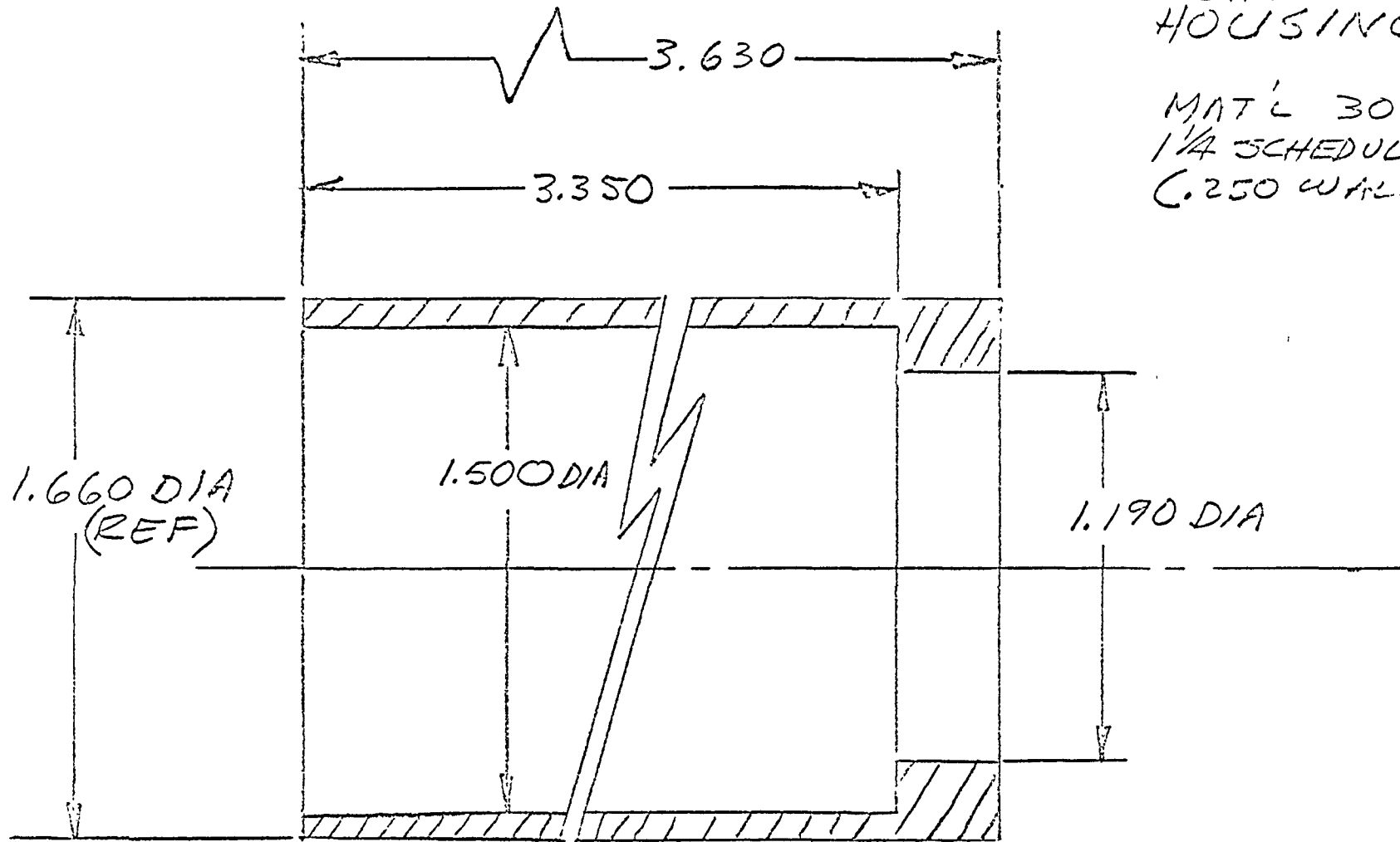


FIGURE 4A

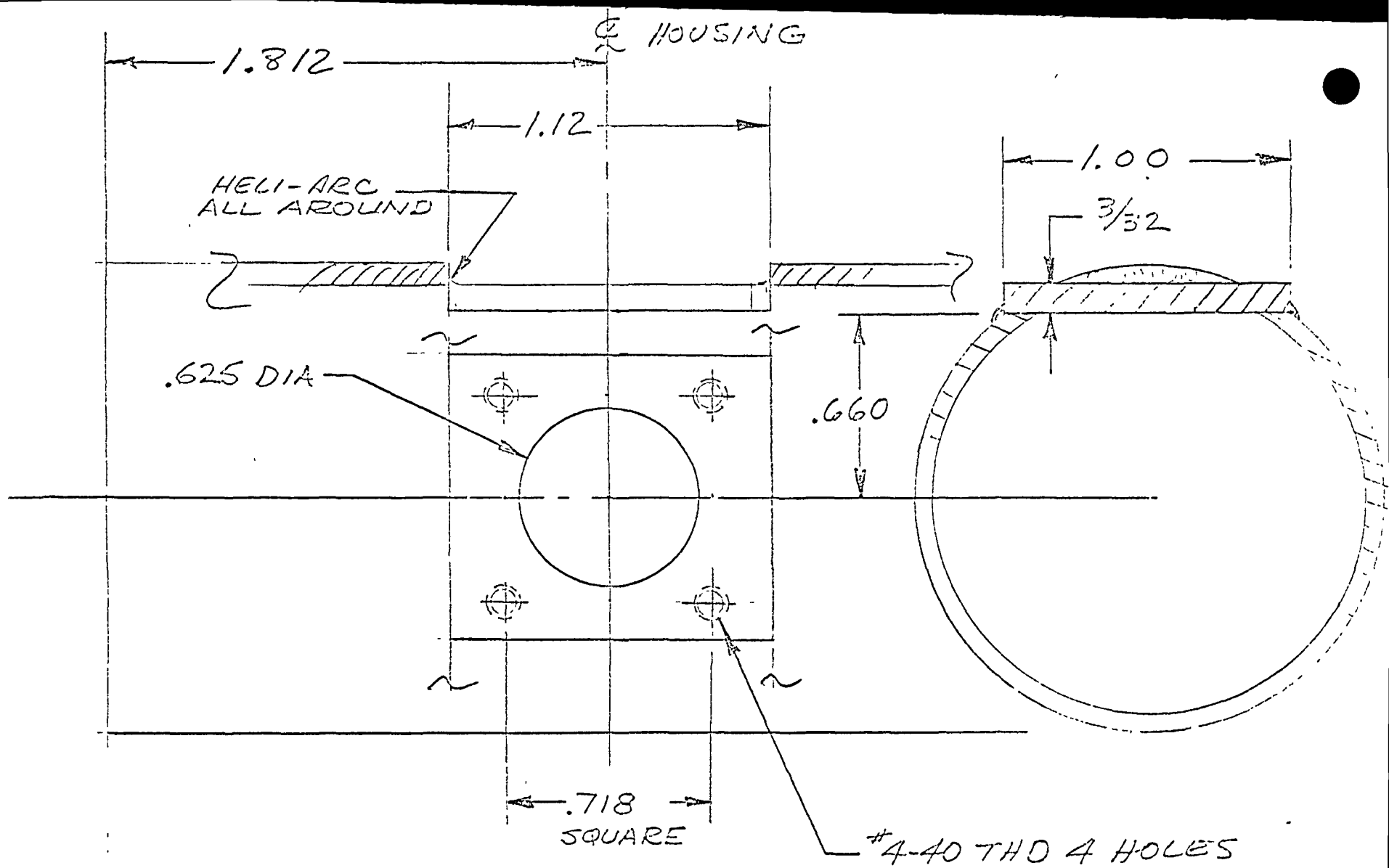
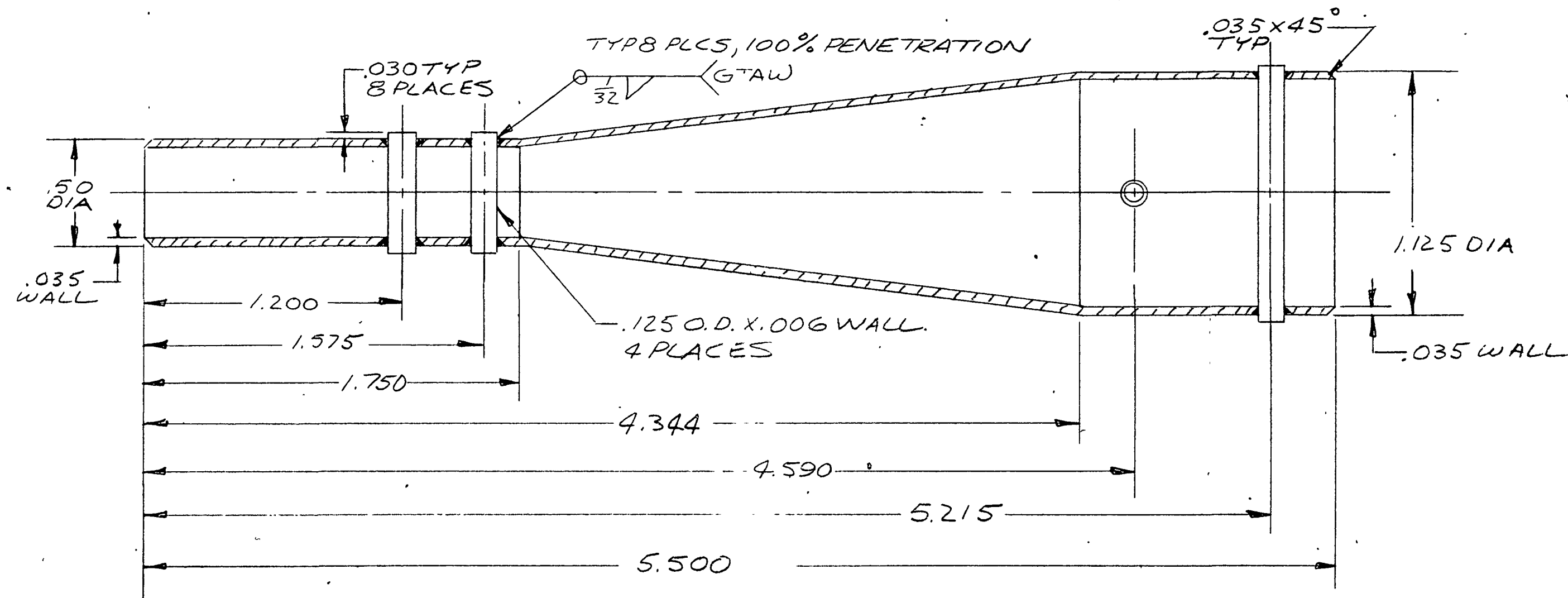


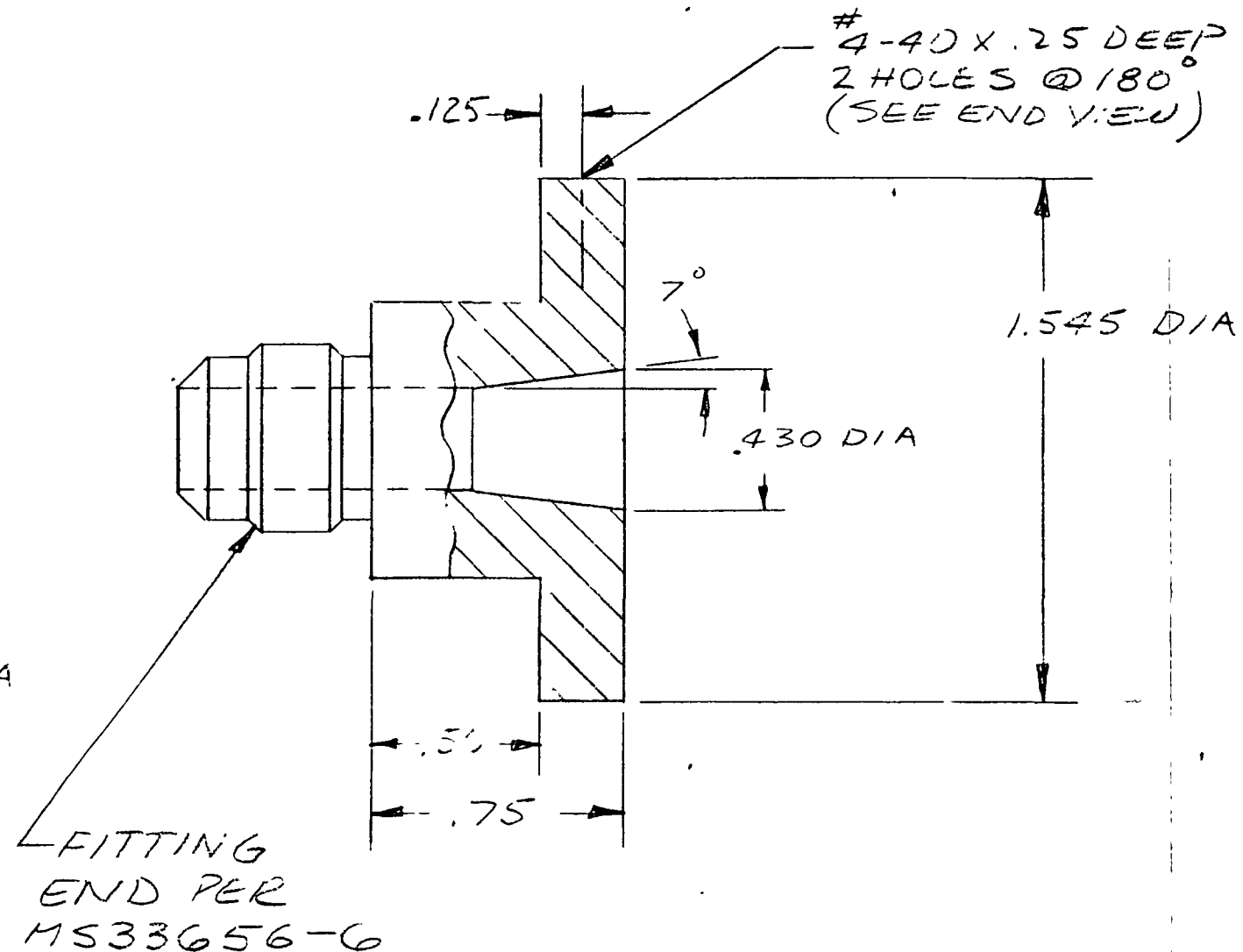
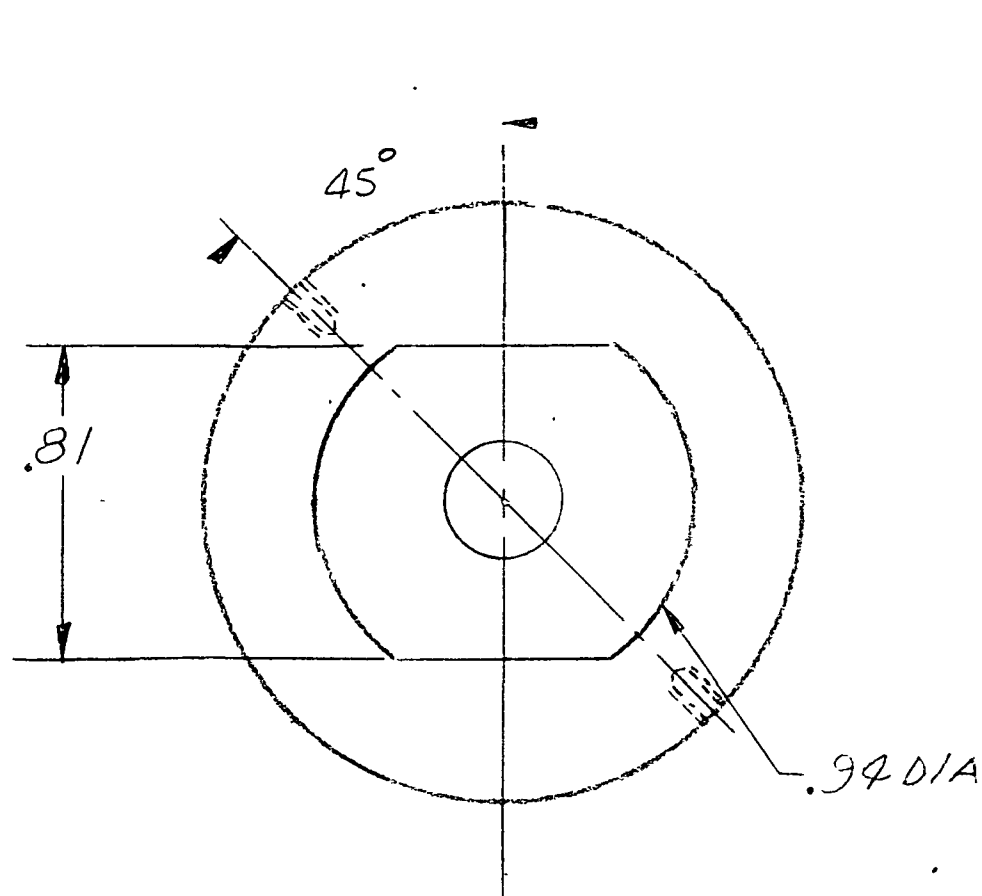
FIGURE 45

SK 000084 A
SHEET 2 OF 2
SCALE 2/1
HOUSING



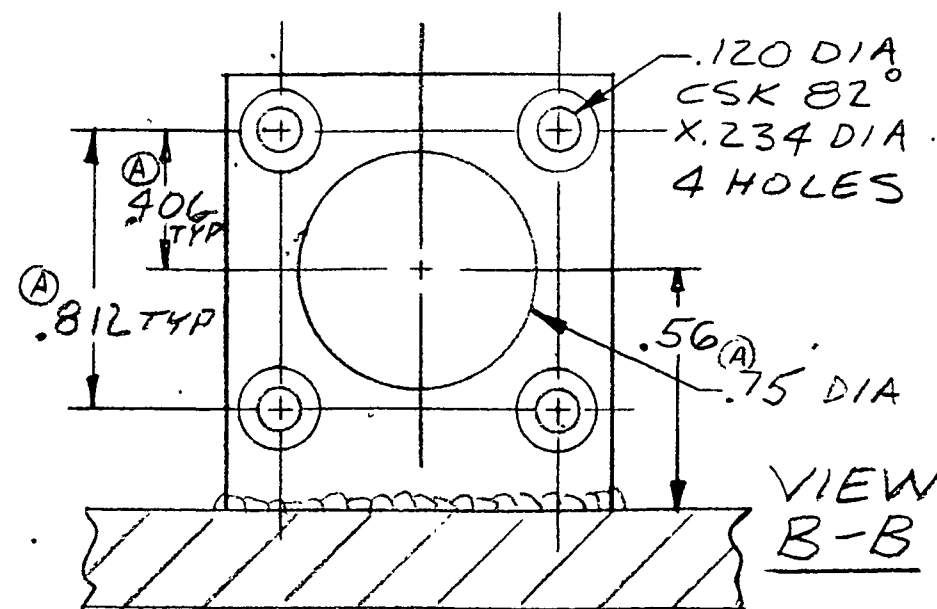
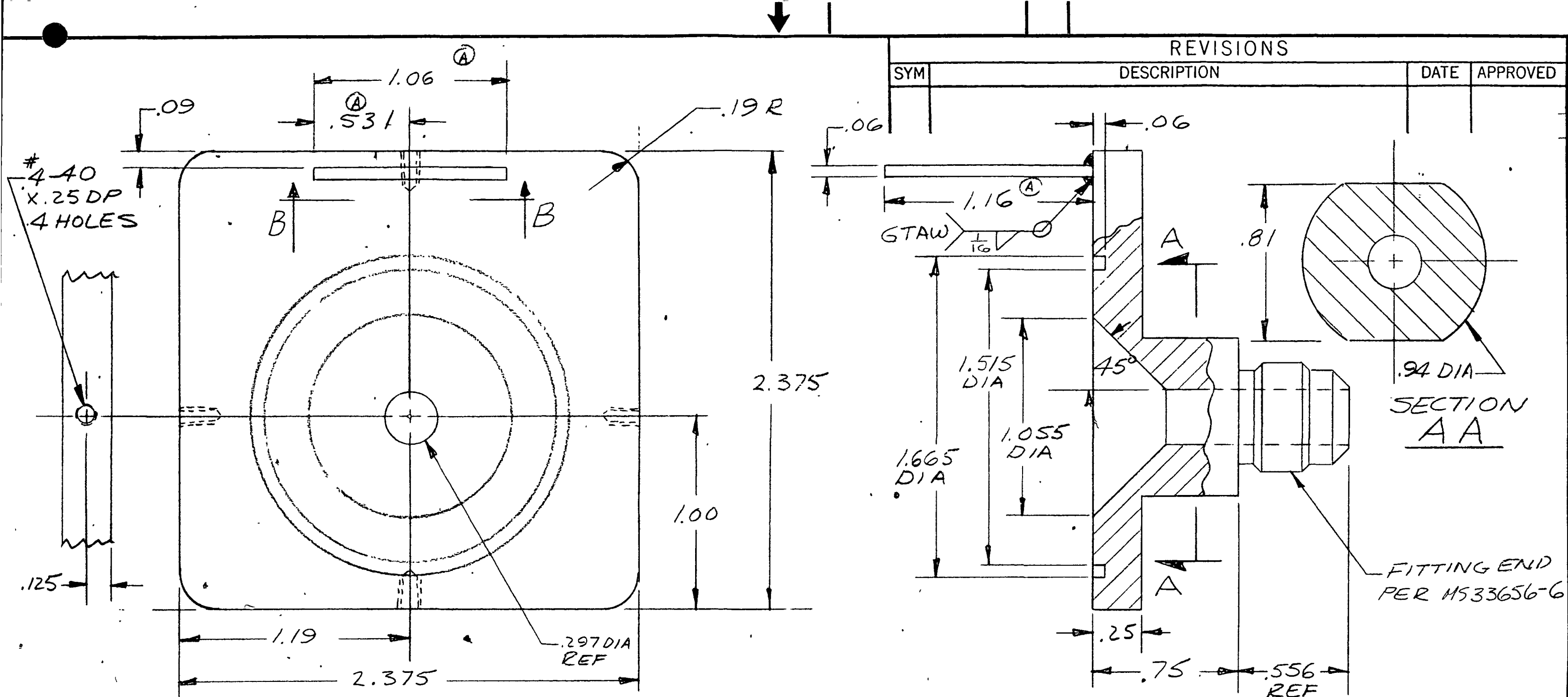
REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED 1. BREAK ALL SHARP EDGES .015 MAX 2. TOLERANCES ON: DECIMALS ANGLES .XX ± .02 ± 0° 30' .XXX ± .010 3. SURFACE ROUGHNESS 125 ✓ PER MIL STD-10	DRAWN	Foywell 1/15/68	
	CHECK		
	APPR		
	APPR		
	PROJECT / W.O.		DETECTOR BODY
	5300		
MATERIAL: 321 ST. STL TUBE	FINISH: NONE	CODE IDENT NO.	SIZE
			B
		SK0000112	
SCALE 2/1		DO NOT SCALE THIS DWG	SHEET 1 OF 1

