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DEVELOPMENT OF HIGH RESPONSE
CRYOGENIC GAS FLOWMETERS

Final Report
March 1971

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Contract No. NAS9-11317

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FOREWORD

This report was prepared by Rocketdyne, a Division of North American Rockwell Corporation, Canoga Park, California, under NASA Contract NAS9-11317, "Development, Fabrication and Documentation of Gas Flowmeters". A period of effort from 25 September 1970 to 19 March 1971 is covered by the overall program.

ABSTRACT

This report describes the results of a research and development effort oriented toward producing two high response, drag-body flowmeters for cryogenic gas application. Operating temperature range of the flowmeters is within -300°F to $+100^{\circ}\text{F}$. Flowrate range is zero to one pound per second of gaseous hydrogen for one meter and zero to two pounds per second of gaseous oxygen for the other. The flowmeters are velocity head (PV^2) devices and are modifications of meters previously developed by Rocketdyne for liquid application.

CONTENTS

Foreword	i
Abstract	i
Illustrations.	iii
Introduction and Summary	1
Design Criteria.	5
Bending Beam and Target Dimensions.	5
Flowmeter Body Dimensions	5
Material Selection.	7
Electrical Description.	7
Results of Research and Development Effort	10
Zero Balance Temperature Compensation	10
Temperature Compensation for Span	11
Thermal Gradient Effects.	12
Frequency Response.	16
Cryogenic Gas Application	17
Calibration	23
Table I - Calibration Data	27
Conclusions.	28

ILLUSTRATIONS

1. Gaseous Oxygen Flowmeter.	2
2. Gaseous Hydrogen Flowmeter.	3
3. Flowmeter Sensor-Housing.	4
4. Flowmeter Electrical Schematics	6
5. Zero Balance Characteristics of S/N 9	8
6. Zero Balance Characteristics of S/N 10.	9
7. Output Temperature Sensitivity.	13
8. Thermal Gradient Response (No Insulation)	15
9. Thermal Gradient Response (Beam Insulated).	15
10. Undamped Natural Frequency of S/N 9	18
11. Undamped Natural Frequency of S/N 10.	18
12. Response to Ambient GN_2 Pulses.	19
13. Response to Ramp-Unload - S/N 9	20
14. Response to Ramp-Unload - S/N 10.	20
15. Small Volume Feed System Resonance.	21
16. Flow Bench Schematic.	22
17. Response to Cryogenic GN_2 Pulses.	24
18. Flow Coefficient Curve for S/N 9.	25
19. Flow Coefficient Curve for S/N 10	26

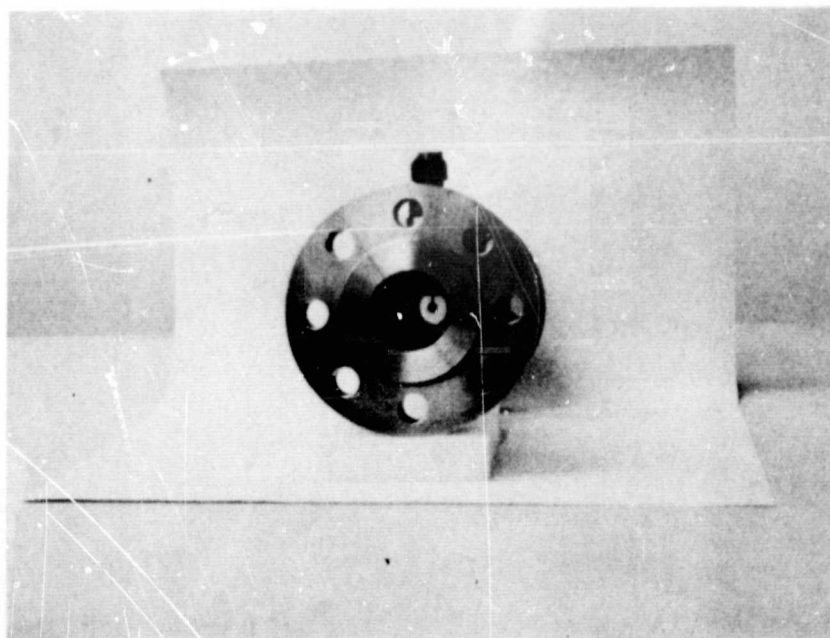
INTRODUCTION AND SUMMARY

The need for high response (1K Hz) flowmeters for gaseous propellant application has been dictated by the development of rocket engines for pulse-mode operation. Rocketdyne had previously developed a high response flowmeter for pulse-mode liquid propellant application, and preliminary investigations had indicated that the liquid meter could be modified for gaseous applications (Ref. 1).*