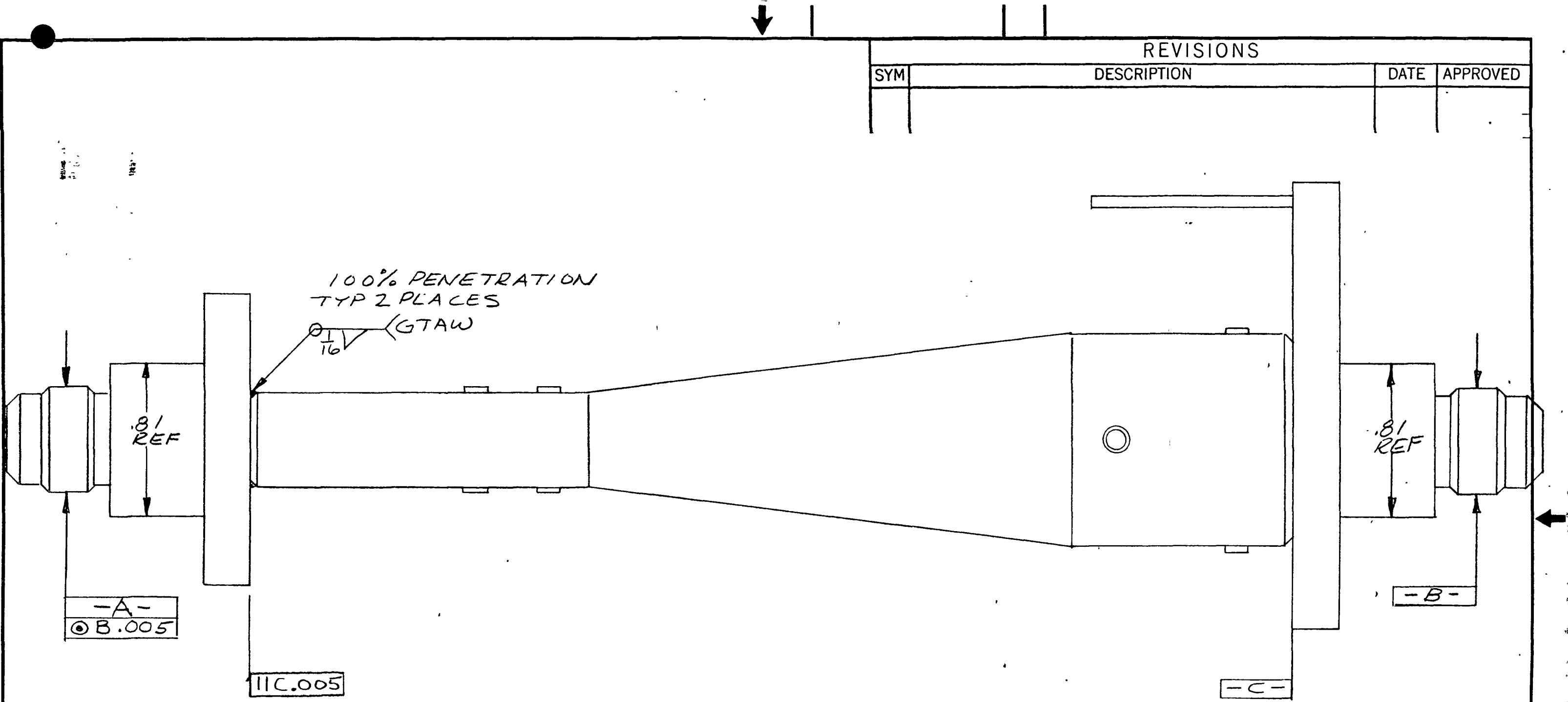


REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED 1. BREAK ALL SHARP EDGES .015 MAX 2. TOLERANCES ON: DECIMALS ANGLES .XX ± .02 ± 0° 30' .XXX ± .010 3. SURFACE ROUGHNESS 125 ✓ PER MIL STD-10	DRAWN	Forwell	1/15/78	END, UPSTREAM	
	CHECK				
	APPR				
	APPR			5300	
PROJECT / W.O.					
MATERIAL: 303-304 ST. STL	FINISH: NONE		CODE IDENT NO.	SIZE B	SK000110
SCALE 2/1		DO NOT SCALE THIS DWG		SHEET 1 OF 1	

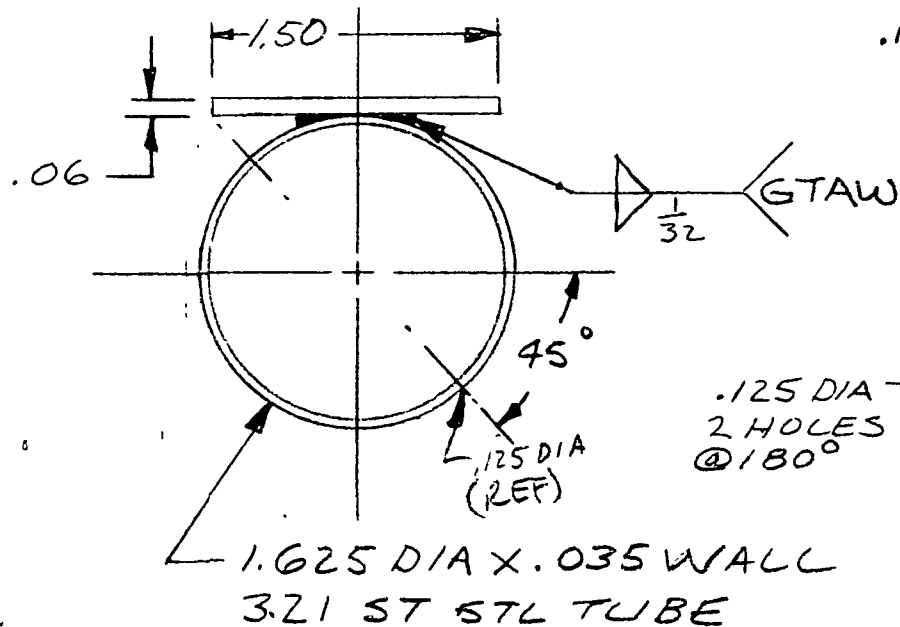


UNLESS OTHERWISE SPECIFIED 1. BREAK ALL SHARP EDGES .015 MAX 2. TOLERANCES ON: DECIMALS .XX ± .02 ANGLES ± 0° 30' .XXX ± .010 3. SURFACE ROUGHNESS 125 ✓ PER MIL STD-10	DRAWN	Foxwell	1/15/68
	CHECK		
	APPR		
MATERIAL: 303-304 ST 57.5%	PROJECT / W.O.		END, DOWNSTREAM 5300
	FINISH:		
	NONE		
	CODE IDENT NO.	SIZE	SK0000113A
	SCALE 2/1		DO NOT SCALE THIS DWG SHEET 1 OF 1



REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED 1.BREAK ALL SHARP EDGES .015 MAX 2.TOLERANCES ON: DECIMALS ANGLES .XX ± .002 ± 0° 30' .XXX ± .010 3.SURFACE ROUGHNESS 125 ✓ PER MIL STD-10	DRAWN	FOXWELL	1/15/8	HOUSING WELDMENT	
	CHECK				
	APPR				
	APPR			PROJECT / W.O. 530.0	
MATERIAL: _____	FINISH: _____		CODE IDENT NO.	SIZE B	SK000111
			SCALE 2/1	DO NOT SCALE THIS DWG	SHEET 1 OF 1



.125 DIA
6 HOLES

.15
TYP

.50
TYP

2.250

5.50

.125 DIA
2 HOLES
@ 180°

.125

.25

.50

.75

2.75

.188 DIA
4 HOLES

5.812

REVISIONS

SYM

DESCRIPTION

DATE

APPROVED

UNLESS OTHERWISE SPECIFIED

1. BREAK ALL SHARP EDGES .015 MAX

2. TOLERANCES ON:

DECIMALS

ANGLES

.XX ± .02

± 0° 30'

.XXX ± .010

3. SURFACE ROUGHNESS 125 ✓

PER MIL STD-10

DRAWN

Forwell

1/15/68

CHECK

APPR

APPR

PROJECT / W.O.

5300

DETECTOR HOUSING

MATERIAL:

ST STL, 304
AND NOTED

FINISH:

NONE

CODE IDENT NO.

SIZE

B

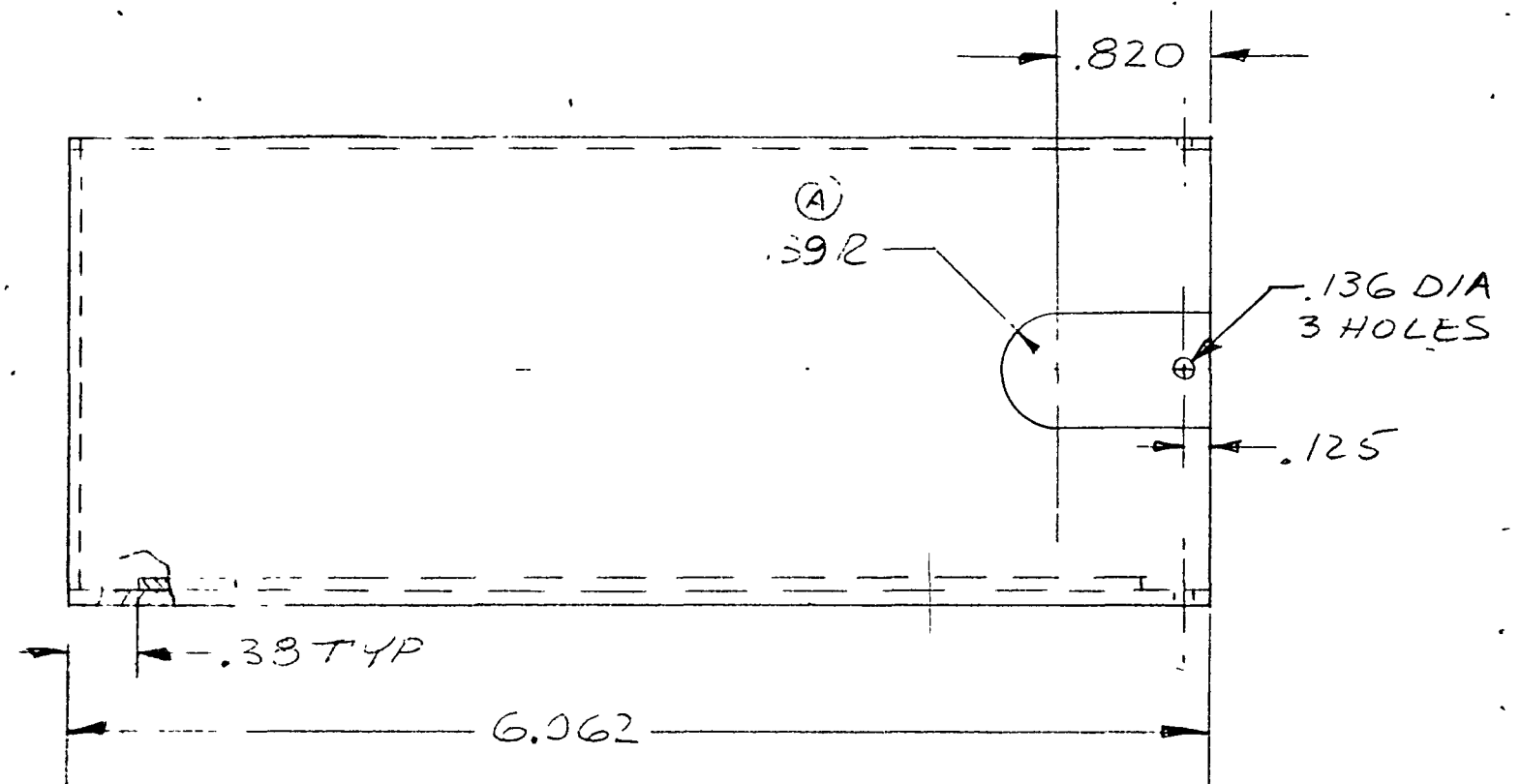
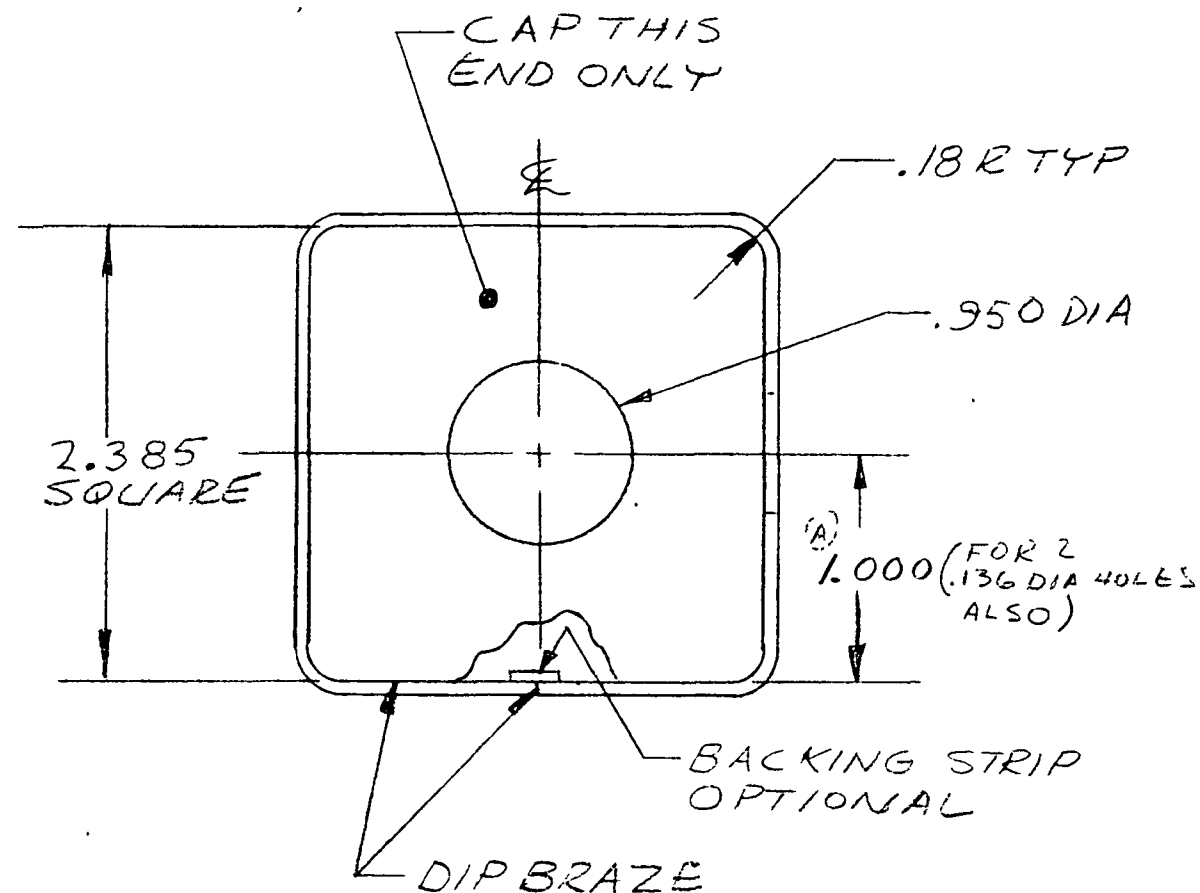
SK0000109

SCALE 1/1

DO NOT SCALE THIS DWG

SHEET 1 OF 1

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED



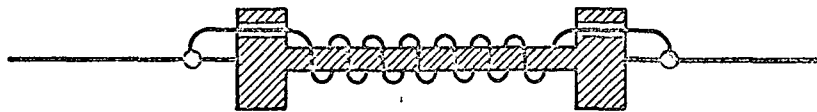
UNLESS OTHERWISE SPECIFIED 1. BREAK ALL SHARP EDGES .015 MAX 2. TOLERANCES ON: DECIMALS ANGLES XX ± .03 ± 0° 30' XXX ± .010 3. SURFACE ROUGHNESS 125 ✓ PER MIL STD-10	DRAWN	FOXWELL	1/15/8	DETECTOR COVER	
	CHECK				
	APPR				
	APPR				
	PROJECT / W.O.				
	5300				
MATERIAL: .062 THK 5052-H34 AL ALLOY	FINISH: ANODIZE PER MIL-A-8625 DYED GREEN		CODE IDENT NO.	SIZE	SK000114A
				B	
			SCALE 1/1	DO NOT SCALE THIS DWG	SHEET 1 OF 1

coated temperature sensitive resistance wire wound on resistor bobbins as shown in Figure 52. The sensors are then inserted in the transducer and potted with high thermal conductive epoxy providing a good thermal path to the fluid. The properties of the temperature sensitive resistance wire and the thermal conductive epoxy are included in Appendix B.

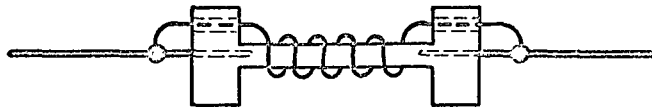
The method used in the PLDS for sensing flow is the constant-temperature system-as in this case, the constant ΔT method. In this method the heater sensor is kept at a constant temperature above the fluid temperature by varying the heating current through the heater wire. The current required is a measure of the heat transfer from the probe and in turn, a measure of the fluid velocity past the probe. The probe is maintained at a constant temperature difference above the fluid temperature through the use of an amplifier and feedback circuit, Figure 53. The bridge circuit (R_h , R_s , R_1 , R_2 , R_3) shown is in balance at same output voltage (e_o) of the feedback amplifier (Z1, Q1 and Q2).

As fluid velocity past the wire changes, the amount of heat lost changes. Since the heater wire temperature and resistance changes, the bridge becomes unbalanced. The feedback amplifier changes the bridge current (I) to bring the heater-sensor resistance back to a null value and the bridge back in balance.

Resistor R_h is the sensitive element due to flow being used as a heater-sensor. Resistor R_s is a temperature sensitive resistor used to sense fluid temperature and is used as a reference upon which R_h is maintained a constant ΔT above the fluid temperature. R_2 is chosen to give the desired ΔT . R_1 and R_4 are chosen to balance the bridge. An analysis of the bridge circuit and determination of its values are given in Appendix B.



FLUID SENSOR

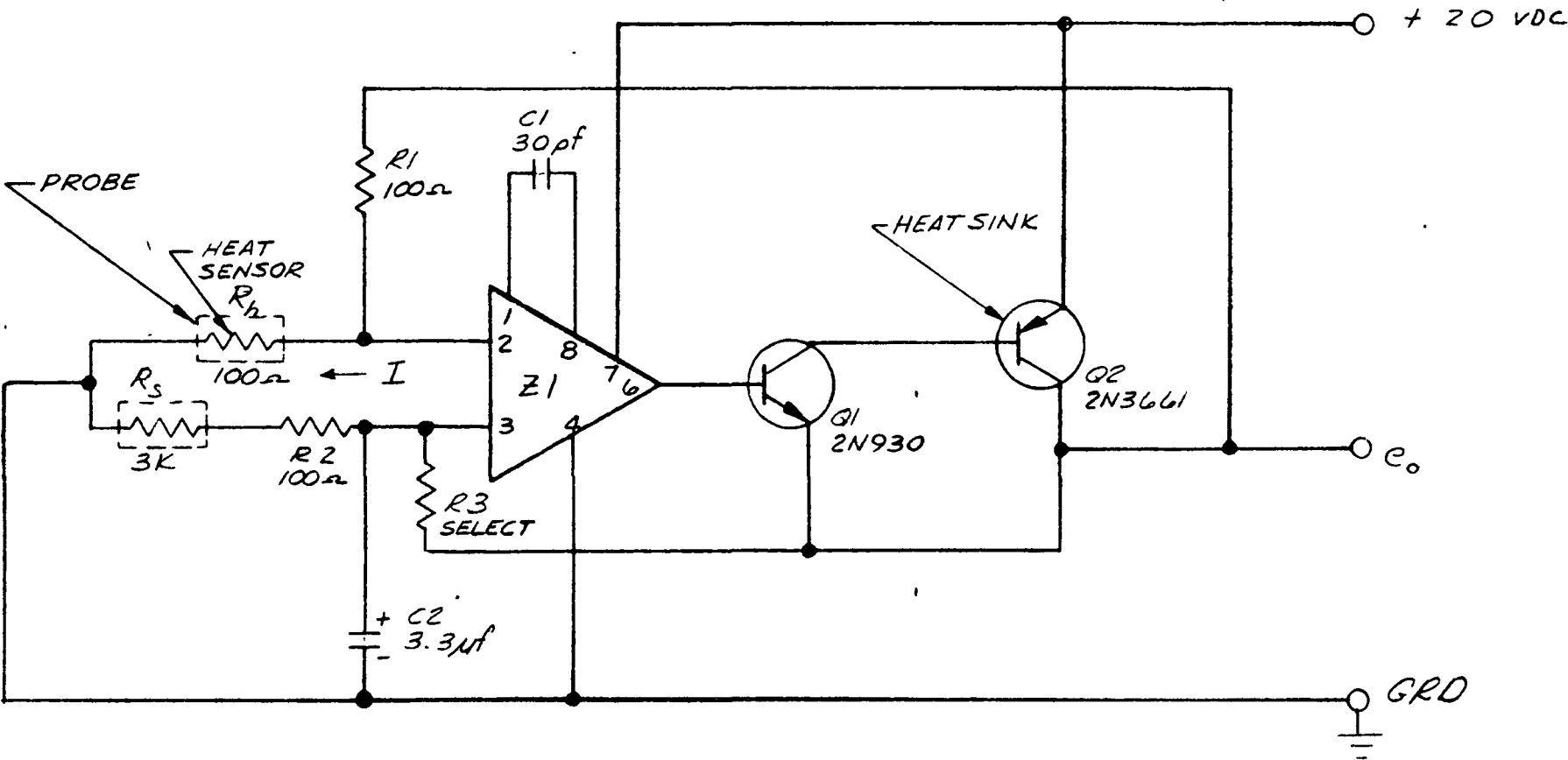


HEATER SENSOR

PROBE INSERTS

FIGURE 52

REVISIONS						
DISPOSITION CODE:		1 MAY BE REWORKED	2 CANNOT BE REWKD.	3 RECORD CHANGE		
		4 NOW SHOP PRACTICE	5 PARTS MADE OK	DISP CODE		APPROVAL & DATE
REV SYM	WORD CODE	DESCRIPTION		MFG EFF	PART	ASSY



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: XX — ± .03 .XXX — ± .010 X'—0' ± 30' WEIGHT IS IN LBS & TENTHS ALL FINISHED SURFACES 125 ✓ PER MIL-STD-10	DRAFT	LFOXWELL	326.8	TITLE SCHEMATIC FLOW METER AMPLIFIER (CONSTANT-TEMPERATURE)	Spacelabs, Inc. 15521 LANARK ST., VAN NUYS, CALIFORNIA	
	DESIGNER					
	STRESS & WEIGHT					
	CHECKER					
	DESIGN ENG					
MFR PER SPEC	MFG ENG				DWG NO	REV N/C
TOLERANCE SYMBOLS PER MIL-STD-8 ELECTRICAL SYMBOLS PER MIL-STD-15 MECHANICAL SYMBOLS PER MIL-STD-17 WELDING SYMBOLS PER JAN-STD-19	STDS ENG					
	PROJ ENG					
				LAYOUT	RELEASE DATE	
				SCALE	WT ACT LB	WT CALC LB
					SHEET /	OF /

B. Leakage Warning System

The purpose of the leakage warning system is to indicate a malfunction whenever high or low leak rate occurs. The system is capable of continuously monitoring the propellant flowrate and to provide a warning in the event a malfunction occurs except when power is applied to the oxidizer or fuel solenoid valves.

The voltage outputs of the oxidizer and fuel flowmeters "O" and "F", respectively, are applied to two independent but similar double limit circuits, high flow (Z1) and low flow (Z2), Figure 55. Each limit circuit is biased (proper choice of select resistor noted by an "*" (see Figure 55) to provide a signal when the voltage proportional to the flowrate exceeds a chosen value.

The flowrate limit values are:

High Flow:	Oxidizer (O_H)	$\approx$	1700 cc/hr
	Fuel (F_H)	$\approx$	1350 cc/hr
Low Flow:	Oxidizer (O_L)	$\approx$	40 cc/hr
	Fuel (F_L)	$\approx$	30 cc/hr

Q1, Q2, Q3 and Q4 serve to inhibit the double limit detectors when the solenoid valves of the RCS System are actuated.

The logic equations satisfied are:

$$H = \overline{RCS} \quad (F_H + \text{to } O_H)$$
$$L = RCS \quad (F_L + O_L)$$

The output of Q11 is low (0 volts d. c.) when the high limit of oxidizer or fuel flow is exceeded and similarly with Q12 when the low limit of oxidizer or fuel flow is exceeded.

NOTE: Logical "1" indicates presence of a positive voltage (+V)
Logical "0" indicates absence of a positive voltage (0 volts d. c.)

C. Ratio Computer

The purpose of the ratio computer is to indicate a malfunction when the utilization rate of oxidizer to fuel differs by more than 50 percent from a normal 2.00.

Let: O = Oxidizer Flowrate

F = Fuel Flowrate

Since the limit for the O/F ratio is specified, we can write:

$$\frac{O}{F} = 2 \pm 1 \quad (1)$$

Equation (1) can be resolved into two different cases to determine when the specified limits have been exceeded.