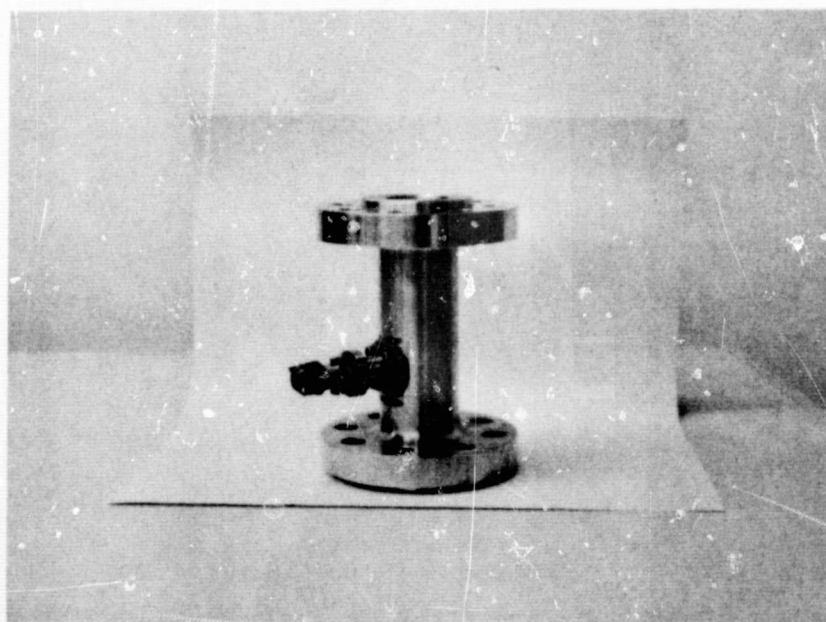
Accordingly, the Thermodynamics Laboratory of NASA's Manned Spacecraft Center funded an effort for the modification of Rocketdyne's liquid flowmeter for pulsed gas application. The effort was oriented toward furnishing the customer with two flowmeters, one each for gaseous hydrogen and oxygen application.

The following sections of this report present design criteria and the results of the limited research and development effort which resulted in the fabrication and delivery of the two flowmeters (see Figs. 1, 2 & 3). For further information on these flowmeters, the reader is referred to Rocketdyne Report R-8474, "Operating Manual for NASA Cryo-Gas Flowmeters," March 1971.

*Ref. 1: RPP-847, "Development of High Response Flowmeters for Cryogenic Gas Application," 16 March 1970, Revised 25 May 1970