Case I:

$$O/F \leq 1 \quad \text{or} \quad O - F \leq 0 \quad (2)$$

Case II:

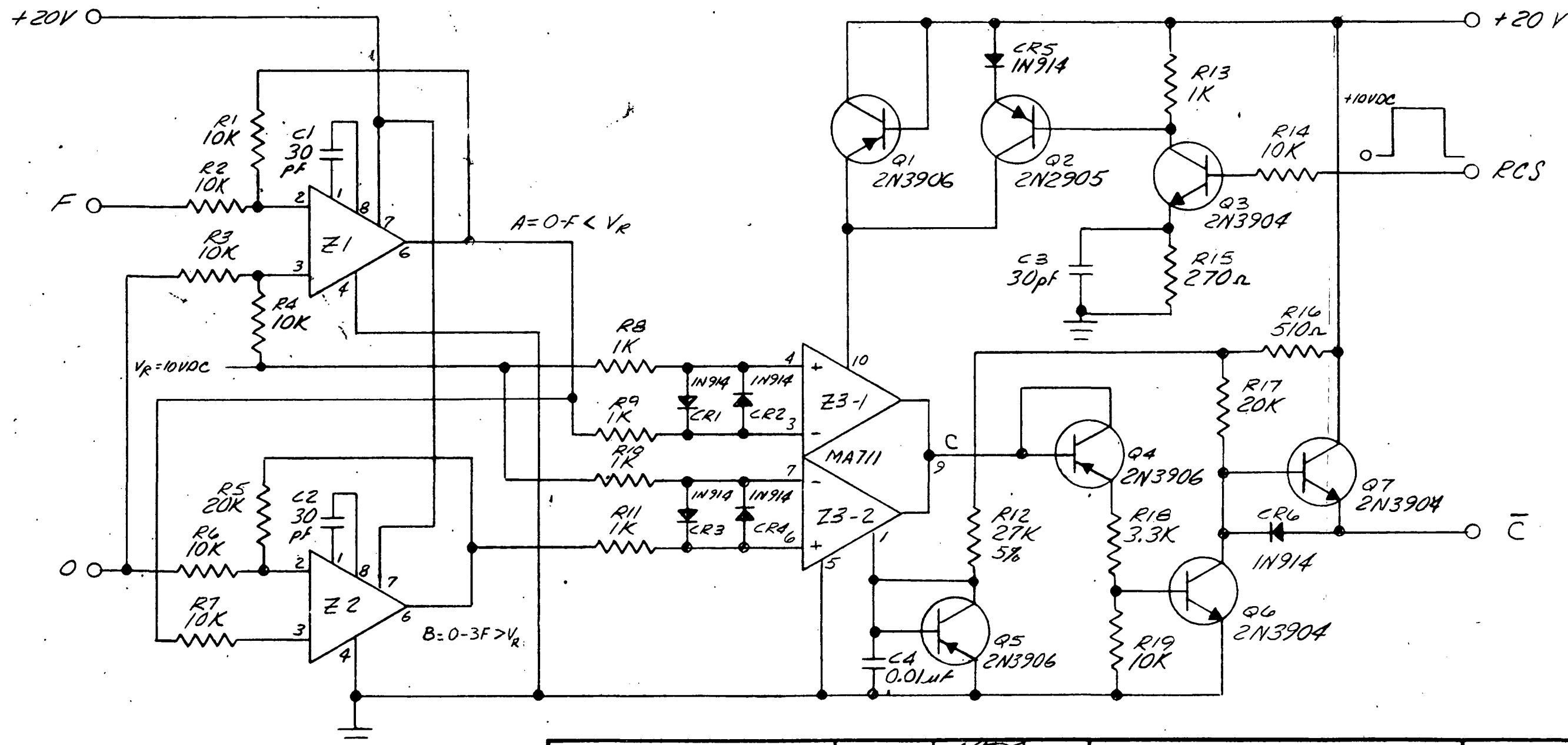
$$O/F \geq 3 \quad \text{or} \quad O - 3F \geq 0 \quad (3)$$

When either Equation (2) or (3) is satisfied a malfunction condition exists.

Assuming that "O" is a voltage linearly proportional to the oxidizer flowrate and "F" is also a voltage linearly proportional to fuel flowrate, then the circuit shown in Figure 54 will implement Equations (2) and (3).

Amplifiers Z1 and Z2 implement Equations (2) and (3), respectively. Z3-1 and Z3-2 is a Fairchild dual comparator used as a double limit detector to satisfy the above equations. The outputs are OR'ed together internally and fed to the output buffers. The purpose of Q1, Q2 and Q3 is to inhibit the double limit detector (Z3) when the oxidizer or fuel flow solenoid valves are not activated.

REVISIONS									
DISPOSITION		1 MAY BE REWORKED	2 CANNOT BE REWKO.	3 RECORD CHANGE	DISP CODE		APPROVAL & DATE		
CODE:		4 NOW SHOP PRACTICE	5 PARTS MADE OK		PART	ASSY			
REV SYM	WORD CODE	DESCRIPTION			MFG EFF				



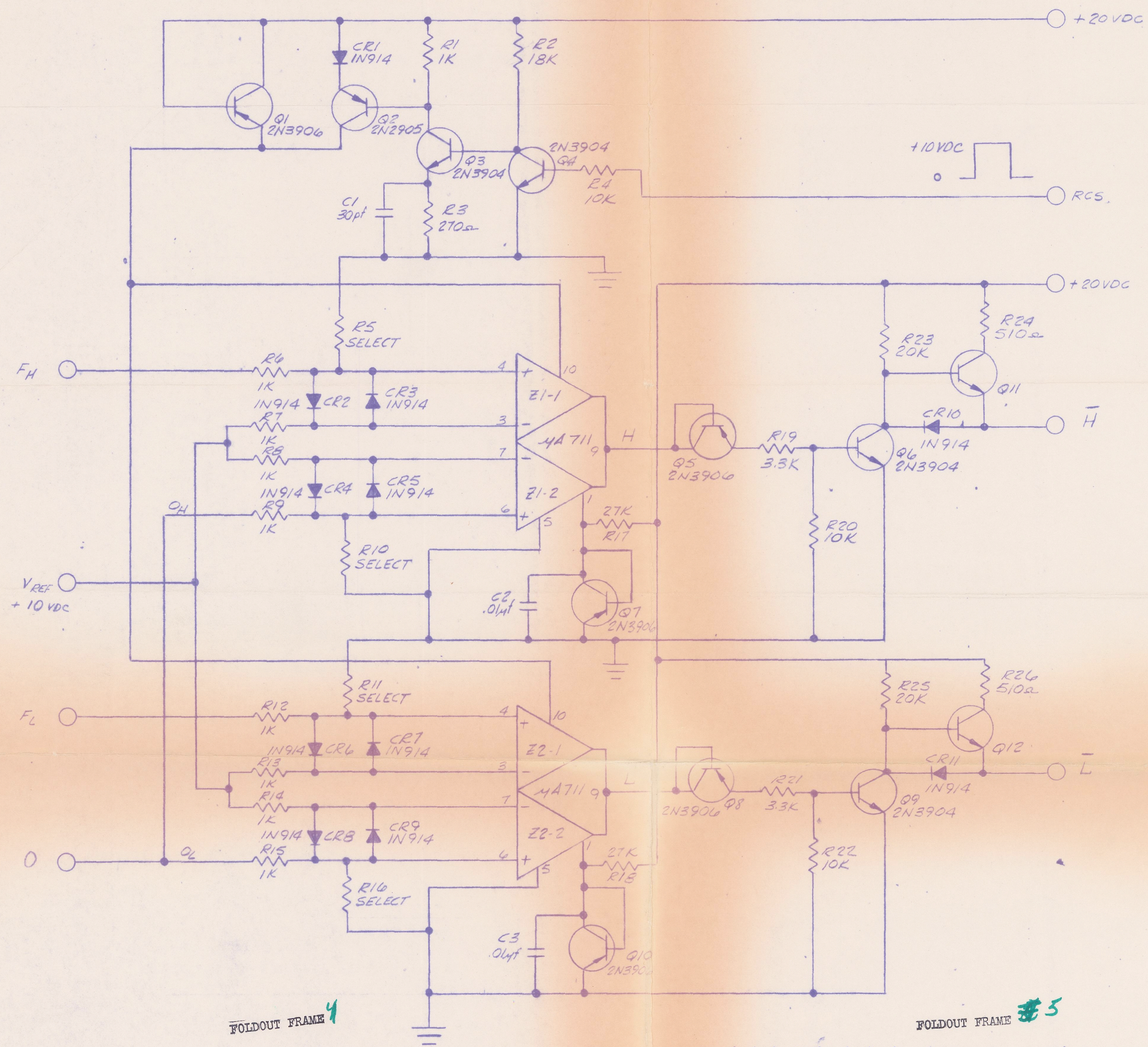
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: .XX — ± .03 .XXX — ± .010 X° — 0° ± 30° WEIGHT IS IN LBS & TENTHS ALL FINISHED SURFACES 125 ✓ PER MIL-STD-10	DRAFT DESIGNER STRESS & WEIGHT CHECKER DESIGN ENG MFG ENG STDS ENG PROJ ENG	4-5-68	TITLE SCHEMATIC, % RATIO - OUT OF LIMIT DETECTOR	Spacelabs, Inc. 15521 LANARK ST., VAN NUYS, CALIFORNIA
MFR PER SPEC			LAYOUT	RELEASE DATE
TOLERANCE SYMBOLS PER MIL-STD-8 ELECTRICAL SYMBOLS PER MIL-STD-15 MECHANICAL SYMBOLS PER MIL-STD-17 WELDING SYMBOLS PER JAN-STD-19			SCALE	WT ACT LB WT CALC LB
				SHEET OF

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

REVISIONS									
DISPOSITION		1 MAY BE REWORKED	2 CANNOT BE REWKD.	3 RECORD CHANGE	DISP CODE		APPROVAL		
CODE:		4 NOW SHOP PRACTICE	5 PARTS MADE OK		PART	ASSY	DATE		
REV	SYM	WORD	CODE	DESCRIPTION	MFG	EFF			



FOLDOUT FRAME 4

FOLDOUT FRAME 5

FOLDOUT FRAME 6

QTY PER ASSY	ITEM	PART NO	DESCRIPTION	MATL	MATL SPEC	ZONE	PART NO	EFF	MOD NO	NEXT ASSY	NEXT ASSY	FINAL ASSY
LIST OF MATERIAL												
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: .XX = ± .03 .XXX = ± .010 X' = 0° ± 30' WEIGHT IS IN LBS & TENTHS ALL FINISHED SURFACES 125 ✓ PER MIL-STD-10			DRAFT	DESIGNER	STRESS & WEIGHT	CHECKER	DESIGN ENG	MFG ENG	STD'S ENG	PROJ ENG	TITLE	
MFR PER SPEC			SCHEMATIC, LEAKAGE WARNING SYSTEM									
TOLERANCE SYMBOLS PER MIL-STD-8 ELECTRICAL SYMBOLS PER MIL-STD-15 MECHANICAL SYMBOLS PER MIL-STD-17 WELDING SYMBOLS PER JAN-STD-19			Spacelabs, Inc.									
REFERENCE TO SIMILAR DWG			DWG NO									
DWG SIZE			REV									
C			SCALE: NONE WT ACT LB WT CALC LB SHEET 1 OF 1									

FIGURE 55

The logic equation satisfied is:

$$C = RCS (A + B)$$

The output of Q7 is high (+20 volts d. c.) when the O/F ratio does not deviate from 2.00 by more than 50 percent. The output is low (0 volts d. c.) when the O/F ratio of 2.00 is exceeded by more than 50 percent, i. e. , see Equations (2) and (3).

SECTION 5

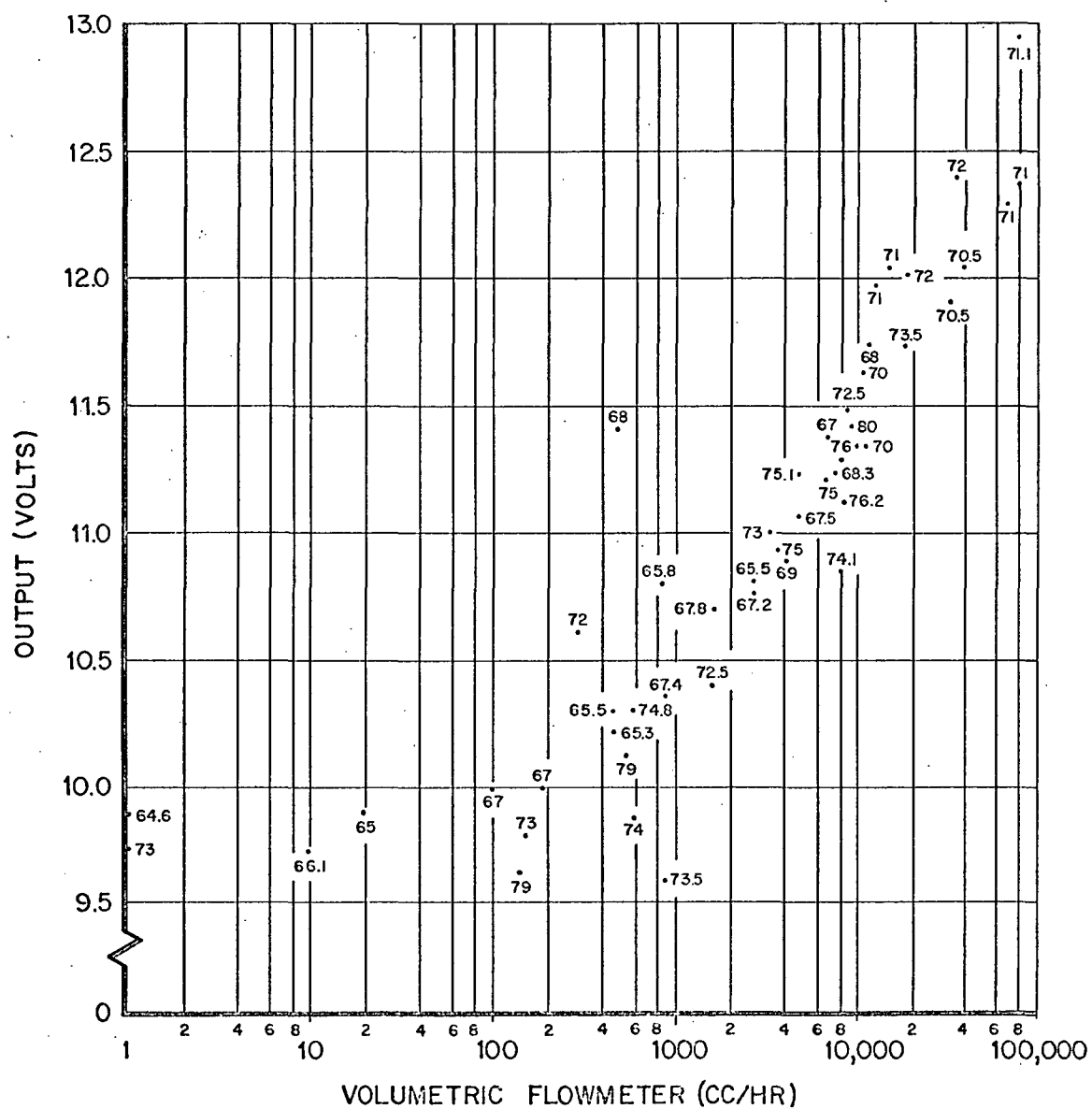
EVALUATION TESTS

After fabrication of the prototype flow sensors a series of tests were conducted with the propellants to demonstrate that the technical objectives of the program had been met.

The evaluation tests were to include combinations of flow, orientation and propellant temperature changes. Not all of these test objectives were met due to failure of the subcontractor (Approved Engineering Test Laboratories) to meet the requirements. Since AETL was unable to control the temperature, the temperature requirement was dropped completely and instead a large amount of data accumulated so that a trend could be predicted. Also, only on the fuel sensor was the effect of orientation tested. The data is presented in Appendix C. It has been rewritten for the convenience of the reader and it must be understood that readings were not necessarily recorded in the order presented here.

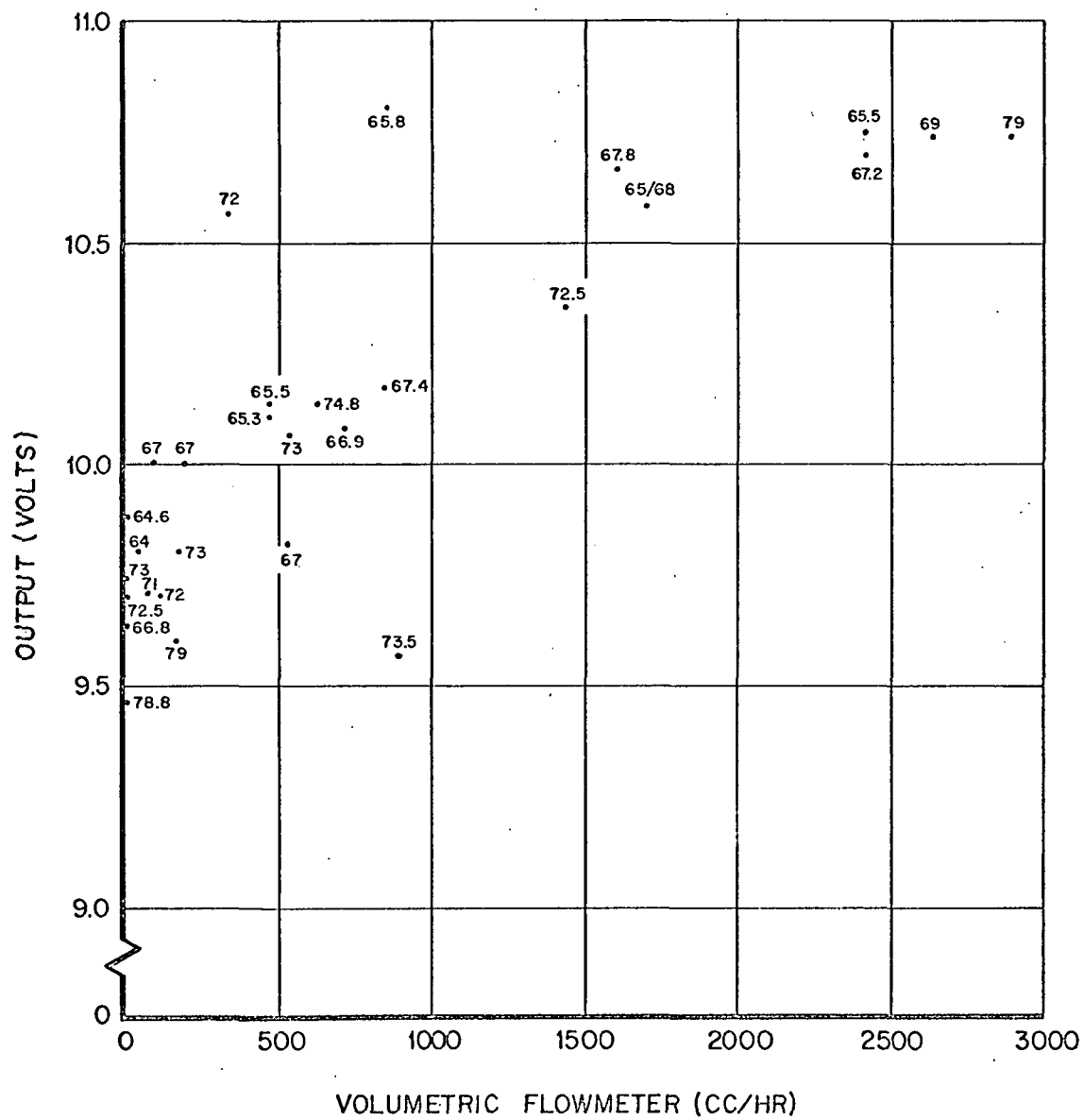
Figures 56 through 58 represent the test data for the oxidizer and Figures 59 through 63 represent the data for the fuel. As many of the data samples as possible were plotted, indicating the temperature in degrees Fahrenheit at each point. The figures clearly demonstrate the need for temperature compensation, though flow can be measured adequately over the required range. The data further indicates that the low flow sensor in the fuel flow meter responded well in the high flow range, its range exceeding that of the high flow sensor.

However, the high range sensor has a high degree of resolution at the design point of 1,000,000 cc/hr. The figures are drawn up in a manner such that the more critical ranges can be readily examined, for example, Figures 57 and 60 indicate the leakage rates for the oxidizer and fuel, respectively.



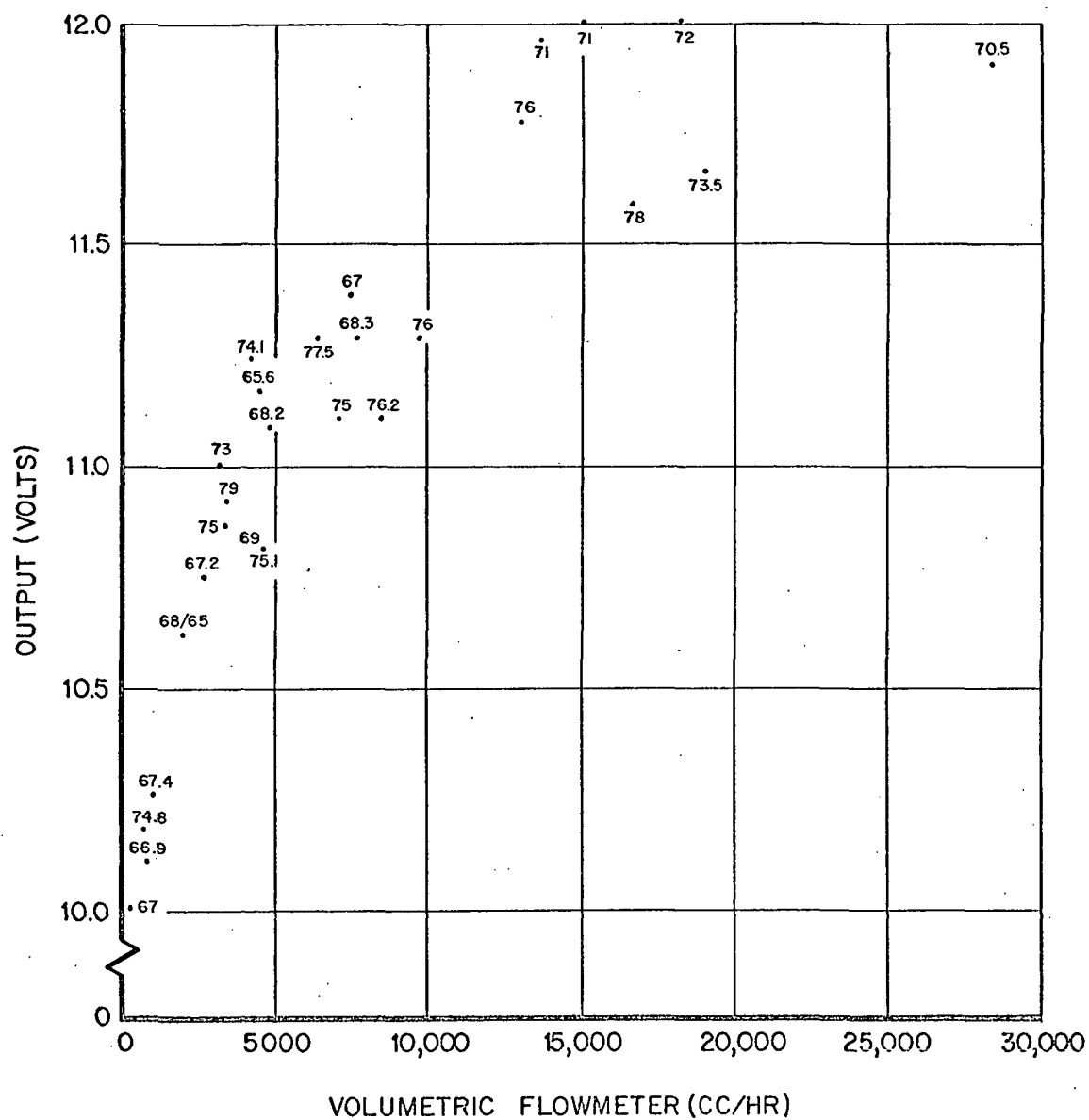
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR N₂O₄

FIGURE 56



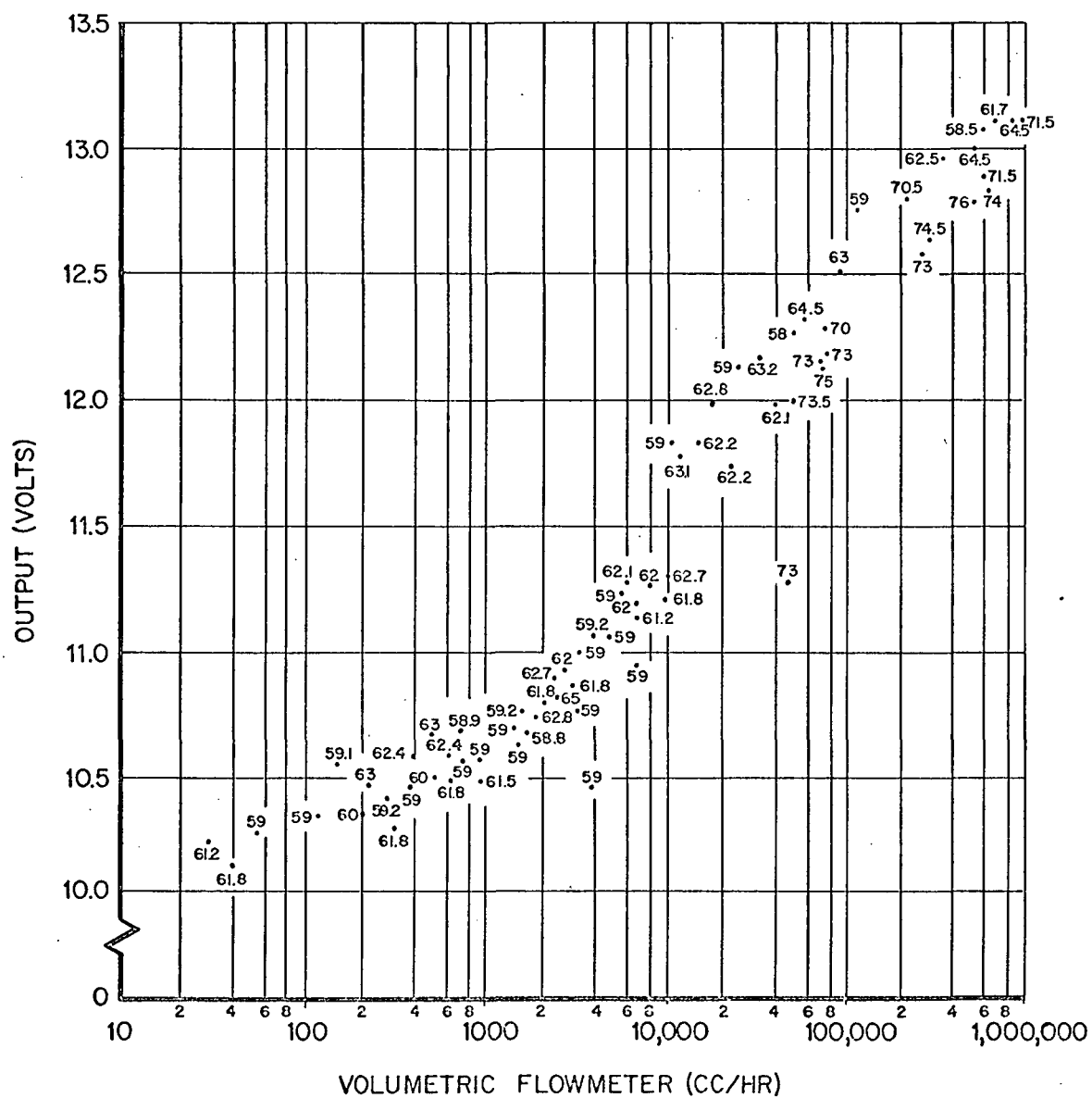
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR N_2O_4

FIGURE 57



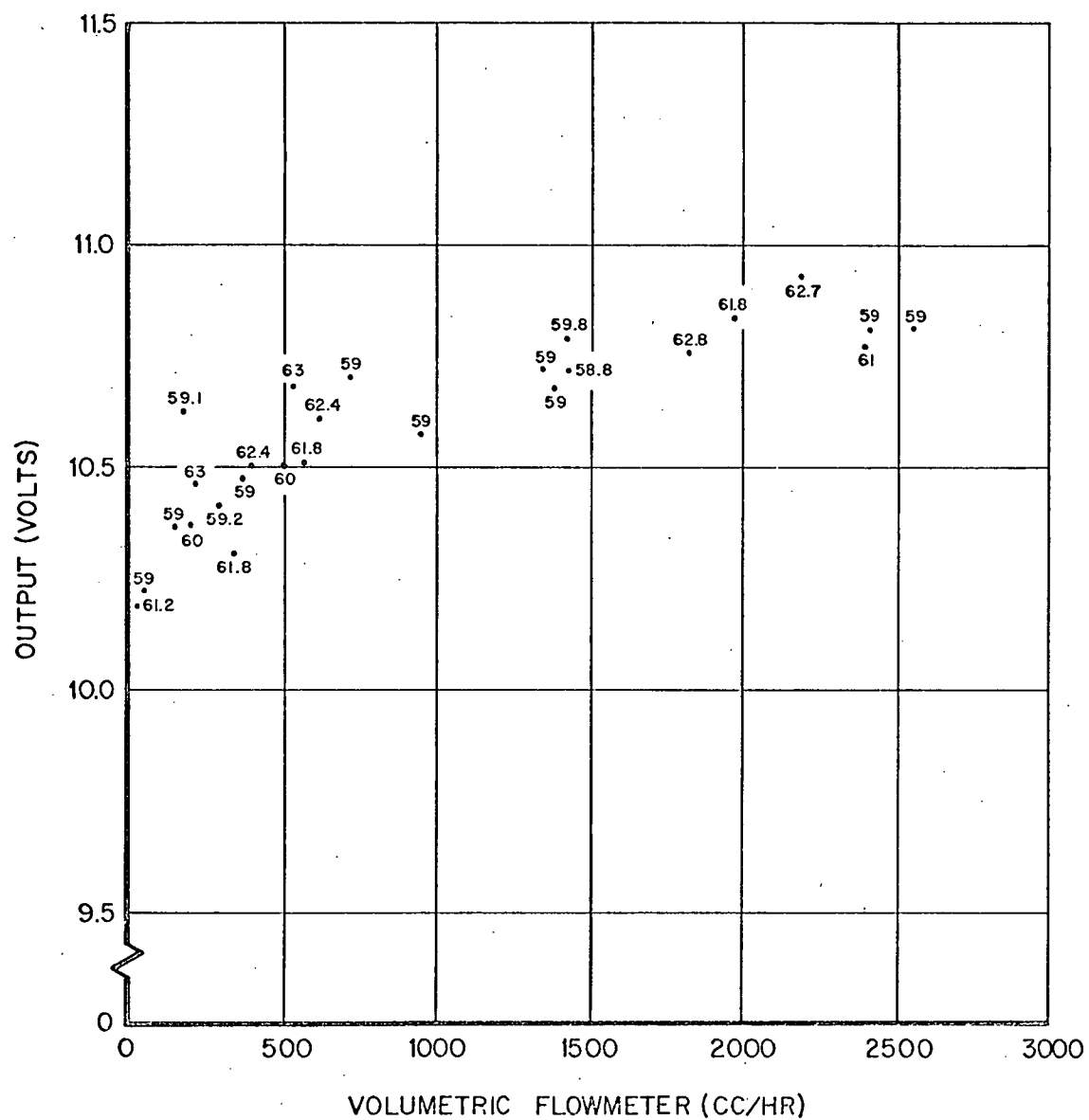
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR N_2O_4

FIGURE 58



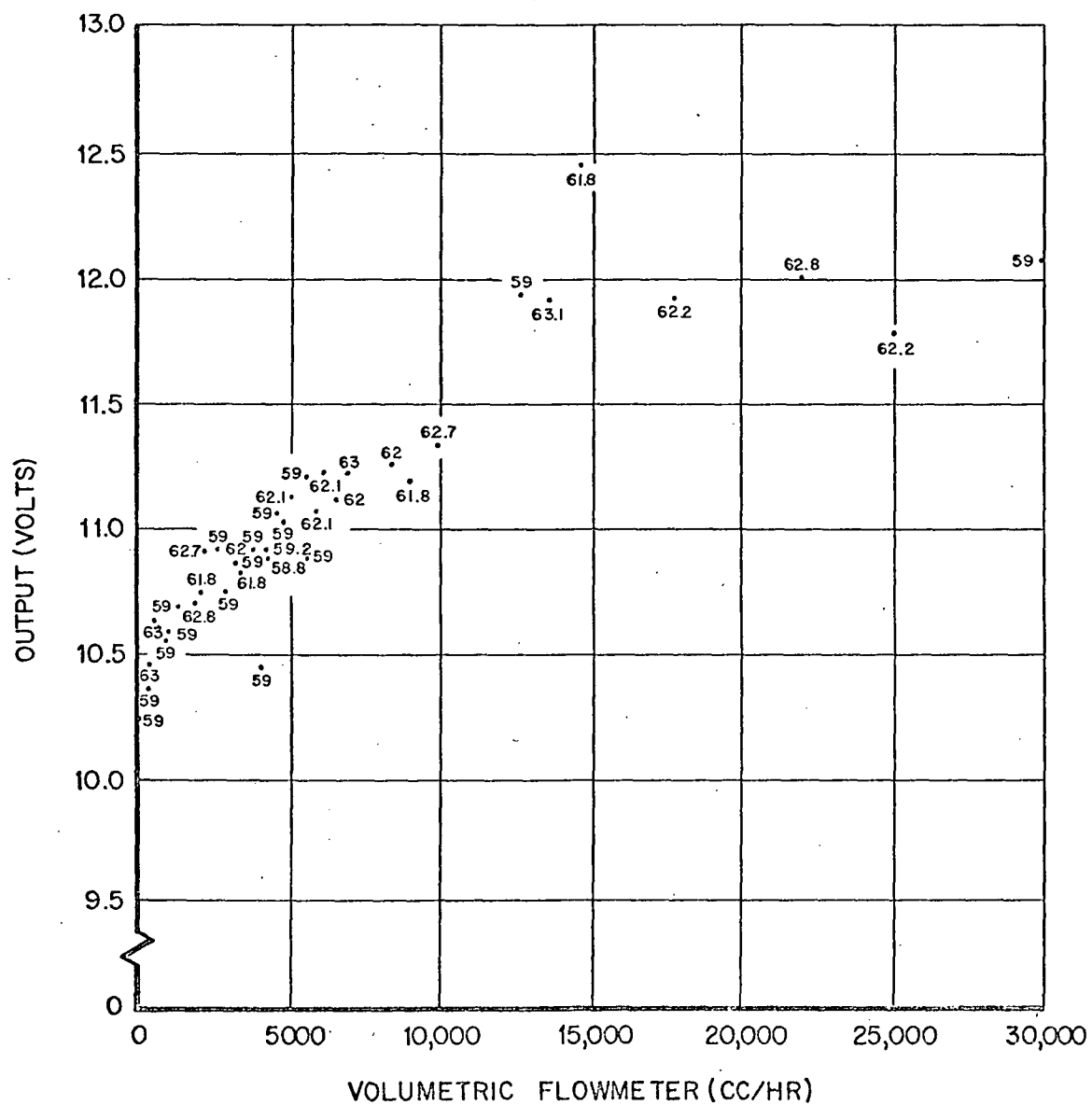
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR UDMH LOW FLOW SENSOR

FIGURE 59



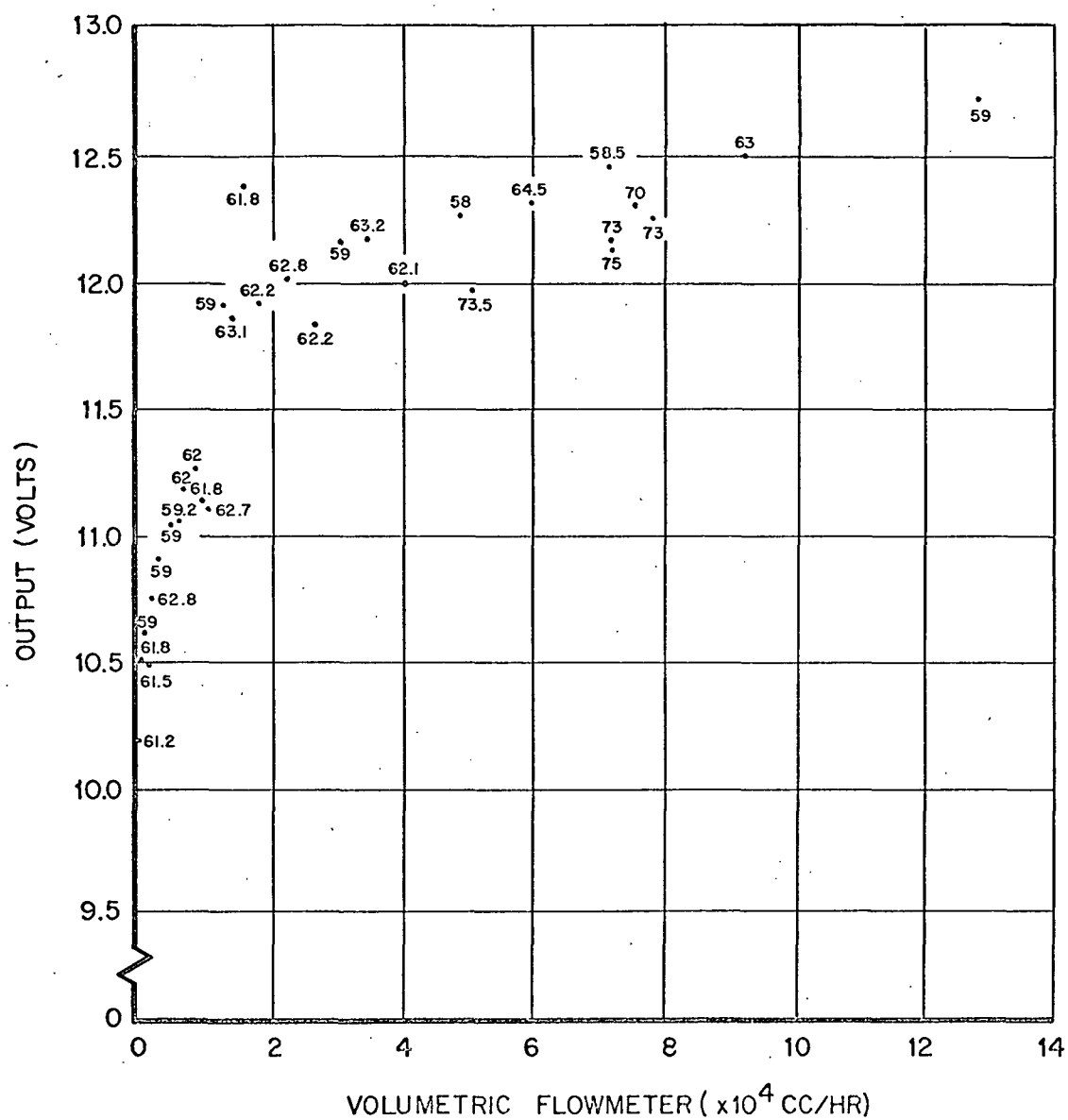
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR UDMH LOW FLOW SENSOR

FIGURE 60



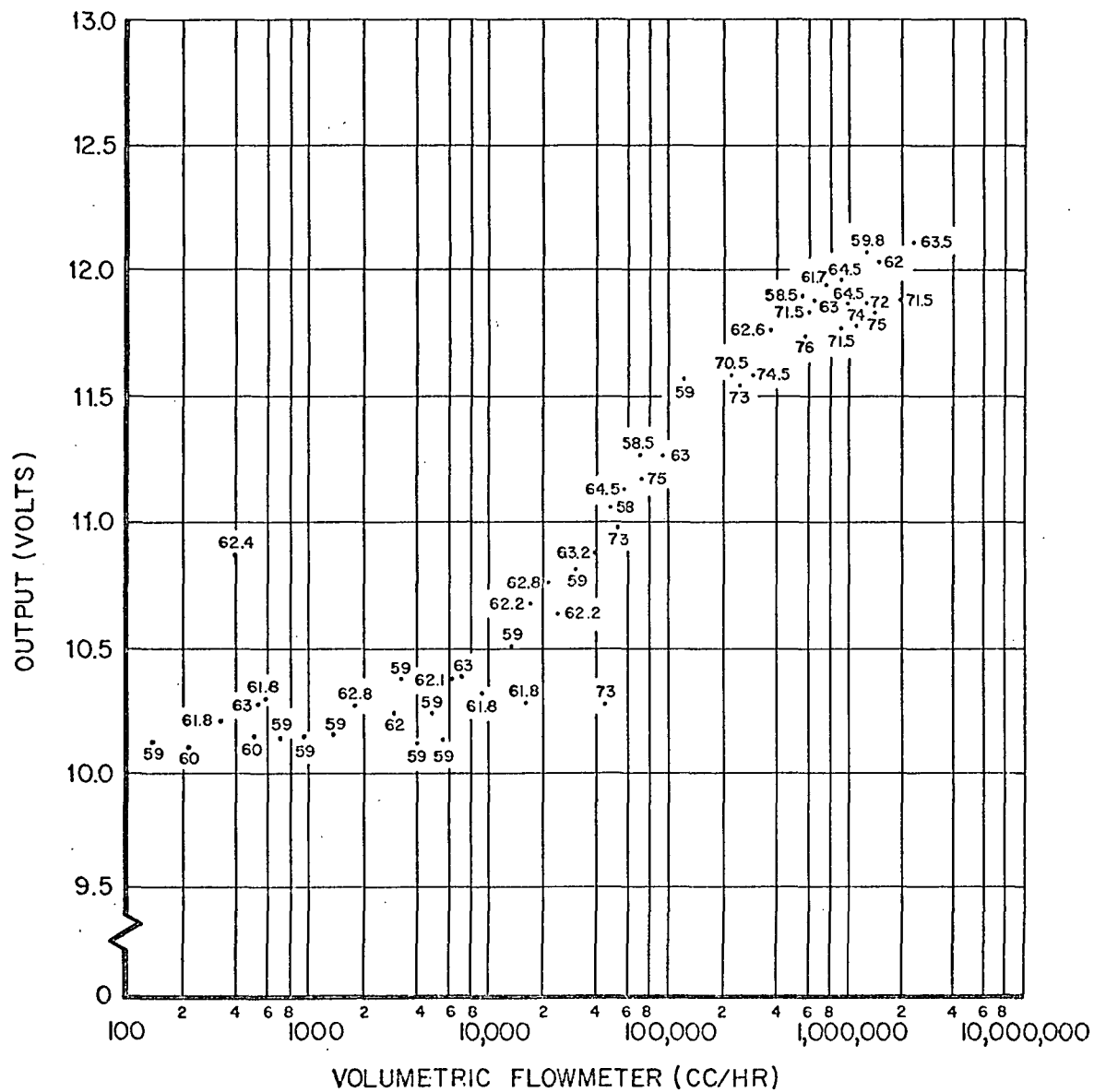
FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR UDMH LOW SENSOR

FIGURE 61



FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR UDMH LOW SENSOR

FIGURE 62

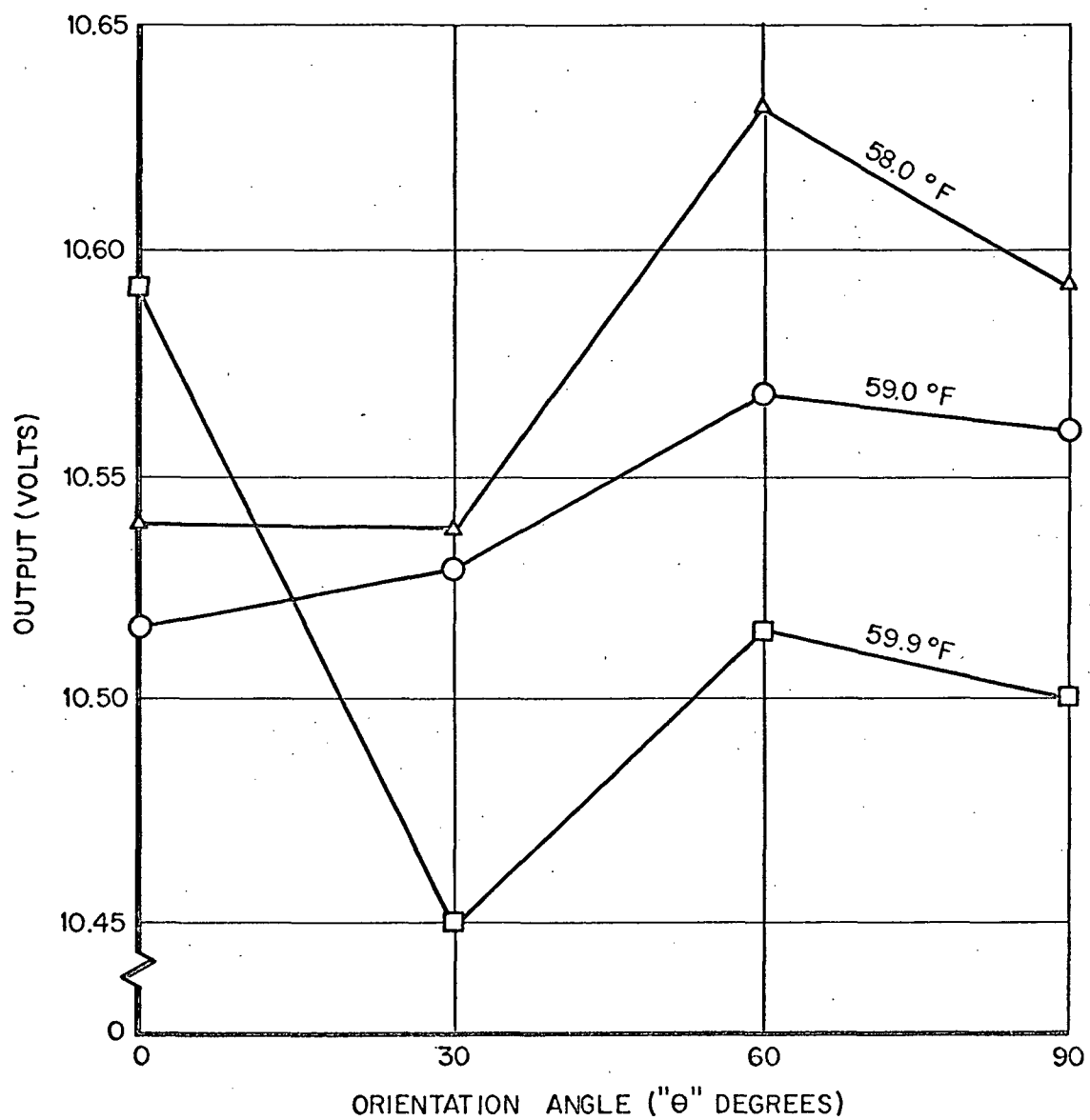


FLOWRATE VS OUTPUT VOLTAGE
AT DIFFERENT FLUID TEMPERATURES
FOR UDMH HIGH FLOW SENSOR

FIGURE 63

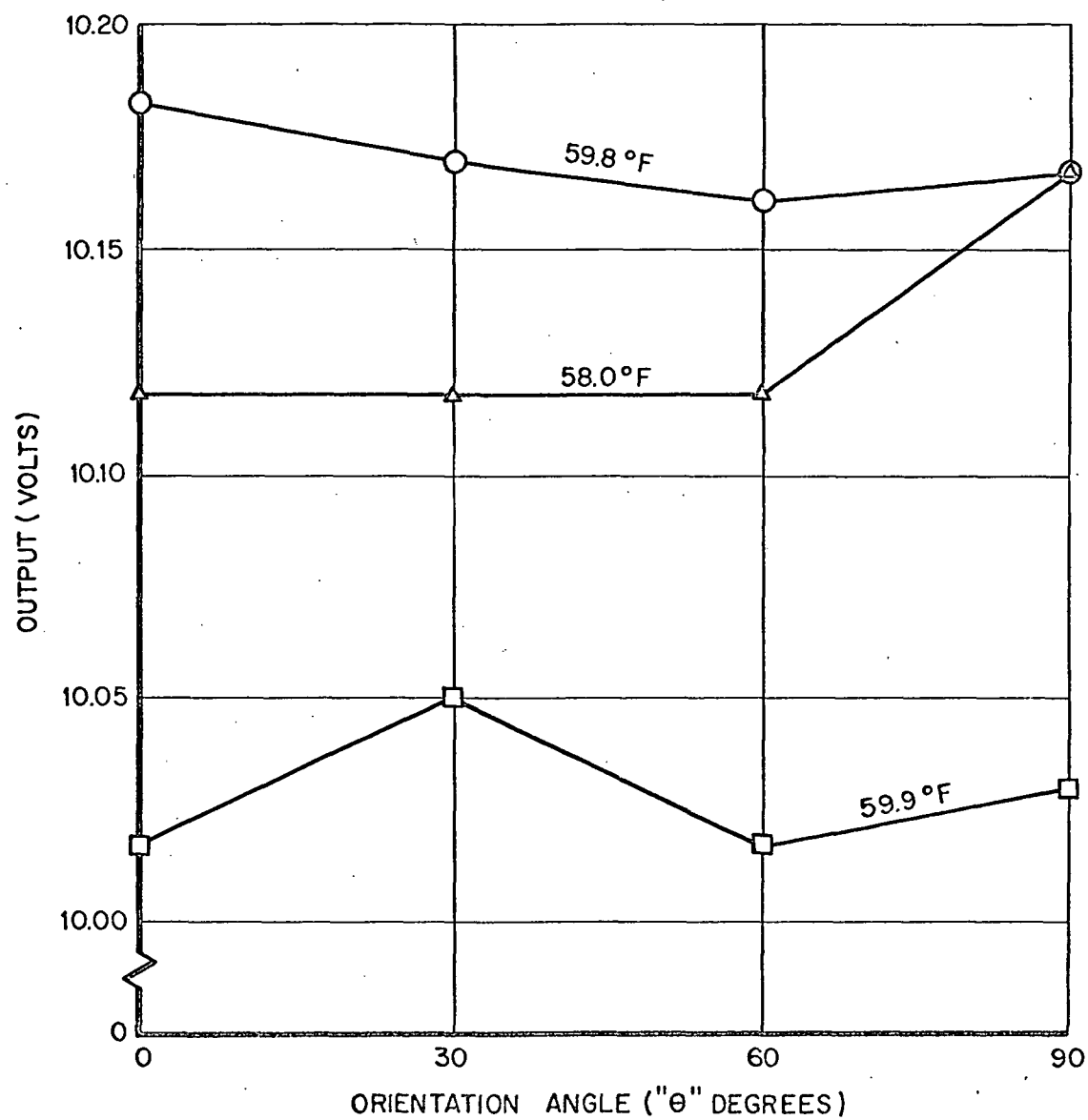
Similar figures are shown to cover ranges up to 30,000 cc/hr. on Cartesian coordinates. The total range is shown on logarithmic coordinates (Figures 56, 59, and 63). The figures further tend to be in good agreement with the theory presented in Appendix C, where the lower temperature results in a higher voltage output for the oxidizer, and a lower voltage output for the fuel.