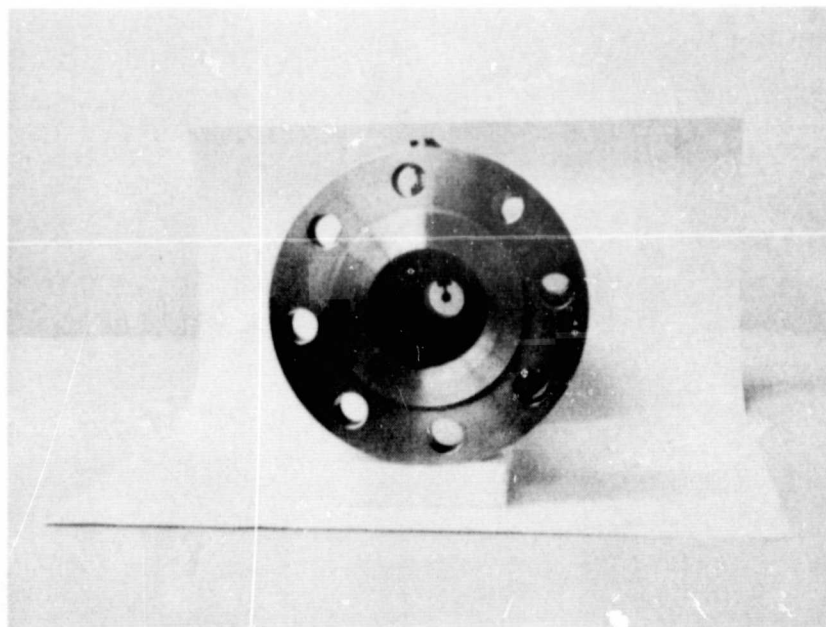
a. End View



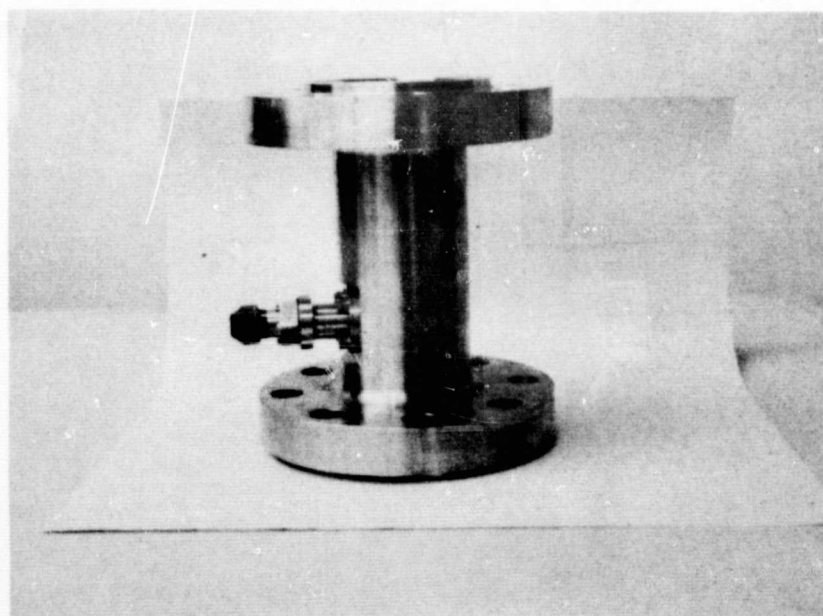
b. Side View

Figure 1. Gaseous Oxygen Flowmeter

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a. End View



b. Side View

Figure 2. Gaseous Hydrogen Flowmeter

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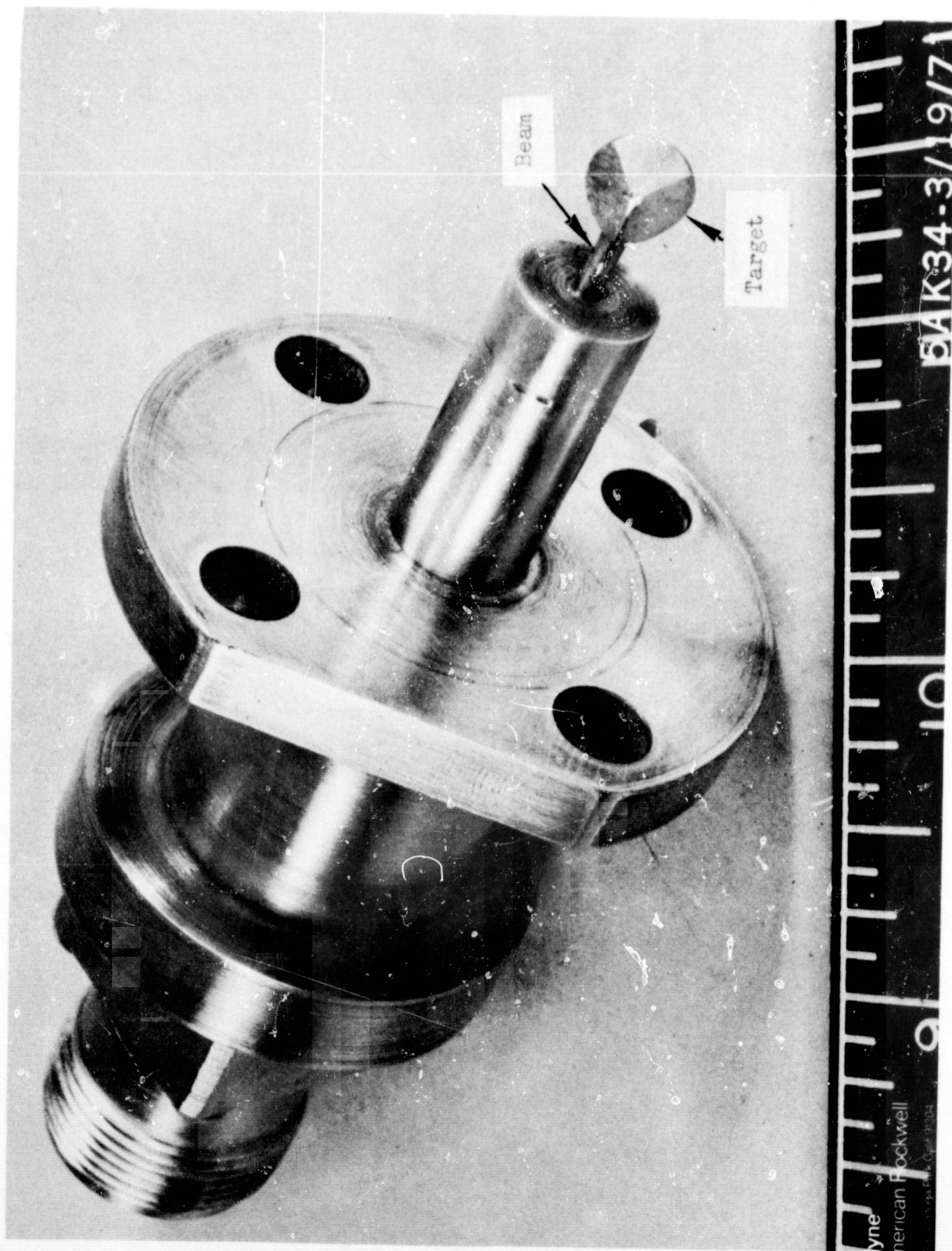