Figures 64 and 65 show the orientation effects for the low flow and high flow sensors, respectively, in the fuel meter. Though the output voltages do not vary a large amount, it is impossible to predict an indicated flowrate from the available flow data.



EFFECTS OF ORIENTATION ON THE OUTPUT
OF THE LOW FLOW SENSOR

FIGURE 64



EFFECTS OF ORIENTATION ON THE OUTPUT
OF THE HIGH FLOW SENSOR

FIGURE 65

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The program objectives were met and prototype hardware was shipped. Of the two design goals, only the 1-g gravitational field effects were virtually eliminated. Temperature compensation was not achieved, and as indicated in the data, compensation certainly remains a problem to be solved. At this time two possible solutions may be postulated. One is to use the flowmeters as built, but in addition to the flow indicating output, also measure the fluid temperature, combining these two outputs in an equation form as the input to a simple built-in computer. This method is widely used in the aerospace industry today, where multiple measurements are put into a computer to arrive at a single dependent variable output. It is not known what the magnitude or complexity of such a device will be. The other method may be to shape the sensor-probe such that the fluid flow pattern due to local velocities around the probe would result in cancellation of temperature effects. This method is considered extremely complex, and could only be accomplished by trial and error with some statistical elimination process. It would, of course, result in a lighter package and simpler electronics.

The evaluation tests further indicated the need for extremely well-controlled flow conditions, as temperature compensation by the first method is based on curve fitting of reliable calibration data.

The transducer configurations developed can be used in those systems where conventional techniques cannot be used due to propellant corrosiveness and/or the extreme range of flows measured.

APPENDIX A

REVIEW OF THE STATEMENT OF WORK

This Appendix relates the accomplishments of the program to the specific requirements enumerated in the Statement of Work. The characteristics of the prototype PLDS fabricated under this program are compared with the Work Statement goals.

I SCOPE

The Propellant Leakage Detection System desired is a lightweight, compact system capable of detection of not only leaks of extremely small magnitude, but also propellant flowrates under RCS operation or the unusually high flowrates as might occur as a result of line rupture or valve failure. The system delivered demonstrated the ability of accomplishing these goals.

II SYSTEM REQUIREMENTS

A. Integration Requirements

- (1) The PLDS shall be designed such that integration with expulsion systems will not require major alterations to essential components of RCS, PLDS or propellant quantity gaging (PQGS).
- (2) Propellants - The propellants to be monitored are nitrogen tetroxide as the oxidizer and members of the hydrazine family as fuels.
- (3) Compatibility - Any portion of the PLDS which will be exposed to the above mentioned propellants shall be constructed of materials which offer long-term chemical resistance to these propellants.

(4) O/F Ratio - The propellants will be delivered to the thrust chamber assemblies at a ratio of 2 by weight of oxidizer and fuel, respectively, during steady-state operation.

(5) Operating Pressure - Storage and operating pressures vary from 100 to 300 psia and fluctuations on the order of +10% and -5% of nominal operating pressure can be expected during a normal duty cycle. The PLDS sensor will also be subjected to pressure transients as high as 400 psi resulting from injector valve operation (water hammer effect).

(6) Operating Temperature - System operating temperature shall be limited on the low end by propellant freezing temperatures and on the high end by vapor pressure considerations. This system shall be capable of operating over a temperature range of 20°F to 105°F; however, this range should not be expected during a normal duty cycle.

(7) Line Size - The line sizes immediately downstream of the storage tanks are 3/4" and 5/8" tube size for oxidizer and fuel, respectively. Through a valve arrangement, thrust chamber assemblies may be isolated in pairs in the event a malfunction develops. The line size between these isolation valves and the thrust chamber valves is 1/2" and 3/8", respectively, for the oxidizer and fuel. The transducers delivered have -6 MS fittings per NASA request.

(8) Flowrates - The transducers are designed to cover the flowrates expected during RCS operation.

(9) Fail-Safe - The PLDS shall be fail-safe with respect to the RCS, that is, no failure in the PLDS shall compromise the reliability of the RCS.

(10) Component Packaging - Since this contract is primarily concerned with leak sensor improvement, the electronics package developed under NAS 9-3427 shall be utilized with modifications only where necessary for superior performance.

B. RCS Failure Modes to be Detected

(1) The modes of failure most likely resulting in leakage rates requiring immediate attention would be a line rupture or a single thrust chamber valve failing in the open condition. To detect a leak of this magnitude before a significant amount of propellant is lost requires a system which could be operated continuously as long as the RCS is active, and give an immediate warning in the event a leakage signal is received. Since a thrust chamber valve (either fuel or oxidizer) failing open would cause a propellant flowrate similar in magnitude to normal usage rate, some method of further establishing the existence of a true leak must be used.

(2) Small leakage rates could result from imperfect seating of a thrust chamber valve or defective assembly of propellant lines,

fittings, or system components. This mode of failure does not always require immediate attention from a propellant loss standpoint; however, the existence and magnitude of such a leak may be of major importance when considering a mission abort before reaching the point of no return. In addition, an accumulation of propellants in the chamber resulting from a valve leak could result in a catastrophic failure. Detection of small leakage rates through the thrust chamber valves will require continuous operation; however, detection of small leakage rates resulting from defective assembly of propellant lines, fittings, or system components will be required only during specific periods when at least one of the two redundant reaction control systems can be placed inactive.

C. Design Goals

(1) Temperature Compensation - A form of temperature compensation is required over the range of the device. The devices delivered have not achieved this goal. However, new methods and techniques are still being investigated without affecting the system configuration.

(2) Removal of 1-g Sensitivity - This includes the removal of altitude sensitivity and capability of 1-g calibration for 0-g operation. The delivered devices meet this objective to a reasonable degree of accuracy.

D. Design Specifications

(1) Pressure Drop - In the event that the proposed system has any components that are required to be installed within the fluid flow path, no restriction to the flow shall be imposed which will result in a pressure drop exceeding one percent of the normal operating pressure at maximum expected flowrate.

(2) Duty Cycle - The PLDS must be capable of detecting and warning against the failures discussed previously under RCS failure modes. Both high and low flow warning systems shall be capable of continuous duty during all expected environmental conditions with the exception of launch.

(3) Threshold Sensitivity - The low flow detection system shall have a threshold leakage sensitivity of 30 cc/hr and 40 cc/hr for the fuel and oxidizer, respectively; and shall have a useful operating range up to and including the operating threshold of the high flow warning system.

The high flow leakage warning system shall be capable of continuously monitoring propellant flowrates and providing a warning in the event a malfunction occurs that requires immediate attention. A malfunction condition requiring immediate attention is defined as a flowrate exceeding 1350 cc/hr of fuel or 1700 cc/hr of oxidizer at any time other than when power is applied to the respective solenoid valves, or exceeding

either, or both, of the above mentioned flowrates over an interval of time for which the utilization rate of oxidizer to fuel differs by more than 50 percent from a normal of 2.00.

(4) Response Time - The low flow detection system shall have a maximum response time which is within the limits of the equation:

$$T = \frac{3600V}{R} \quad (\text{For low flow only})$$

Where:

T = Response Time (sec)

V = Critical Leak Accumulation (cc)

R = Leakage Rate (cc/hr)

From present considerations, the value of V shall be 0.5 cubic centimeters for Phase II design purposes. The low flow system shall be capable of detecting injector valve leakage according to the above specifications even during periods of attitude control. Under no conditions shall the low flow sensor fail to detect leakage rates large enough to produce a critical chamber accumulation during an engine off-time if the leakage rate is above the threshold level.

The high flow warning system shall have a response time not to exceed the time required for 60 cc of fuel or 75 cc of oxidizer to pass the detector at the rate of flow at which leakage is occurring.

(5) Spacecraft Disturbances - Spacecraft angular accelerations resulting from attitude control of the RCS must be considered. The maximum expected acceleration in all three axes about the spacecraft center of gravity is 0.1 RAD/SEC^2 .

(6) Location - The location of the leak sensing package is expected to be approximately six feet from the spacecraft center of gravity. The location with respect to the flow schematic will be between the storage tanks and thrust chamber valve assemblies.

(7) Power Requirements - Power will be available at 28 volts d.c. Available power is, of course, limited and the PLDS shall be designed with minimum power utilization as a definite objective; however, power requirements shall not be limited to the extent as to be detrimental to system performance. Power demand will not exceed the requirements of the Contract NAS 9-3427 (3.2 watts per dual sensor) PLDS.

(8) Reliability - A system with a high inherent reliability shall be produced through the elimination of extraneous components and the system shall be fail-safe with respect to the RCS.

(9) Weight and Volume - The prototype transducers weigh about 470 grams and 777 grams for the oxidizer and fuel, respectively. This could easily be reduced substantially in an optimized production version.

(10) Component Development - Components vital to system operation have been developed.

(11) Radiation - The PLDS should function properly in the presence of radiation levels normally encountered during interplanetary space travel.

(12) Propellant Leakage - Construction of the assembly prevents propellant leakage from the system at any pressure up to and including 300 psig at any temperature from 20°F to 140°F.

(13) Acceleration - The PLDS will perform in an environment of zero gravity as well as under sustained accelerations of up to 6-g's.

(14) Shock - The system will withstand sawtooth shock loading with a linear rise time of 11 ± 1 milliseconds and with a 1 ± 1 milliseconds decay time at an intensity of 15-g's after potting of electronics.

(15) Vibration - The entire system will withstand and operate under the following vibration environment:

Random

5 cps - $0.0051 \text{ g}^2/\text{cps}$.

5-100 cps linear increase to $0.0415 \text{ g}^2/\text{cps}$.

100-500 cps constant $0.415 \text{ g}^2/\text{cps}$.

550-200 cps linear decrease $0.0415 \text{ g}^2/\text{cps}$ to $0.0296 \text{ g}^2/\text{cps}$.

Sinusoidal Vibration

5-400 cps linear increase 0.123 to 5.39 g.

400-2000 cps constant 5.39 g.

III SPECIFIC REQUIREMENTS

- A. A prototype PLDS has been developed and tested. It provides the specified sensitivity over the range of environments, integration requirements and design specifications outlined in the Statement of Work, with the exception of the temperature compensation portion.
- B. This report completes the reporting requirement.
- C. Sufficient knowledge has been generated to enable the design and fabrication of a full-scale optimized system under a later program.
- D. Further development will be required to solve the temperature compensation problem.

APPENDIX B

ANALYTICAL STUDIES

THIS APPENDIX CONTAINS SOME OF
THE ANALYTICAL STUDIES PERTINENT
TO THE DEVELOPMENT OF A THERMAL
FLOWMETERING DEVICE.

Of importance in the development of a thermal flow measuring device is the determination of values of the heat transfer coefficient h . This function is found to be dependent upon the fluid motion of the resulting boundary layer at the sensor proper. With the use of the Navier Stokes equations, the boundary thickness may be found. A number of observers have performed experiments to determine the heat transfer coefficient for a variety of shapes. Of particular interest, of course, is the flow of fluids perpendicular to cylindrical tubes. Experiments where the mean heat transfer coefficients were measured, resulted in a number of empirical equations. One of these, the Ulsamer equation:

$$h_m = 0.91 \frac{k_F}{D_o} (N_{Re})^{0.385} (N_{Pr})^{0.31} \quad (1)$$

for:

$$0.1 < N_{Re} < 50$$

and:

$$h_m = 0.60 \frac{k_F}{D_o} (N_{Re})^{0.50} (N_{Pr})^{0.31} \quad (2)$$

for:

$$50 < N_{Re} < 10,000$$

Later, a more complex relation was proposed by Kramers:

$$h_m = \frac{k_F}{D_o} \left[0.42 (N_{Pr})^{0.2} + 0.57 (N_{Pr})^{0.33} (N_{Re})^{0.5} \right] \quad (3)$$

$$50 < N_{Re} < 10,000$$

However, the difficulties encountered in a leak detector are the extremely low flowrates. Here, the heat transfer coefficient is dominated primarily by natural convection. Actually, with the introduction of a higher temperature in the sensing probe, buoyancy forces are present throughout the flow range. The important factor, then, is to know when or at what flowrate such forces can be neglected. It can be expected that for large Reynolds Numbers and small Grashof Numbers, the influence of natural convection currents can be neglected. On the other hand, for small Reynolds Numbers and large Grashof Numbers, the natural convection should be the dominating factor. Several theories have produced various solutions. According to the McAdams rule, one calculates the heat transfer coefficient for both forced and free convection and uses the larger. This results in sometimes highly inaccurate solutions.

The heat transfer coefficient due to natural convection may be written as:

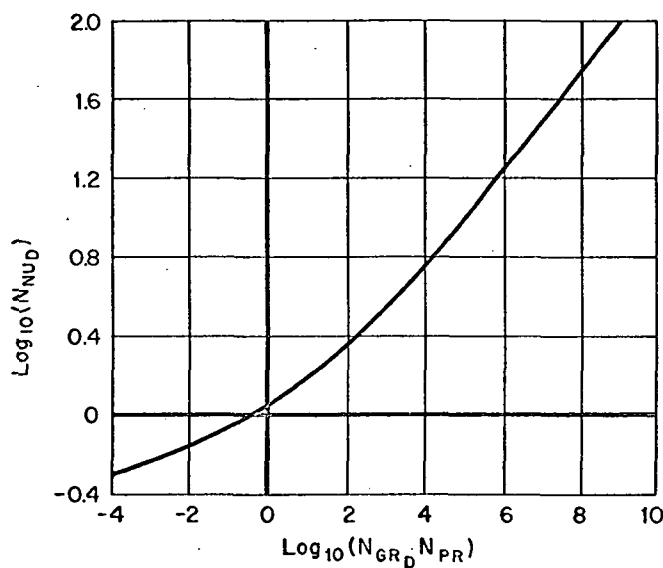
$$h = C \frac{k_F}{D} (N_{GR_D} N_{PR_D})^m \quad (4)$$

where the constants C and m are described in Figure B-1.

Upon investigation of the convection flow field around a single cylinder, one can see that over a relatively large range of orientation changes, the fluid velocity due to buoyancy is nearly unaffected (Figure B-2).

Basically, both forced and natural convection are dependent upon the velocities in the fluid boundary layer. In forced convection these velocities are quite high, but in natural convection the velocities are low and this results in a thicker boundary layer. It seems then that there are two approaches to solving

a. RECOMMEND CORRELATION FOR FREE CONVECTION AROUND HORIZONTAL CYLINDERS



$$N_{NUD} = C(N_{GRD} N_{PR})^m$$

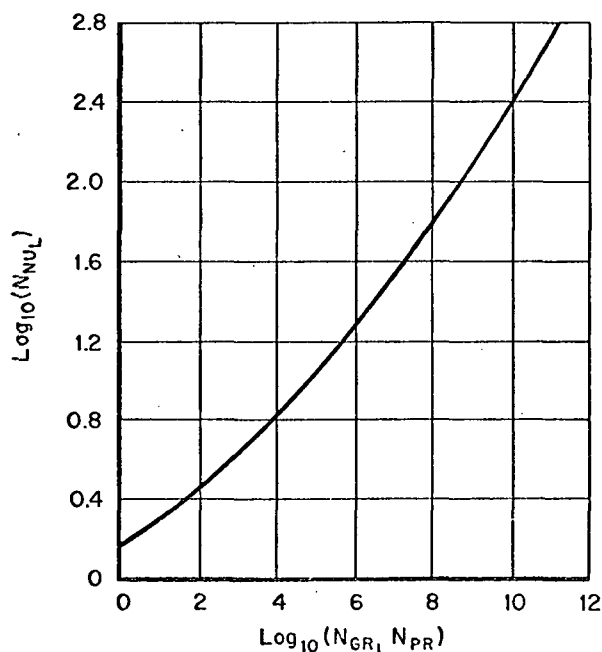
$$0 < (N_{GRD} N_{PR}) < 10^{-5}: C = 0.4, m = 0$$

$$10^{-5} < (N_{GRD} N_{PR}) < 10^4: \text{USE FIGURE a.}$$

$$10^4 < (N_{GRD} N_{PR}) < 10^9: C = 0.525, m = \frac{1}{4}$$

$$10^9 < (N_{GRD} N_{PR}) < 10^{12}$$

b. RECOMMENDED CORRELATION FOR FREE CONVECTION AROUND VERTICAL CYLINDERS



$$N_{NUL} = C(N_{GRL} N_{PR})^m$$

$$10^{-1} < (N_{GRL} N_{PR}) < 10^4: \text{USE FIGURE b.}$$

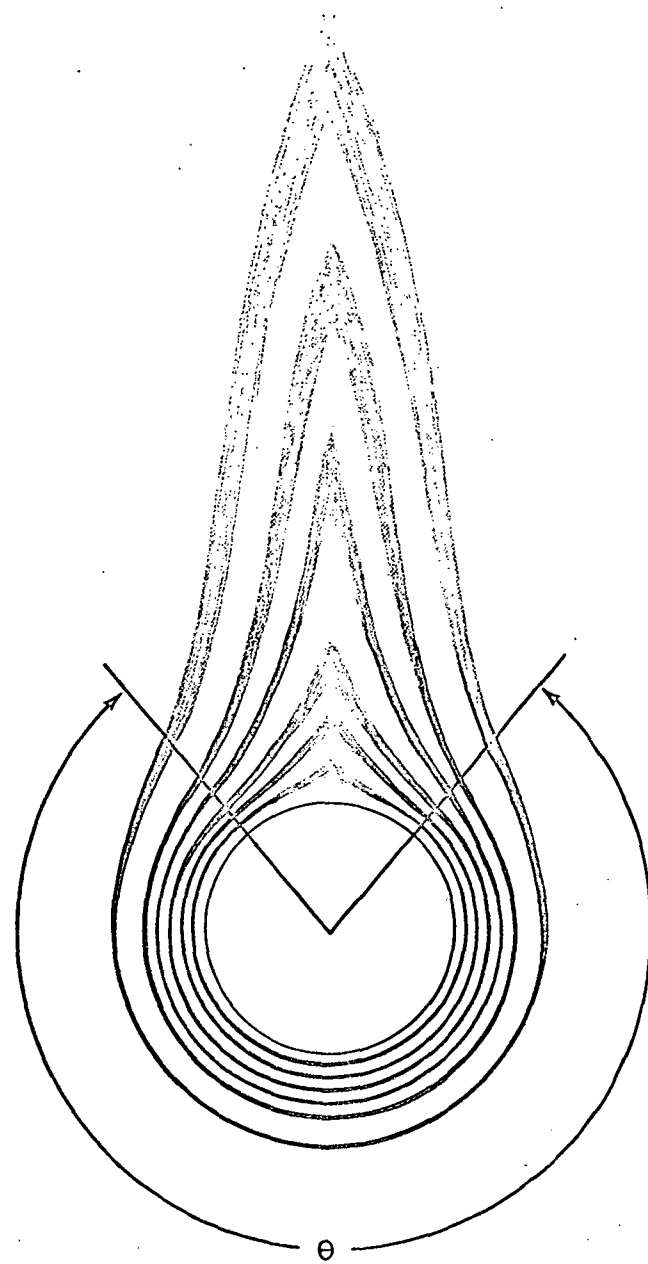
$$10^4 < (N_{GRL} N_{PR}) < 10^9: C = 0.59, m = \frac{1}{4}$$

$$10^9 < (N_{GRL} N_{PR}) < 10^{12}: C = 0.129, m = \frac{1}{3}$$

(FROM McADAMS, W.H.: HEAT TRANSMISSION,
3rd ed., NEW YORK, MCGRAW-HILL, 1954.)

NATURAL CONVECTION AROUND
HORIZONTAL AND VERTICAL CYLINDERS

FIGURE B-1



ISOTHERMS AROUND A HORIZONTAL TUBE
IN FREE-CONVECTION FLOW

FIGURE B-2

for the heat transfer coefficient under low flow conditions. The first is to determine the velocities due to both forced and natural convection and add them vectorially, and then using the forced convection equations, arrive at the solution. The other method would be to solve for the boundary layer thickness under both conditions, and using the simple fluid conductivity equations around a cylinder, determine the heat transfer coefficient.

When the influence of natural convection is included in the forced convection case, a general equation may be written, such that:

$$N_{Nu} = \Psi (N_{Re})_o N_{Pr} N_{Gr} \quad (5)$$

where Ψ is a function symbol and the subscript o indicates that the Reynolds Number must be taken at the undisturbed velocity, V_o .

However, upon determination of the Reynolds Number (Table B-I) it was found that the Ulsamer equations adequately covered the range of flows higher than 30 cc/hr for both propellants. Only at flowrates of less than 30 cc/hr must the influence of natural convection be included.

Since the indication of flow is the measurement of power input to maintain a fixed temperature difference between heater-sensor and fluid, the heat transfer equation is:

$$q = h A \Delta T \quad (6)$$

and can be written as:

$$\frac{E^2}{R} = h A \Delta T \quad (7)$$

or:

$$E = R h A \Delta T$$

(8)

where R is the resistance of the heater. Since R varies with temperature, the solution becomes difficult unless R can be written as a function of temperature.

The heat Transfer coefficients were calculated from the properties given in Tables B-II, B-III and B-IV for water, nitrogen-tetroxide and UDMH respectively. The results of these calculations are presented in Figures B-3 through B-7.

Q cc/hr	WATER		N ₂ O ₄		UDMH	
	T = 50°F	T = 90°F	T = 50°F	T = 90°F	T = 50°F	T = 90°F
	Re	Re	Re	Re	Re	Re
30	0.215	0.366	0.0885	0.105	0.194	0.288
60	0.430	0.732	0.1770	0.210	0.388	0.576
90	0.645	1.098	0.2655	0.315	0.582	0.864
300	2.15	3.66	0.885	1.05	1.94	2.88
600	4.30	7.32	1.770	2.10	3.88	5.76
900	6.45	10.98	2.655	3.15	5.82	8.64
3,000	21.5	36.6	8.85	10.5	19.4	28.8
6,000	43.0	73.2	17.70	21.0	38.8	57.6
9,000	64.5	109.8	26.55	31.5	58.2	86.4
30,000	215.0	366.0	88.5	105.0	194.0	288.0
60,000	430.0	732.0	177.0	210.0	388.0	576.0
90,000	645.0	1,098.0	265.5	315.0	582.0	864.0
300,000	2150.0	3,660.0	885.0	1050.0	1940.0	2880.0
600,000	4300.0	7,320.0	1770.0	2100.0	3880.0	5760.0
900,000	6450.0	10,980.0	2655.0	3150.0	5820.0	8640.0

REYNOLDS NUMBER VERSUS VOLUMETRIC FLOWRATE

TABLE B-I

PROPERTIES OF WATER

Temperature °F	Thermal Conductivity Btu/hr-°F-ft	Density lbm/ft ³	Viscosity lbm	Heat Capacity Btu/lbm-°F	Prandtl Number
20	-	-	-	-	-
32	0.327	62.42	4.33	1.009	13.37
40	0.332	62.42	3.75	1.005	11.36
50	0.338	62.38	3.17	1.002	9.41
60	0.344	62.34	2.71	1.000	7.88
70	0.349	62.27	2.37	0.998	6.78
80	0.355	62.17	2.08	0.998	5.85
90	0.360	62.11	1.85	0.997	5.13
100	0.364	61.99	1.65	0.997	4.52
110	0.368	61.84	1.49	0.997	4.04
120	0.372	61.73	1.36	0.997	3.65

TABLE B-II

PROPERTIES OF N₂O₄

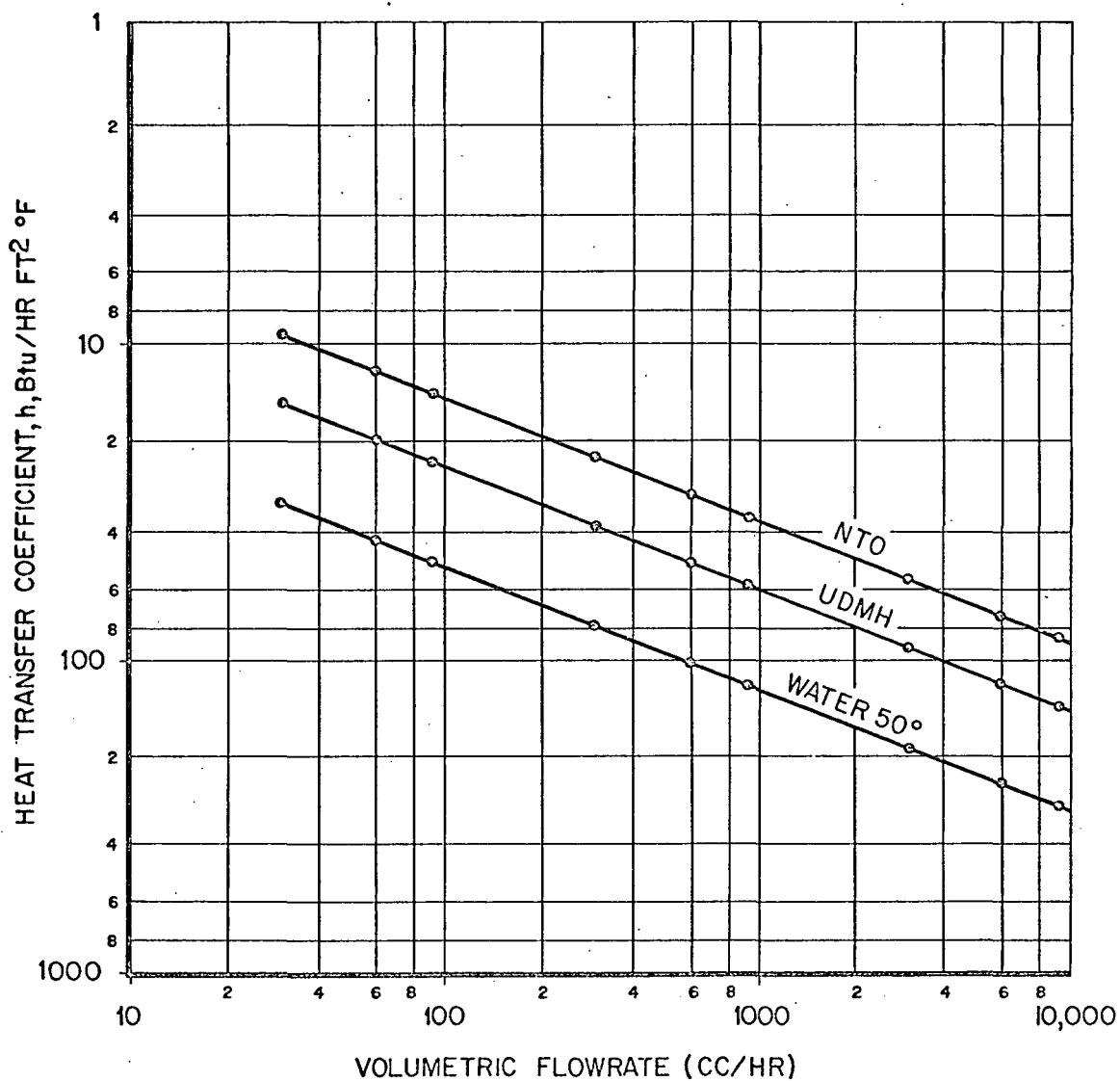
Temperature °F	Thermal Conductivity Btu/hr-°F-ft	Density lbm/ft ³	Viscosity lbm	Heat Capacity Btu/lbm-°F	Prandtl Number
20	0.0830	91.6	13.80	0.355	59.0
30	0.0820	90.4	13.10	0.357	57.2
40	0.0800	90.4	12.10	0.3585	53.7
50	0.0795	90.0	11.10	0.360	50.3
60	0.0782	88.5	10.65	0.362	49.4
70	0.0767	87.9	9.94	0.366	47.5
80	0.0750	87.2	9.44	0.370	46.0
90	0.0733	86.3	8.97	0.373	45.7
100	0.0715	85.4	8.50	0.376	44.7
110		84.8	8.23	0.380	
120		84.2	7.03	0.385	

TABLE B-III

PROPERTIES OF UDMH

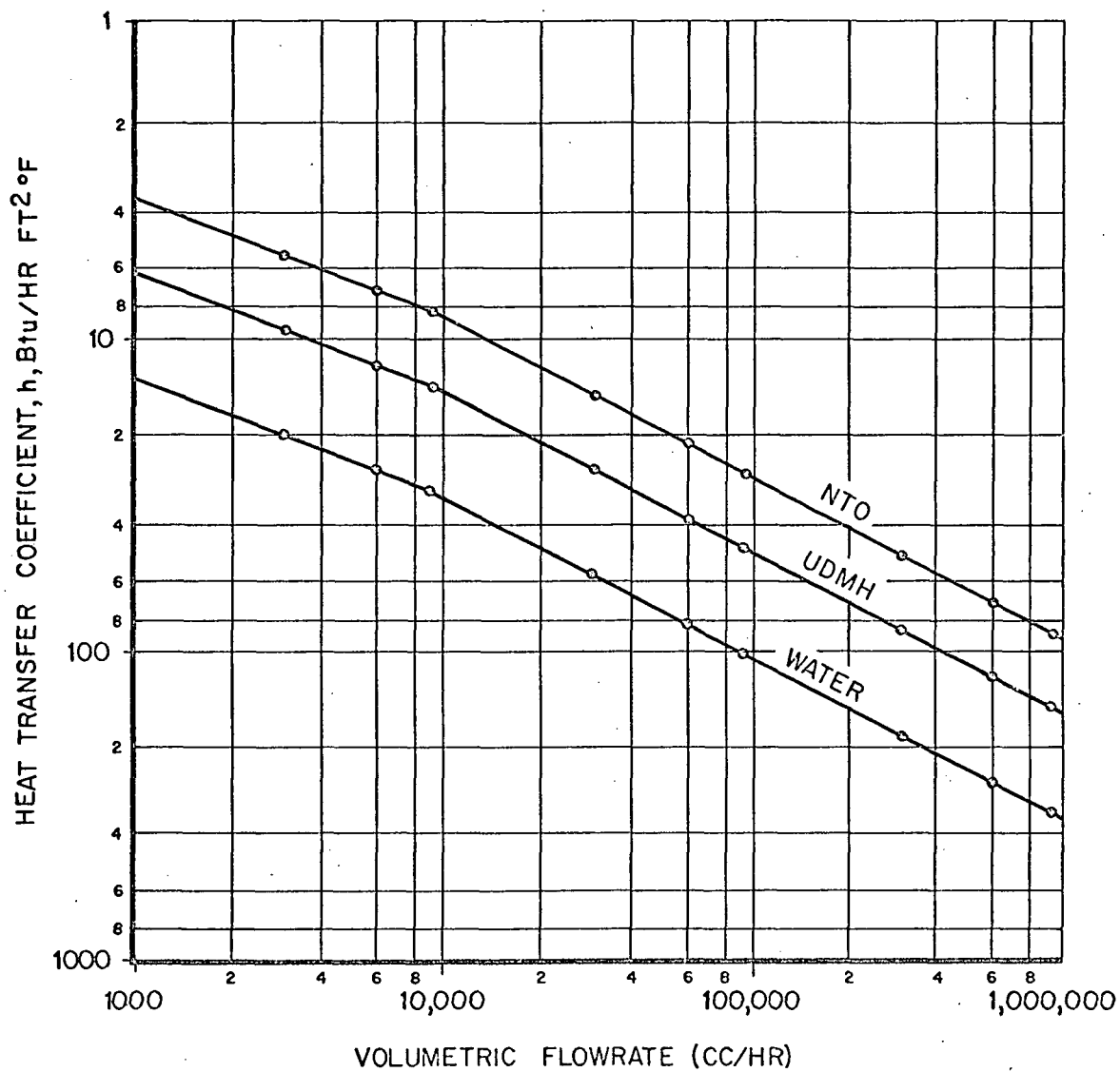
Temperature °F	Thermal Conductivity Btu/hr-°F-ft	Density lbm/ft ³	Viscosity lbm	Heat Capacity Btu/lbm-°F	Prandtl Number
20	-	51.2	3.64	0.680	-
30	-	51.0	-	0.681	-
40	-	50.4	3.13	0.682	-
50	0.1510	50.06	2.77	0.684	12.8
60	0.1506	50.0	2.44	0.685	11.8
70	0.1502	49.3	2.12	0.687	10.7
80	0.1498	49.0	1.96	0.688	9.7
90	0.1494	48.65	1.85	0.689	9.0
100	0.1490	48.3	1.71	0.690	8.5
110	0.1486	47.95	-	0.691	8.0
120	0.1482	47.6	1.59	0.692	7.4

TABLE B-IV



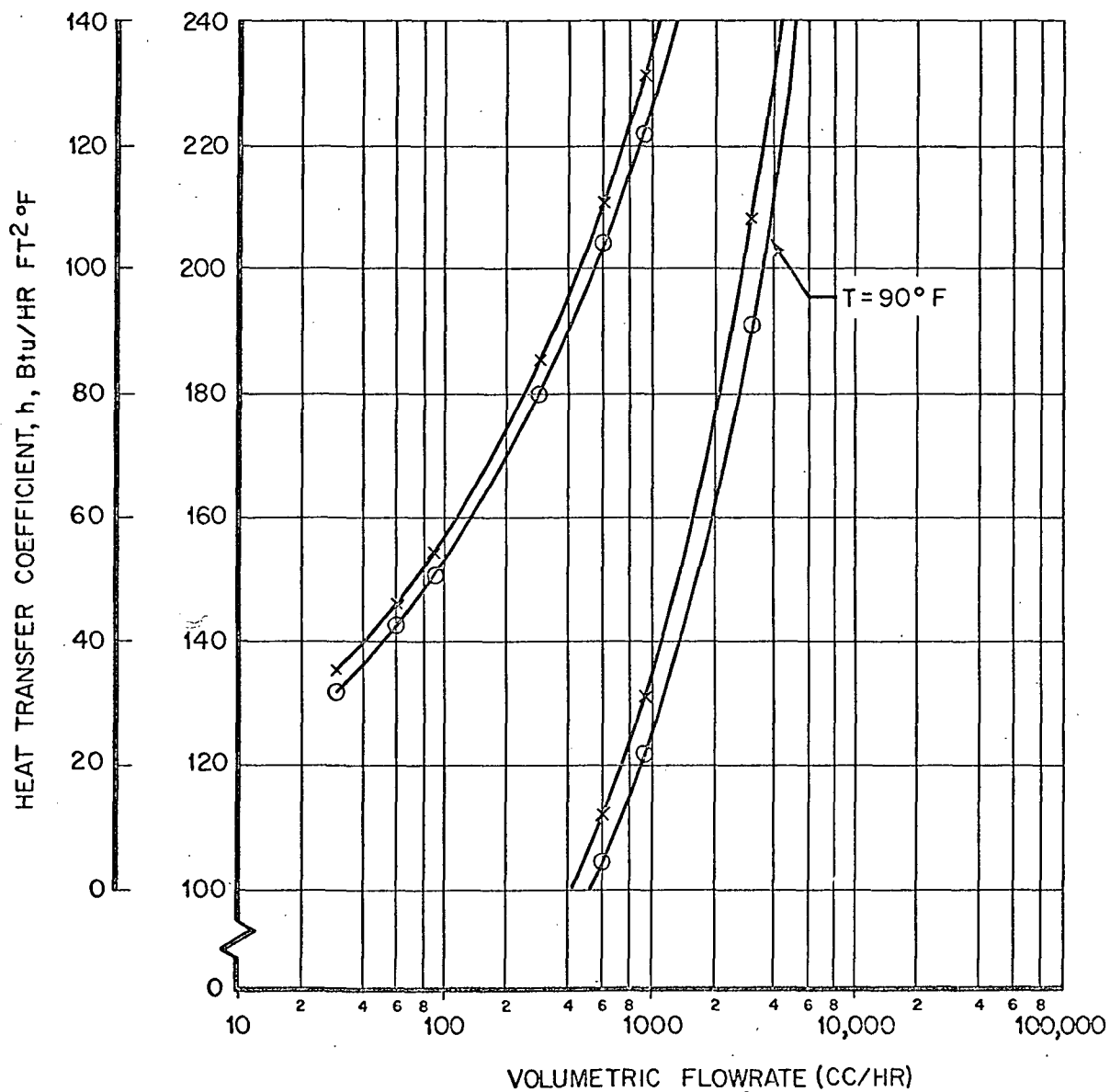
HEAT TRANSFER COEFFICIENT VS. FLOWRATE
BASED ON ULSAMER EQUATION

FIGURE B-3



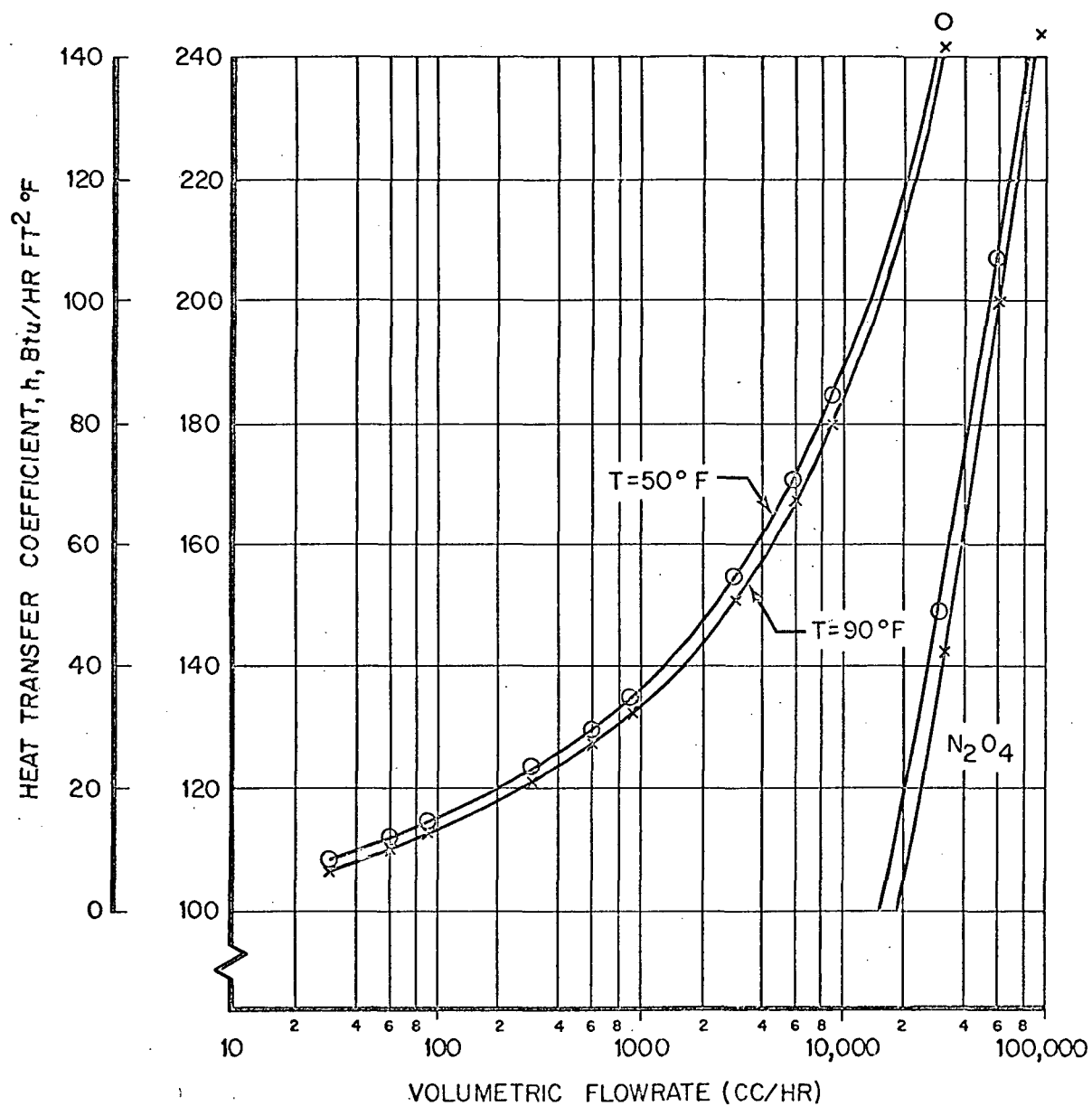
HEAT TRANSFER COEFFICIENT VS. FLOWRATE
BASED ON ULSAMER EQUATION

FIGURE B-4



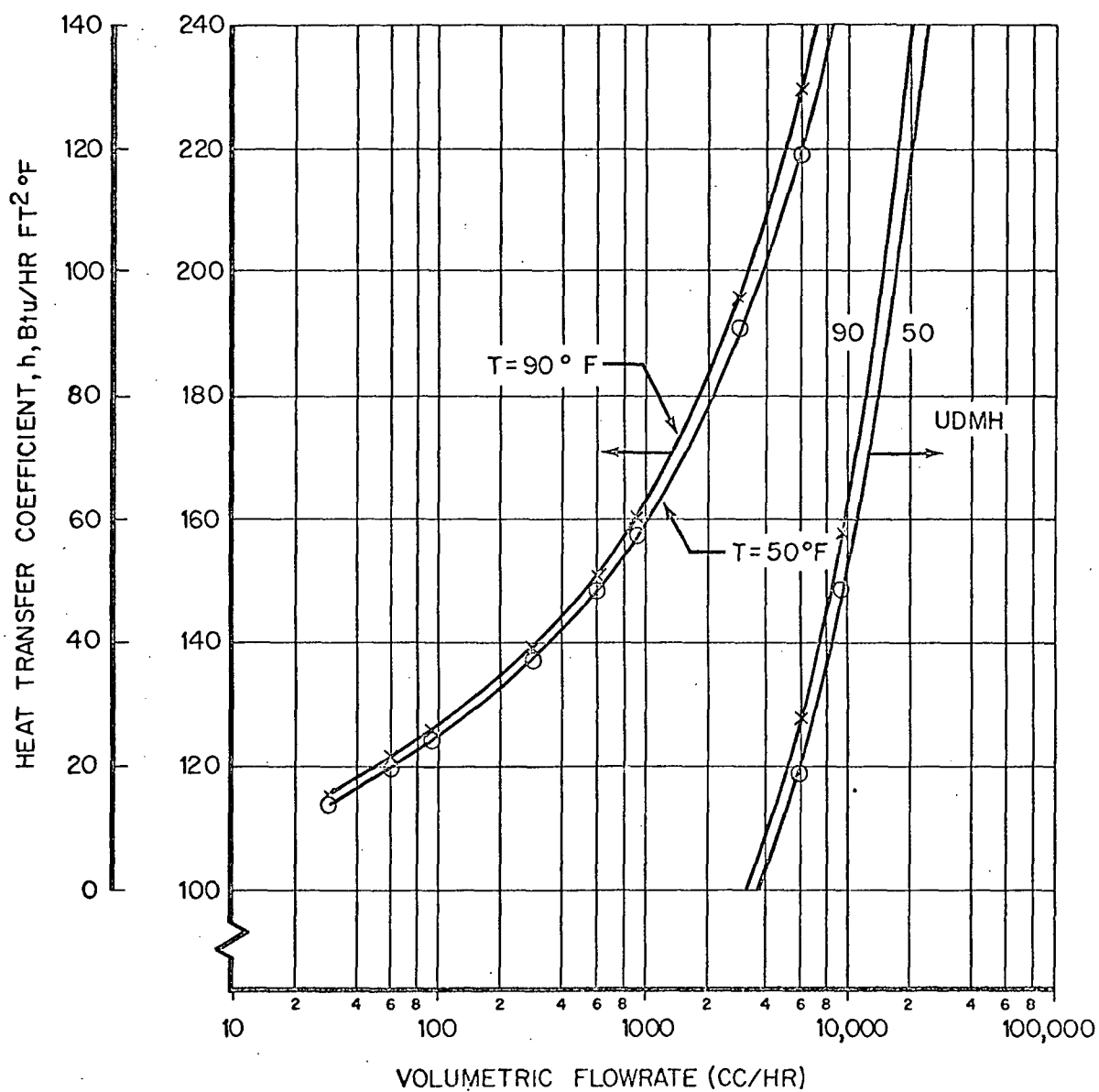
HEAT TRANSFER COEFFICIENT VS. FLOWRATE
 BASED ON ULSAMER EQUATION
 FOR WATER

FIGURE B-5



HEAT TRANSFER COEFFICIENT VS. FLOWRATE
 BASED ON ULSAMER EQUATION
 FOR N_2O_4

FIGURE B-6



HEAT TRANSFER COEFFICIENT VS. FLOWRATE
BASED ON ULSAMER EQUATION
FOR UDMH

FIGURE B-7

Alternate Method of Flow Measuring

If the body has a large thermal conductivity and a corresponding low film heat transfer coefficient, the heat flow from the body is controlled principally by the convection resistance with little or no temperature gradients in the body, i.e., the body is spacewise isothermal with the temperature varying only with time (τ).

The advantages of this approach are:

- (a) Electronic and mechanical implementation appear to be simpler than for the three probe arrangement shown in Figure 9.
- (b) Since the heating of the body will be aperiodic instead of continuous, the effects of free convection currents may be minimized, thus reducing gravity effects. In addition, power requirements may be lowered.

The basic equation for transient cooling is:

$$\frac{\Delta T_1}{\Delta T_0} = e^{-(hA/\rho CV)\tau} \quad (9)$$

where:

ΔT_1 = Temperature difference between heated body and fluid at time $t = \tau$

ΔT_0 = Temperature difference between heated body and fluid at time $t = 0$

ρ = Density of the heated body

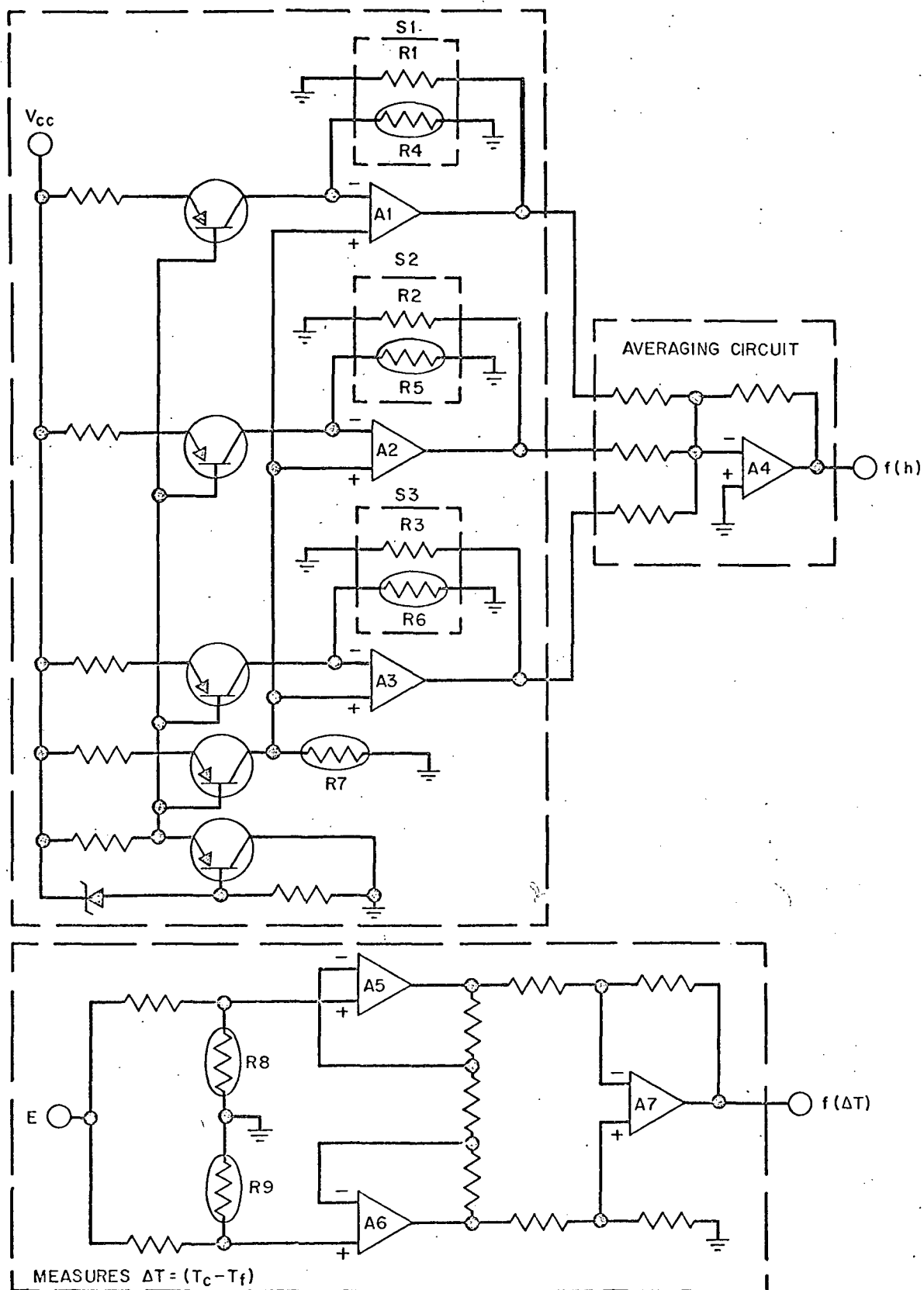
C = Heat capacity of heated body

V = Volume of heated body

A = Surface area of heated body

h = Heat transfer coefficient

τ = Time



SCHEMATIC OF THREE PROBE HEATER-SENSOR SYSTEM

FIGURE 9

Since "h" is the variable to be measured, it is necessary only to keep τ constant and measure $\frac{\Delta T_1}{\Delta T_o}$ or to keep $\frac{\Delta T_1}{\Delta T_o}$ constant and measure τ .