Figure 3. Flowmeter Sensor-Housing

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DESIGN CRITERIA

The various design elements are discussed generally in terms of performance requirements and the trade-offs involved.

BENDING BEAM AND TARGET DIMENSIONS

Previous work (liquid flowmeters) dictated that a beam length of 0.350" and a target diameter of 0.300" would best approach the 4000 to 5000 Hz natural frequency goal. Increased beam length or target size reduces f_n , whereas decreasing these two parameters results in lower output sensitivity.

The I.D. of the beam was selected as 0.060" as that was the smallest within which four strain gages could be bonded. The O.D. of 0.074" resulted when the trade-off between spring constant (high for maximum f_n , low for maximum output sensitivity) and output sensitivity dictated a wall thickness of 0.007".

FLOWMETER BODY DIMENSIONS

Since the outside envelope of the flowmeter bodies had been established by the customer as a 3" line size for the GH_2 meter and a 2" line size for the GO_2 meter, venturi-type restrictions had to be designed into the meter bodies to provide sufficient ρV^2 forces at the sensor targets. The required restrictions resulted in a 1.20" diameter at the target for the 3" meter and a 1.00" diameter for the 2" meter.

The trade-offs involved were the required pressure drop of 10 psid or less (a minimum restriction consideration) versus output sensitivity (a maximum restriction consideration).