Solving for (τ):

$$\tau = \frac{\rho c V}{h A} \ln \frac{\Delta T(\tau)}{\Delta T_o} \quad \text{for: } \Delta T(\tau) < \Delta T_o \quad (10)$$

or:

$$\tau = \frac{B}{h} \quad (11)$$

where:

$$B = \frac{\rho c V}{A} \ln \frac{\Delta T(\tau)}{\Delta T_o} \quad \text{is a constant if: } \frac{\Delta T(\tau)}{\Delta T_o}$$

and the fluid temperature is maintained a constant.

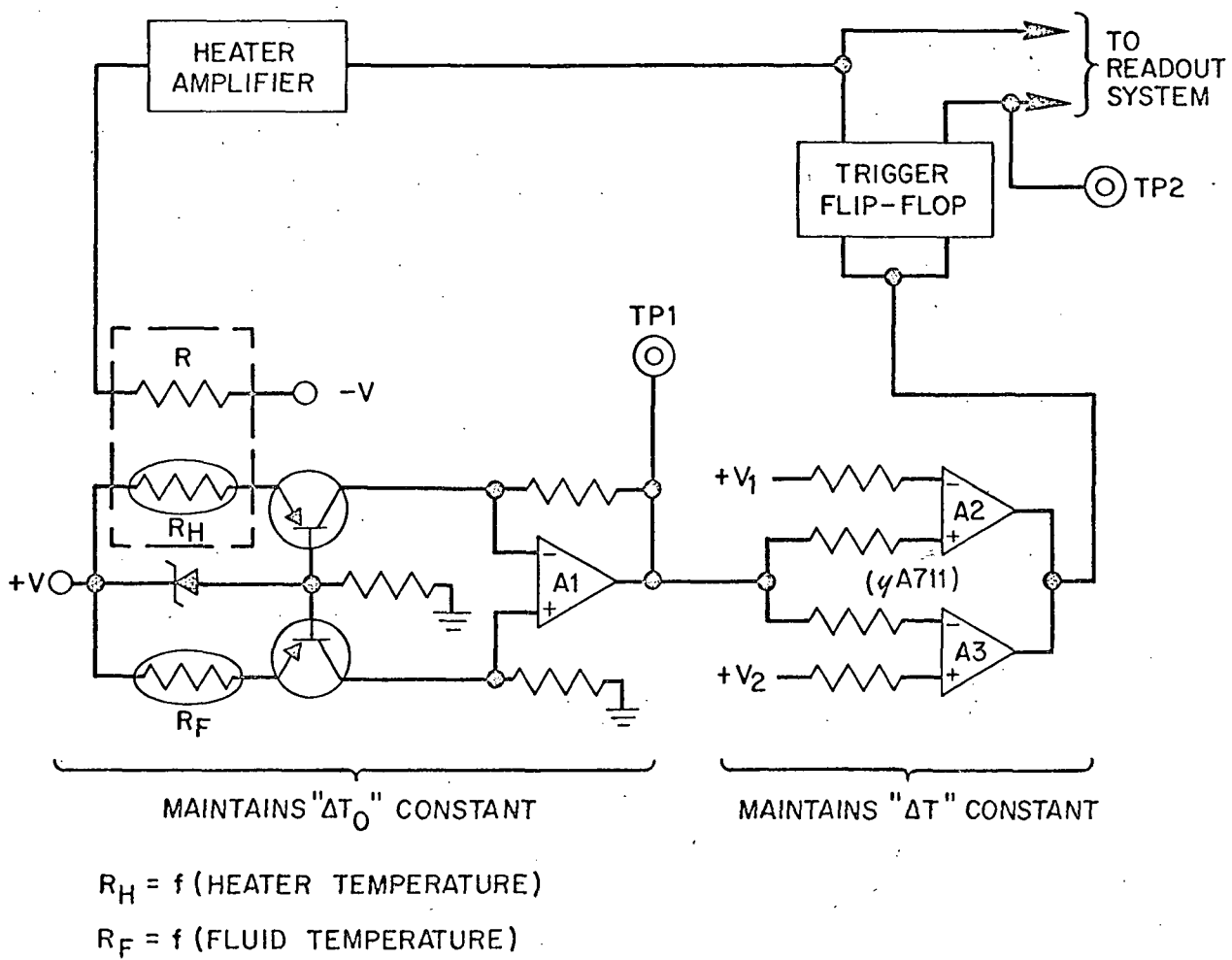
A schematic of the transient response system is shown in Figure B-8.

Amplifier A1 with its constant current drives Q1 and Q2, coupled with comparator A2, maintains a constant temperature differential between the heater resistor "R" and the fluid temperature, i.e., $\Delta T_o = (t_h - t_f)$.

Comparator A3 is biased such that $\Delta T(\tau)$ is a constant. Comparator A2 and A3 are coupled together to form a window discriminator. The outputs are OR'ed to drive a trigger flip-flop. The heater amplifier is a transistor switch which is on when the body is being heated and off when cooling. The waveform of the closed loop system is shown in Figure B-9.

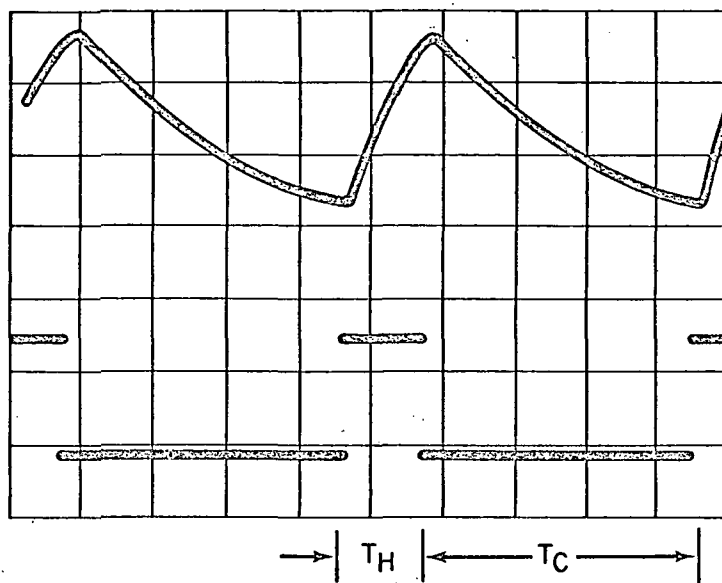
Sensitivity Analysis of the three-probe heater-sensor system.

The principle of flow sensing utilizes the electrothermal technique. The



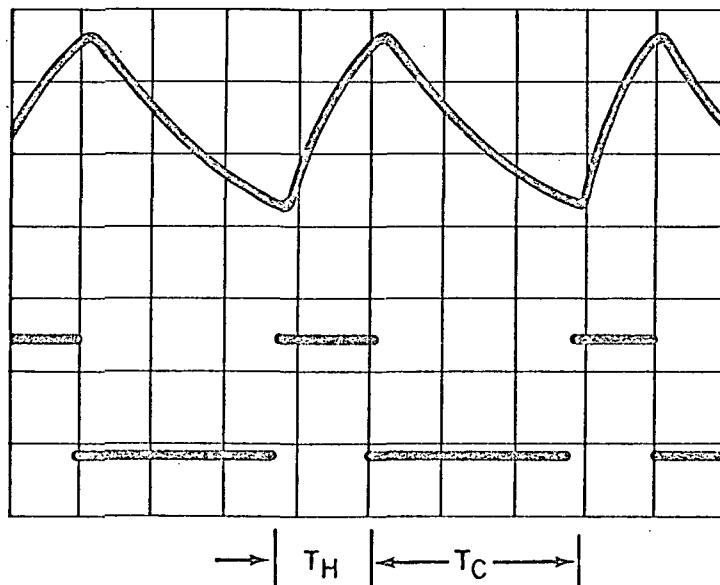
SCHEMATIC OF TRANSIENT RESPONSE SYSTEM

FIGURE B-8



HORIZONTAL DEFLECTION = 5.0 SEC/CM

TRANSIENT RESPONSE SYSTEM FLOW RATE = 0

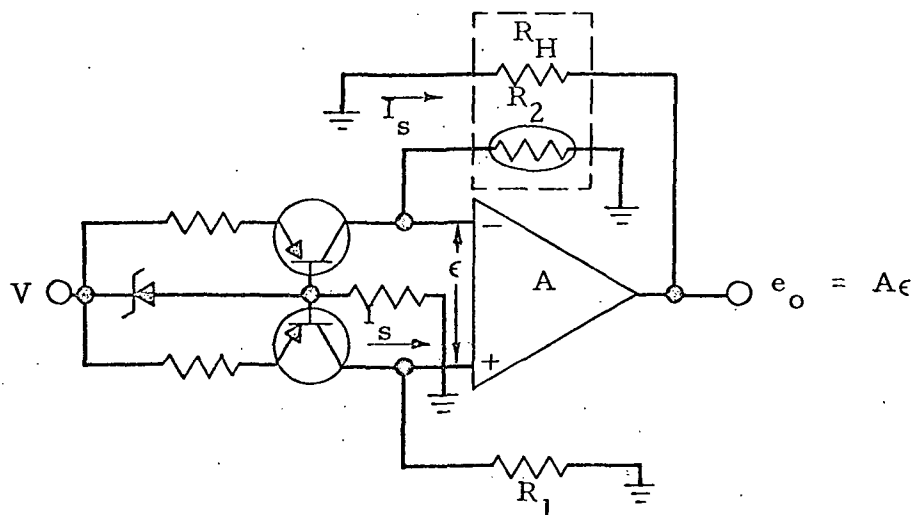


HORIZONTAL DEFLECTION = 5.0 SEC/CM

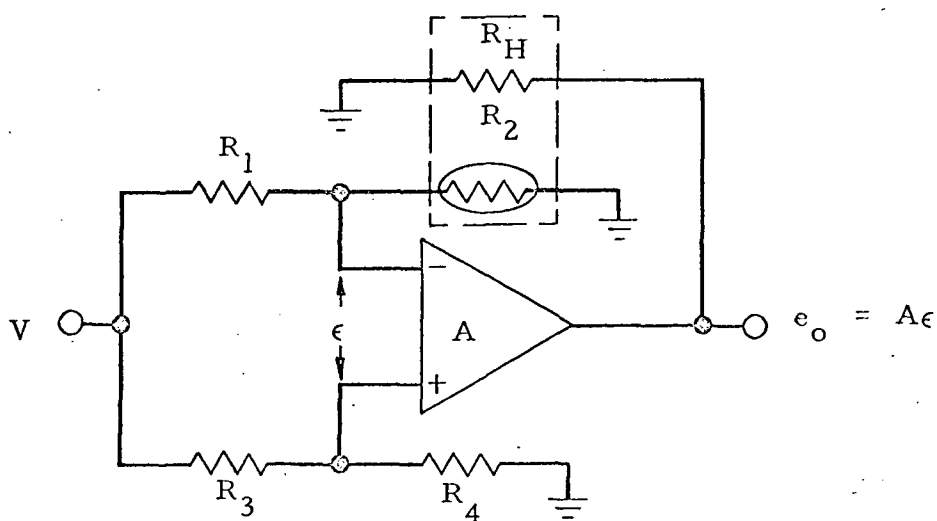
TRANSIENT RESPONSE SYSTEM FLOW RATE = 0.1 FT³/MIN OF N₂

FIGURE B-9

temperature differential $\Delta T = (T_H - T_f)$ is held constant by means of a self-balancing circuit consisting of control amplifiers (A_1 to A_3) and its associated circuits. For the purpose of analysis, the control circuits are shown below in simplified form:



CIRCUIT "A"



CIRCUIT "B"

Assume that the temperature sensitive resistors are not self-heated and their resistance is given by:

$$R_2 = R_o (1 + C\Delta T) \quad (12)$$

where:

C = Temperature coefficient of resistivity and is usually given at 20°C

ΔT = Temperature change from T_o , i.e., $T_H - T_o$

T_H = Heater temperature as sensed by the temperature sensitive resistor (R_2)

T_o = Reference temperature (constant) where the value of R_o is given

The error voltage " ϵ " is zero as long as the flowrate remains constant. If the flowrate changes, the heater temperature changes due to a change in the heat transfer coefficient (h). The circuit becomes unbalanced and an error signal appears which is amplified. The amplified signal increases or decreases the power input to the heater to maintain " ϵ " = 0.

Since the error voltage is a function of temperature changes in the heater, and it is this temperature change that must be detected to keep the system in balance, the sensitivity can be defined as the change in the error voltage " ϵ " due to a change in the heater temperature (T_H).

CIRCUIT "A"

$$\epsilon = I_s (R_1 - R_2) \quad (13)$$

Substituting (12) into (13):

$$\epsilon = I_s [R_1 - R_o (1 + C\Delta T)] \quad (14)$$

By definition, the sensitivity "S" is given by:

$$S = \frac{d\epsilon}{d(\Delta T)} \quad (15)$$

The sensitivity for Circuit "A":

$$S_1 = -I_s R_o C \quad (16)$$

CIRCUIT "B"

$$\epsilon = V \frac{R_4}{R_3 + R_4} - \frac{R_o (1 + C\Delta T)}{R_o (1 + C\Delta T) + R_1} \quad (17)$$

Let $R_1 = R_o$

$$\epsilon = V \frac{R_4}{R_3 + R_4} - \frac{(1 + C\Delta T)}{(2 + C\Delta T)} \quad (18)$$

$$S_2 = - \frac{VC}{(2 + C\Delta T)^2} \quad (19)$$

To obtain a measure of the difference in magnitude of the sensitivities between S_1 and S_2 , values for I_s and V are chosen such that the power dissipated in the sensor be equal at some reference temperature.

Choose the reference temperature such that the sensor resistance $R_2 = R_o$.

The power dissipated in Circuit "A" is:

$$P_{DA} = I_s^2 R_o \quad (20)$$

The power dissipated in Circuit "B" is:

$$P_{DB} = \frac{V^2}{4R_o} \quad \text{for:} \quad R_1 = R_o = R_2 \quad (21)$$

$$\text{Let } P_{DA} = P_{DB}$$

$$I_s = \frac{V}{2R_o} \quad (22)$$

Substituting Equation (22) into (16) and (19), the sensitivities for both methods are:

$$S_1 = \left[\frac{d\epsilon}{d(\Delta T)} \right]_A = -1/2 \quad VC \quad (23)$$

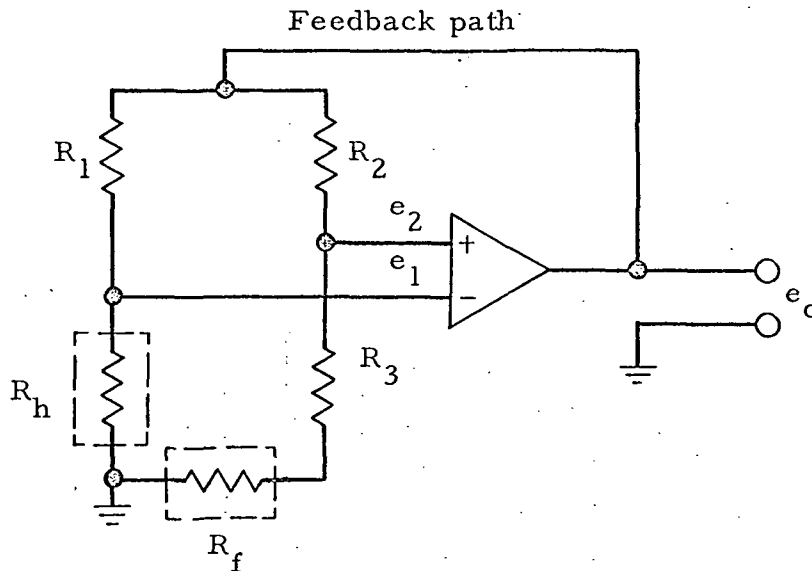
$$S_2 = \left[\frac{d\epsilon}{d(\Delta T)} \right]_B = - \frac{1}{(2 + C\Delta T)^2} \quad VC \quad (24)$$

We note that the sensitivities differ only by their denominator:

For any value of $\Delta T \geq 0$

$$\left[\frac{d\epsilon}{d(\Delta T)} \right]_A \geq \left[2 \frac{d\epsilon}{d(\Delta T)} \right]_B \quad (25)$$

Bridge Circuit Analysis



As a first order approximation, R_1 and R_2 have the following characteristics:

$$R_h = R_{ho} [1 + C (T_h - T_o)] \quad (26)$$

$$R_f = R_{fo} [1 + C (T_f - T_o)] \quad (27)$$

where:

- C = Temperature coefficient of resistivity $\frac{\Omega}{\Omega - ^\circ C}$
- R_{ho} = Resistance at $T_h = T_o$
- R_{fo} = Resistance at $T_f = T_o$
- T_h = Heater Temperature
- T_f = Fluid Temperature
- T_o = Reference Temperature

When the bridge is balanced:

$$e_2 = e_1$$

Therefore:

$$\frac{R_3 + R_f}{R_2 + R_3 + R_f} = \frac{R_h}{R_1 + R_h} \quad (28)$$

which gives:

$$R_f = \frac{R_2}{R_1} R_h - R_3 \quad (29)$$

At any given fluid temperature, Equation (29) must be satisfied. To determine R_{fo} and R_{ho} , substitute Equation (26) and (27) into (29) to give:

$$R_{fo} \frac{1 + C (T_f - T_o)}{R_1} + R_3 = \frac{R_2}{R_1} R_{ho} \frac{1 + C (T_h - T_o)}{R_1} \quad (30)$$

$$\text{Let } T_h = T_f + \Delta T$$

where ΔT is the temperature differential to be kept constant with changes in fluid temperature.

Hence, Equation (30) reduces to:

$$R_{fo} \frac{1 + C (T_f - T_o)}{R_1} + R_3 = \frac{R_2}{R_1} R_{ho} \frac{1 + C (T_f + \Delta T - T_o)}{R_1} \quad (31)$$

Solving for:

$$\frac{d(\Delta T)}{dT_f}$$

$$\frac{d(\Delta T)}{dT_f} = 1 - \frac{R_1 R_{fo}}{R_2 R_{ho}} \quad (32)$$

For ΔT to be constant with changes in fluid temperature (T_f):

$$\frac{d(\Delta T)}{dT_f} = 0 = 1 - \frac{R_1}{R_2} \frac{R_{fo}}{R_{ho}}$$

Hence:

$$R_{fo} = \frac{R_2}{R_1} R_{ho} \quad (33)$$

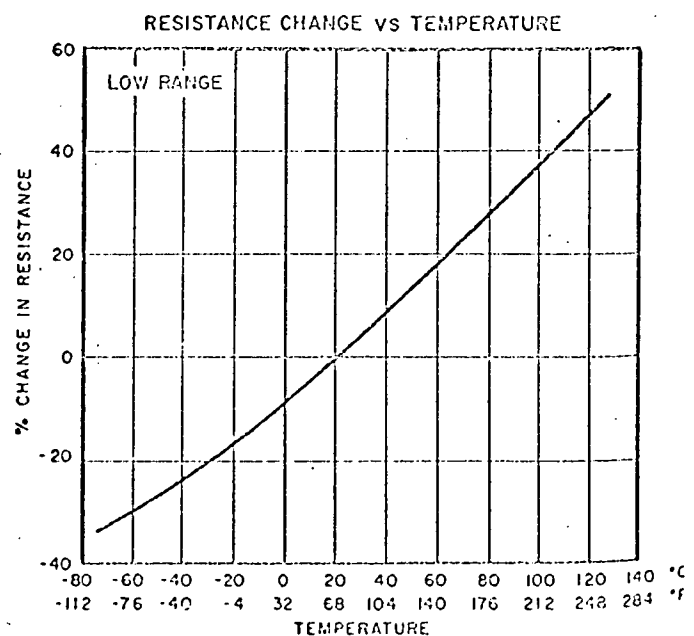
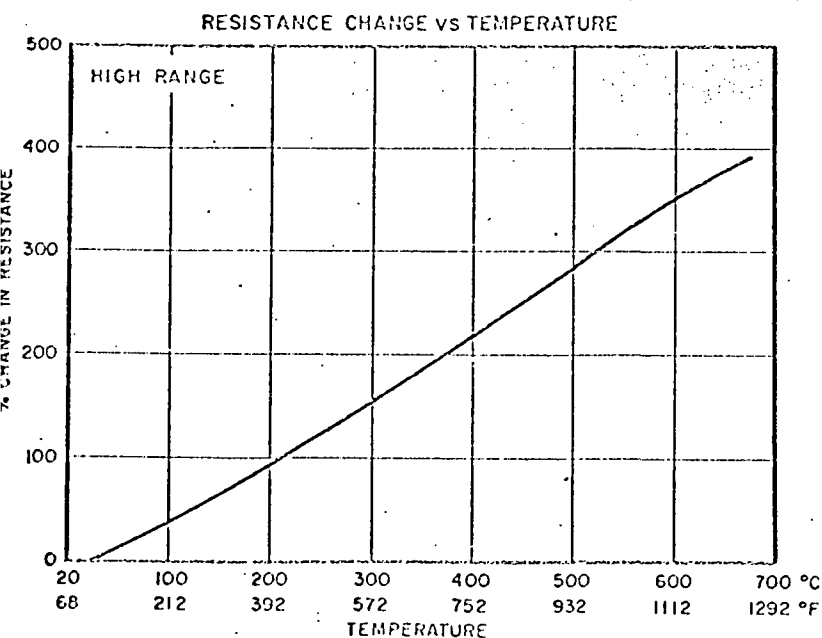
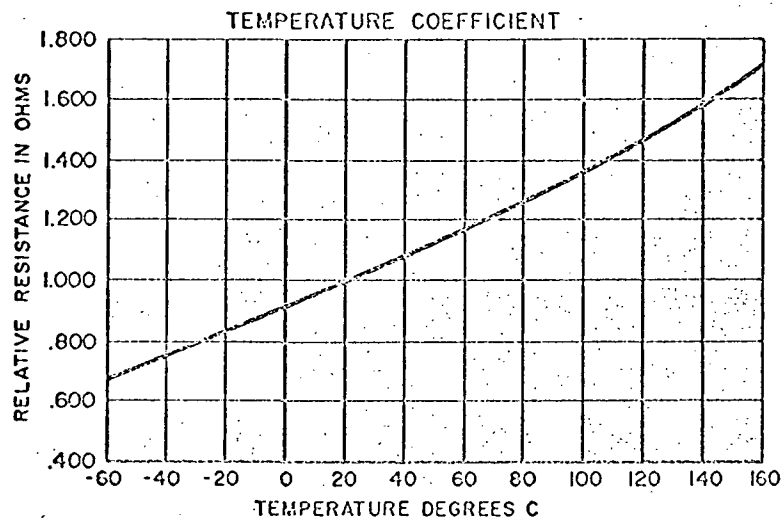
R_3 can be determined from Equations (31) and (33):

$$R_3 = \frac{R_2}{R_1} R_{ho} C \Delta T \quad (34)$$

Equations (33) and (34) are the design equations for the bridge circuit.

TEMPERATURE SENSITIVE RESISTANCE WIRE CHARACTERISTICS

The resistance wire is essentially an alloy of 70% Nickel and 30% Iron. The unique property of this alloy is its high temperature coefficient of resistance. It is 4500 ppm between the temperature range of 0° to 100°C. This alloy can be used in a variety of electronic components utilizing this property.



Resistivity 120 Ohms Per Circular Mil Foot at 20°C. (68°F.)

Wt. Per Cubic Inch = .305 Lbs.

Specific Gravity 8.46

Factors for Determining Resistance at Various Temperatures

Temperature °C.	20	100	200	300	400	500	600	700
Temperature °F.	68	212	392	572	752	932	1112	1292
Factor	1.00	1.40	1.97	2.65	3.33	3.93	4.48	4.98

B & S	Dia. in Inches	Ohms Per Ft. at 20°C. (68°F.)	Pounds Per M Feet	Feet Per Pound Bare Wire	Ohms Per Pound Bare Wire
30	.010	1.2000	.2873	3,481.0	4,177.0
31	.0089	1.515	.2276	4,394.0	6,657.0
32	.008	1.875	.1839	5,438.0	10,200.0
33	.0071	2.380	.1448	6,906.0	16,440.0
34	.0063	3.022	.1140	8,772.0	26,510.0
35	.0056	3.826	.09011	11,000.0	42,090.0
36	.005	4.800	.07184	13,920.0	66,820.0
37	.0045	5.926	.05816	17,190.0	101,900.0
38	.004	7.500	.04598	21,750.0	163,100.0
39	.0035	9.796	.03517	28,430.0	278,500.0
40	.0031	12.49	.02758	36,260.0	452,900.0
	.00275	15.86	.02172	46,029.0	730,342.0
	.0025	19.20	.01795	55,696.0	1,069,363.0
	.00225	23.70	.01454	68,760.0	1,629,612.0
	.002	30.00	.01149	87,025.0	2,610,750.0
	.00175	39.18	.00879	113,665.0	4,453,394.0
	.0015	53.33	.00646	154,711.0	8,250,737.0
	.0014	61.22	.00563	177,602.0	10,872,794.0
	.0013	71.01	.00485	205,976.0	14,626,355.0
	.0012	83.33	.00413	241,736.0	20,143,860.0
	.0011	99.17	.00347	287,685.0	28,530,584.0
	.001	120.00	.00287	348,100.0	41,722,000.0
	.0009	148.2	.00233	429,800.0	63,696,000.0
	.0008	187.5	.00184	543,800.0	101,960,000.0
	.0007	244.9	.00141	710,000.0	173,900,000.0
	.0006	333.3	.00103	967,000.0	322,300,000.0
	.0005	480.0	.00072	1,392,000.0	668,200,000.0

PHYSICAL CHARACTERISTICS

NOMINAL ANALYSIS

Per Cent 70 Nickel - 30 Iron

SPECIFIC RESISTIVITY

Ohms CMF 120

Microhm CM 19.9

TEMPERATURE COEFFICIENT OF RESISTANCE

Parts Per Million, + 25° C. to + 100° C. 4500

Parts Per Million, + 25° C. to - 50° C. 3900

SPECIFIC GRAVITY 8.46

POUNDS PER CUBIC INCH305

COEFFICIENT OF LINEAR EXPANSION

20° - 100° C.000015

THERMAL CONDUCTIVITY

Watts/CM/°C.289

SPECIFIC HEAT

Grams Calories125

APPROXIMATE MELTING POINT

° Centigrade 1425

MAGNETIC ATTRACTION Strong

MAXIMUM OPERATING TEMPERATURE

° Centigrade 593

TENSILE STRENGTH AT 20° C.

Pounds per sq. in. Max. 150,000

Min. 70,000

THERMAL CONDUCTIVE EPOXY

PRELIMINARY TECHNICAL BULLETIN 3-2-17

ECCOBCND 285

Thixotropic General Purpose Epoxide Adhesive

Eccobond 285 is a highly versatile general purpose adhesive which may be cured with any one of three curing agents. All curing agents impart some degree of thixotropy to the uncured material even at elevated temperatures. This property virtually insures freedom from sag or runs on vertical or overhead surfaces or runout when applied to loose fitting mating parts such as pipe joints.

Eccobond 285, when cured, produces a rigid, high strength bond to most materials including metals, glass, ceramics, and most plastics. Being a 100% solid adhesive, it performs equally well on porous or non-porous surfaces.

Eccobond 285, when cured, has two outstanding properties which should be of special interest in many applications. The coefficient of thermal expansion of Eccobond 285 is well matched to brass, copper, and aluminum and generally much lower than commonly available adhesives. The thermal conductivity is high. This combination works well to overcome bond failure due to thermal cycling.

TYPICAL PROPERTIES: Bond Shear Strength, 1" overlap, psi

Room Temp.

2,100

-70° F

1,800

+200° F

1,400

Bond Shear Strength, after 30 days immersion in water

Unaffected

Flexural Strength, psi

15,000

Thermal Conductivity, BTU/ft. ²/hr./°F/in.

4.5

Coefficient of thermal expansion, per °F

15 x 10⁻⁶

Volume Resistivity, ohm-cm

Room Temp.

10¹⁶

+200° F

10¹³

CHOICE OF CURING AGENT: From the information supplied below select that catalyst which best suits your requirements.

CATALYST 24 LV Room temperature cure - 30 minute pot life - lowest thixotropy and viscosity - improved thermal and mechanical shock - not recommended for applications subjected to temperatures above 300°F - will soften slightly above 250°F.

CATALYST 9 Room temperature cure - 45 minute pot life - highest thixotropy and viscosity - paste-like consistency - can be applied to vertical or overhead surfaces in thick sections without flow or sag - may be used up to 300°F.

CATALYST 11 Requires oven cure - 4 hour pot life - high thixotropy with medium viscosity - paste-like consistency - will not flow under application of heat during cure - may be used up to 350°F continuous duty with short time exposures to 400°F.

INSTRUCTIONS FOR USE: General Instructions: Roughen, mating surfaces with emery cloth or other suitable abrading material to remove oxidation, scale, paint or other foreign matter and degrease with solvent such as toluene or trichlorethylene.

If using Catalyst 24 LV

1. Add and thoroughly blend 7 to 8 parts of Catalyst 24 LV by weight for each 100 parts of Eccobond 285.
2. Apply to both surfaces to be bonded - mate surfaces and squeeze out excess.
3. Cure at any of the following schedules:
24 hours at room temperature 6 hours at 100° F 30 minutes at 200° F

If using Catalyst 9

1. Add and thoroughly blend 3 to 4 parts of Catalyst 9 by weight for each 100 parts of Eccobond 285.
2. Apply to both surfaces to be bonded - mate surfaces and squeeze out excess.
3. Cure at any one of the following schedules:
24 hours at room temperature 6 hours at 100° F 30 minutes at 250° F

If using Catalyst 11

1. Add and thoroughly blend 4 to 5 parts of Catalyst 11 by weight to 100 parts of Eccobond 285.
2. Apply to both surfaces to be bonded - mate surfaces and squeeze out excess.
3. Cure at any one of the following schedules:
8 hours at 150° F 2 hours at 250° F 20 minutes at 375° F

Propellant to Water Conversion

This analysis calculates the water flowrates that will give the same signal as the propellants under RCS operation. Since:

$$h = 0.60 \frac{K_f}{D_o} (N_{Re})^{0.50} (N_{Pr})^{0.31} \quad (35)$$

or:

$$h = 0.60 \frac{K_f}{D_o} \left(\frac{\rho V D}{\mu} \right)^{0.50} \left(\frac{C_p \mu}{K_f} \right)^{0.31} \quad (36)$$

or:

$$h = 0.60 \frac{K_f^{0.69}}{\mu^{0.19}} \left(\frac{\rho V}{D_o} \right)^{0.50} C_p^{0.31} \quad (37)$$

The flowmeter signal will be identical when the heat transfer coefficients are the same. Rewriting the equation for heat transfer coefficient:

$$\rho V = \frac{1.667 h \mu^{0.19} D_o^{0.50}}{K_f^{0.69} C_p^{0.31}} \quad (38)$$

Using subscript "p" for propellant, we can write:

$$\frac{(\rho V)_W}{(\rho V)_P} = \frac{\mu_W^{0.19} K_{fP}^{0.69} C_{pP}^{0.31}}{\mu_P^{0.19} K_{fW}^{0.69} C_{pW}^{0.31}} \quad (39)$$

For the oxidizer at 70°F:

$$\left(\frac{\mu_W}{\mu_P}\right)^{0.19} = 0.762 \quad (40)$$

$$\left(\frac{K_{fP}}{K_{fW}}\right)^{0.69} = 0.352 \quad (41)$$

$$\left(\frac{C_{PP}}{C_{PW}}\right)^{0.31} = 0.733 \quad (42)$$

Combining these ratios shows that 0.88 lbs/sec of N_2O_4 may be simulated by 0.173 lbs/sec of water.

Similarly we find that for UDMH 0.44 lbs/sec may be simulated by 0.224 lbs/sec of water. These mass flowrates are equal to 283,000 cc/hr and 366,000 cc/hr, respectively.

APPENDIX C

TEST DATA

THIS APPENDIX CONTAINS THE
DATA OBTAINED DURING
PROPELLANT FLOW TESTS

PROPELLANT: N_2O_4

TEMPERATURE (°F)	FLOW RATE (CC/HR)	e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
64.6	0	9.94	-	No pressure
64.6	0	9.86	-	Pressurized
66.8	0	9.65	-	Pressurized
63.0	0	9.93	-	Pressurized
64.9	0	9.88	-	Pressurized
73.0	0	10.00	-	No pressure
73.0	0	9.72	-	Pressurized
72.5	0	9.70	-	
78.8	0	9.48	-	
66.1	10	9.73	-	
66.1	15	9.90	-	
65.0	20	9.90	-	
66.5	24	9.60	-	
74.0	25	9.57	-	
71.0	30	9.70	-	
74.2	31.3	9.54	1 m 55 s	
64.0	43.4	9.80	1 m 23 s	
72.0	84.8	9.70	42.5 s	
67.0	100	10.00	36 s	
79.0	144	9.62	50 s	
73.0	153	9.80	47 s	
67.0	195	10.00	37 s	↓

PROPELLANT: $N_2 O_4$

TEMPERATURE (°F)	FLOW RATE (CC/HR)	e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
72.0	324	10.59	18 m 30 s	Pressurized
65.5	480	10.20	15 s	
65.3	480	10.16	15 s	
68.0	494	11.40	73 s	
67.0	514	9.83	14 s	
73.0	533	10.10	13.5 s	
74.8	600	10.20	12 s	
74.0	600	9.90	12 s	
66.9	654	10.12	11 s	
67.4	845	10.26	8.5 s	
65.8	847	10.80	8.5 s	
73.5	900	9.58	4 s	
72.5	1440	10.34	5 s	
67.8	1600	10.66	9 s	
65.0	1690	10.60	8.5 s	
68.0	1690	10.60	8.5 s	
67.2	2400	10.73	6 s	
65.5	2400	10.76	6 s	
76.5	2570	11.18	2 m 20 s	
69.0	2620	10.75	5.5 s	
79.0	2880	10.76	5 s	
73.0	3000	11.00	2 m	

PROB. FLANT: N_2O_4

TEMPERATURE (°F)	FLOW RATE (CC/HR)	e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
75.0	3320	10.90	6.5s	Pressurized
79.0	3350	10.95	4.3s	
69.0	3510	10.87	4.1s	
67.5	4500	10.96	4.8s	
75.1	4500	11.22	4.8s	
74.1	4500	10.80	4.8s	
65.6	4630	11.16	6.2s	
68.2	4800	11.08	6 s	
77.5	6200	11.30	58 s	
75.0	6920	11.10	5.2s	
67.0	7200	11.42	5 s	
68.3	7500	11.30	4.8s	
76.2	8300	11.10	2.6s	
73.0	8680	11.56	8.3s	
80.0	9000	11.40	7.2s	
72.5	9000	11.40	4 s	
76.0	9960	11.30	5.2s	
70.0	11200	11.60	5.8s	
70.0	11240	11.30	3.2s	
68.0	12000	11.70	6 s	
76.0	12800	11.80	2.8s	
76.5	13270	11.90	3.8s	

●

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
61.22	25	10.18		
61.8	38.7	10.12		
59.0	55.4	10.23		
59.0	138.5	10.37		
59.1	160	10.58		
60.0	209	10.38		
63.0	218	10.47		
59.2	272	10.44		
61.8	334	10.32		
59.0	389	10.47		
62.4	400	10.54		
60.0	496	10.50		
63.0	533	10.63		
61.8	554	10.50		
62.4	600	10.56		
58.9	720	10.67		
59.0	720	10.56		
61.5	960	10.49		
59.0	960	10.58		
59.0	1350	10.68		
59.0	1368	10.64		
58.8	1440	10.68		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
59.2	1440	10.78		
62.8	1800	10.71		
61.8	1960	10.80		
62.7	2160	10.90		
61.0	2395	10.86		
59.0	2400	10.90		
59.0	2540	10.80		
62.0	3180	10.94		
61.8	3270	10.90		
59.0	3600	11.00		
59.0	4000	10.47		
59.2	4110	11.06		
58.8	4115	10.98		
59.0	4800	11.06		
59.0	4910	11.03		
62.1	5040	11.13		
59.0	5490	10.90		
59.0	5800	11.20		
62.1	6540	11.24		
62.1	6540	11.10		
62.0	6960	11.16		
63.0	7200	11.24		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e _o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
62.0	8,220	11.25		
61.8	9,000	11.15		
62.7	9,900	11.30		
59.0	12,600	11.90		
63.1	13,500	11.86		
61.8	14,600	12.40		
62.2	17,600	11.90		
62.8	21,800	12.00		
62.2	25,900	11.80		
59.0	30,000	12.14		
63.2	34,300	12.17		
62.1	40,300	11.99		
73.0	45,000	11.25		
58.0	48,000	12.26		
73.5	50,300	11.98		
64.5	60,000	12.32		
75.0	72,000	12.14		
73.0	72,000	12.16		
70.0	75,800	12.26		
73.0	77,200	12.20		
58.5	72,000	12.48		
63.0	92,400	12.50		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e _o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
59.0	128,500	12.78		
70.5	223,500	12.60		
64.5	231,000	12.81		
73.0	253,000	12.56		
74.5	296,000	12.60		
62.6	380,000	12.96		
76.0	554,000	12.74		
64.5	576,000	13.00		
58.5	582,000	13.07		
59.8	581,000	13.05		
71.5	617,000	12.82		
74.0	626,000	12.77		
63.0	655,000	13.06		
61.7	758,000	13.08		
64.5	900,000	13.08		
64.5	960,000	13.08		
71.5	960,000	12.86		
73.0	1,030,000	12.84		
74.0	1,110,000	12.83		
72.0	1,260,000	12.90		
59.8	1,355,000	13.18		
62.0	1,440,000	13.16		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
73.0	1,440,000	12.86		
75.0	1,520,000	12.88		
71.5	1,600,000	12.90		
71.5	1,950,000	12.91		
63.5	2,220,000	13.18		
67.7	0	10.02		
71.5	0	10.14		
74.0	0	10.13		
75.5	0	10.07		
57.0	0	10.24		
58.0	0	10.23		
59.0	0	10.13		
73.5	0	10.11		
68.0	0	10.28		
69.0	0	10.15		
70.0	0	10.12		
70.0	0	10.12		
70.0	0	10.14		
70.0	0	10.14		
70.0	0	10.14		
72.0	2900	10.66		
58.0	4090	11.08		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	LOW e _o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
57.5	4,340	11.14		
58.0	5,380	11.24		
72.0	6,000	11.12		
64.4	6,430	11.40		
73.0	6,730	11.20		
73.0	6,730	11.14		
64.4	8,280	11.50		
72.5	8,380	11.40		
73.0	8,380	11.36		
66.5	12,000	11.40		
58.0	12,000	11.76		
58.0	20,000	11.89		
58.0	21,200	11.86		
58.0	22,500	12.00		
73.0	23,500	11.65		
74.0	24,000	11.66		
64.5	24,000	11.90		
58.0	25,100	12.08		
73.0	30,000	11.75		
68.0	34,300	11.90		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
61.2	25	10.16		
61.8	38.7	10.18		
59.0	55.4	10.10		
59.0	138.5	10.10		
59.1	160	9.53		
60.0	209	10.08		
63.0	218	10.19		
59.2	272	9.78		
61.8	334	10.17		
59.0	389	10.12		
62.4	400	10.88		
60.0	496	10.14		
63.0	533	10.27		
61.8	554	10.26		
62.4	600	10.29		
58.9	720	9.84		
59.0	720	10.13		
61.5	960	--		
59.0	960	10.14		
59.0	1350	10.09		
59.0	1368	10.12		
58.8	1440	10.10		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
59.2	1,440	10.10		
62.8	1,800	10.27		
61.8	1,960	10.23		
62.7	2,160	10.23		
61.0	2,395	10.14		
59.0	2,400	10.20		
59.0	2,540	10.14		
62.0	3,180	10.25		
61.8	3,270	10.10		
59.0	3,600	10.38		
59.0	4,000	10.10		
59.2	4,110	9.99		
58.8	4,115	10.17		
59.0	4,800	10.20		
59.0	4,910	10.10		
62.1	5,040	10.13		
59.0	5,490	10.11		
59.0	5,800	10.25		
62.1	6,540	10.50		
62.1	6,540	10.40		
62.0	6,960	10.34		
63.0	7,200	10.40		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_0 (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
62.0	8,220	10.32		
61.8	9,000	10.34		
62.7	9,900	10.60		
59.0	12,600	10.50		
63.1	13,500	10.51		
61.8	14,600	11.30		
62.2	17,600	10.65		
62.8	21,800	10.74		
62.2	25,900	10.64		
59.0	30,000	10.80		
63.2	34,300	10.88		
62.1	40,300	--		
73.0	45,000	10.30		
58.0	48,000	11.08		
73.5	50,300	10.99		
64.5	60,000	11.12		
75.0	72,000	11.14		
73.0	72,000	11.19		
70.0	75,800	11.14		
73.0	77,200	11.13		
58.5	72,000	11.30		
63.0	92,400	11.30		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_0 (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
59.0	128,500	11.59		
70.5	223,500	11.58		
64.5	231,000	11.64		
73.0	253,000	11.55		
74.5	296,000	10.58		
62.6	380,000	11.79		
76.0	554,000	11.72		
64.5	576,000	11.85		
58.5	582,000	11.90		
59.8	581,000	11.89		
71.5	617,000	11.84		
74.0	626,000	11.76		
63.0	655,000	11.89		
61.7	758,000	11.92		
64.5	900,000	11.93		
64.5	960,000	11.89		
71.5	960,000	11.80		
73.0	1,030,000	11.84		
74.0	1,110,000	11.82		
72.0	1,260,000	11.92		
59.8	1,355,000	12.03		
62.0	1,440,000	12.02		

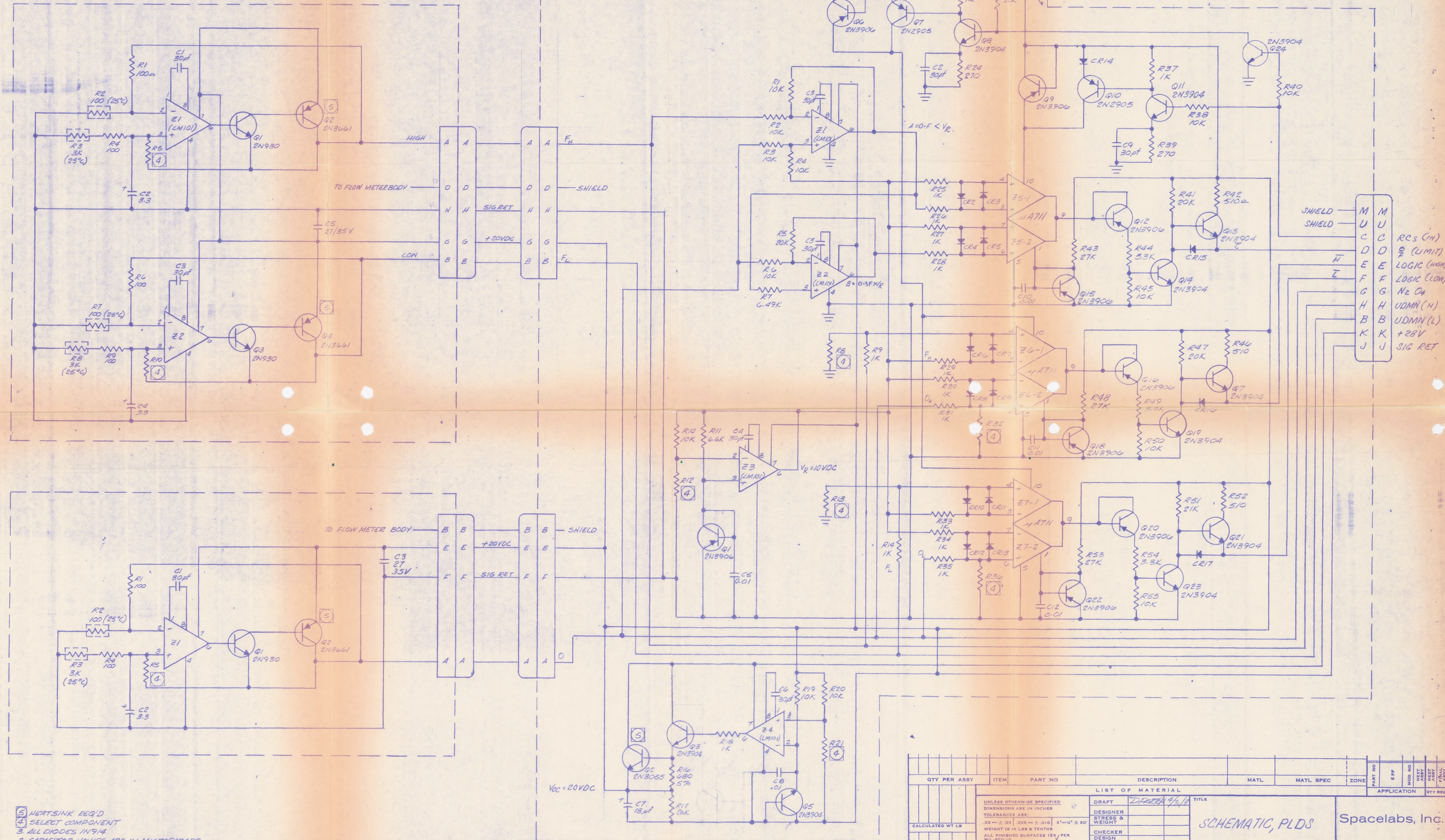
PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_o (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
73.0	1,440,000	11.89		
75.0	1,520,000	11.88		
71.5	1,600,000	--		
71.5	1,950,000	11.90		
63.5	2,220,000	12.08		
67.7	0	10.18		
71.5	0	10.24		
74.0	0	10.13		
75.5	0	10.24		
57.0	0	10.14		
58.0	0	10.20		
59.0	0	10.16		
73.5	0	10.12		
68.0	0	10.15		
69.0	0	10.11		
70.0	0	10.31		
70.0	0	10.19		
70.0	0	10.16		
70.0	0	10.18		
70.0	0	10.19		
72.0	2,900	10.15		
58.0	4,090	10.30		

PROPELLANT: UDMH

TEMPERATURE (°F)	FLOW RATE (CC/HR)	HIGH e_0 (VOLTS)	SAMPLING DURATION (MIN - SEC)	COMMENTS
57.5	4,340	10.30		
58.0	5,380	10.30		
72.0	6,000	10.24		
64.4	6,430	10.37		
73.0	6,730	10.38		
73.0	6,730	10.28		
64.4	8,280	10.35		
72.5	8,380	10.50		
73.0	8,380	10.49		
66.5	12,000	10.46		
58.0	12,000	10.58		
58.0	20,000	10.76		
58.0	21,200	10.74		
58.0	22,500	10.80		
73.0	23,500	10.66		
74.0	24,000	10.66		
64.5	24,000	10.70		
58.0	25,100	10.83		
73.0	30,000	10.80		
68.0	34,300	10.84		

REVISIONS									
DISPOSITION CODE:		1 MAY BE REWORKED	2 CANNOT BE REWORKED	3 RECORD CHANGE					
REV	SYM	WORD	CODE	DESCRIPTION	MFG	EFF	PART	ASSY	DATE



QTY PER ASSY	ITEM	PART NO	DESCRIPTION	MATL	MATL SPEC	ZONE	PART NO	EFF	MOD NO	TEST	RETEST	QTY REQ
LIST OF MATERIAL												
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: XX = ±.03, XXX = ±.010, X" = 0" ±.30 WEIGHT IS IN LBS & TENTHS ALL FINISHED SURFACES 125 PER MIL-STD-10			DRAFT	DESIGNER	STRESS & WEIGHT	CHECKER	DESIGN	ENG	MFG ENG	STDS ENG	PROJ ENG	
MFR PER SPEC												
TOLERANCE SYMBOLS PER MIL-STD-8 ELECTRICAL SYMBOLS PER MIL-STD-15 MECHANICAL SYMBOLS PER MIL-STD-17 WELDING SYMBOLS PER JAN-STD-19												
REFERENCE TO SIMILAR DWG												
DWG SIZE												
PART NO												
CALCULATED WT LB												
TITLE			SCHEMATIC, PLDS									
DWG NO			Spacelabs, Inc.									
RELEASE DATE												
SCALE			None									
SHEET			1 OF 1									