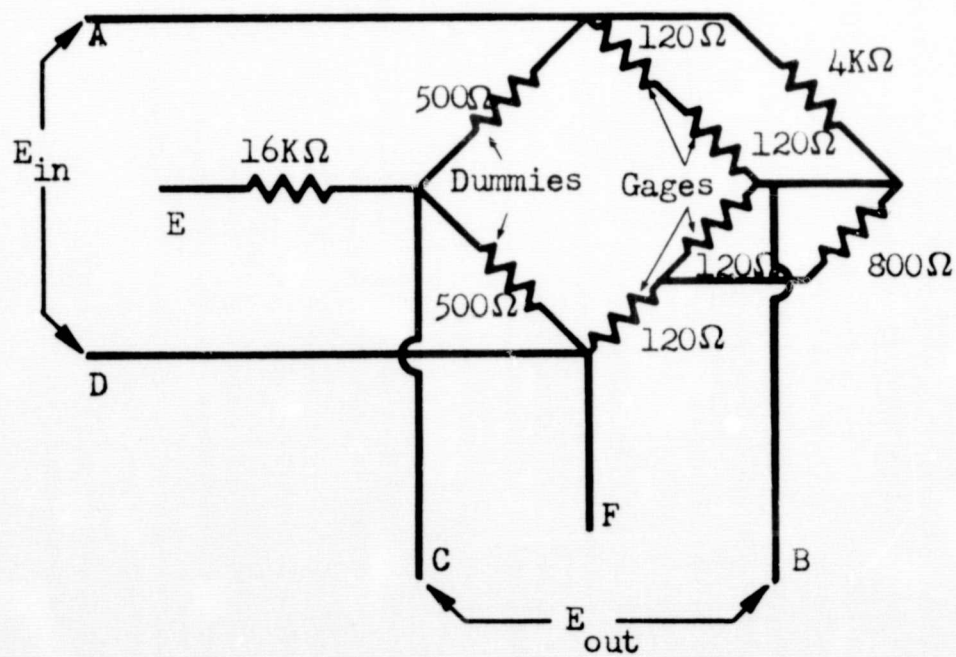
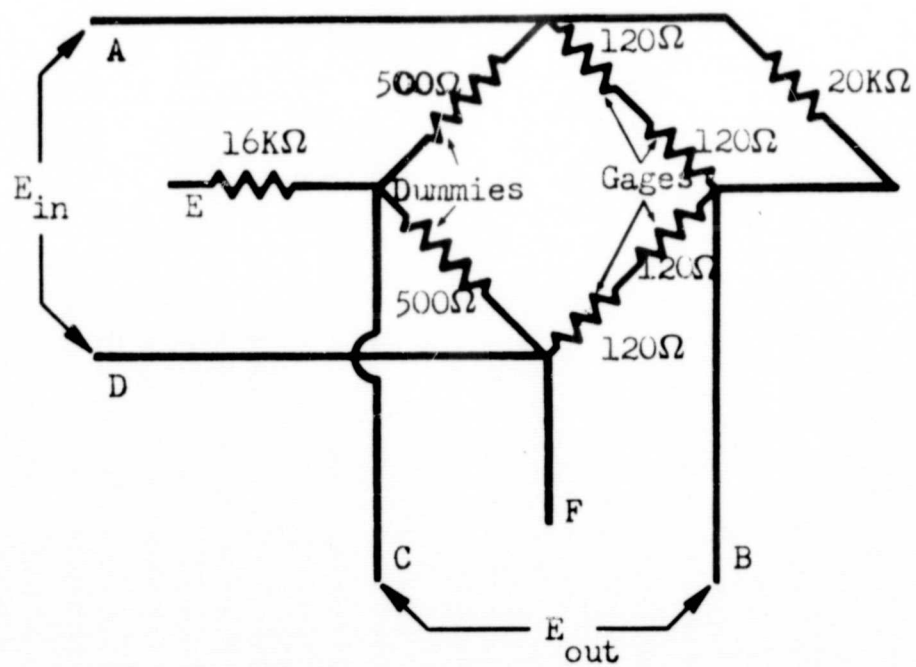
MATERIAL SELECTION

17-4 PH was selected as the bending beam material because its thermal expansion coefficient, over the operating temperature range, more closely approaches that of the semi-conductor strain gages, than any other available corrosion resistant steel. This match in thermal expansion coefficients is necessary to limit zero balance shift due to the apparent strain caused by differences in expansion coefficients.

ELECTRICAL DESCRIPTION

Electrical schematics for the two flowmeters are shown in Fig. 4. The sensor bridge circuit consists of two active semi-conductor strain gage legs and two dummy legs. Each of the two active legs consists of two 120Ω strain gages connected in series. The half-active bridge concept is necessary so that electrical R-cal techniques may be applied to the appropriate dummy leg.

Highly-doped semi-conductor strain gages (Kulite type ALP-120-180) were chosen because of their low gage factor change with temperature. Kulite specifications indicate that ALP-120-180 gages mounted on steel should result in no gage factor change with temperature. This in turn should minimize flowmeter output sensitivity (span) with temperature.



S/N 10

Figure 4. Flowmeter Electrical Schematics

R-8702

RESULTS OF RESEARCH AND DEVELOPMENT EFFORT

ZERO BALANCE TEMPERATURE COMPENSATION

Zero shifts with temperature for semi-conductor gaged devices result from two effects, gage resistivity differences, and apparent strain caused by differences in expansion between the substrate and semi-conductor. If the gages had matched electrical resistivity characteristics with temperature, zero shift from this factor alone would be negligible, and apparent strain effects would be the only effect involved. Compensation for both apparent strain and resistivity differences is accomplished by shunting the strain gage leg which has the greatest overall change in resistance with temperature. A shunt resistance value is chosen so that the effective resistance change matches that of the other leg. If the overall thermal resistance characteristics were linear, compensation would result in zero balance shift with temperature. Thermal resistance characteristics are usually non-linear, however, and the resultant compensation is a compromise between (1) minimizing the zero shift over a certain portion of the temperature spectrum, and (2) limiting the zero shift to some maximum value for the entire temperature range.

Figures 5 and 6 are the zero balance characteristics of the flowmeters before and after compensation had been applied.

Flowmeter S/N 9 balance compensation was achieved by shunting the one strain gage leg with a 20K Ω resistor. This resulted in a curve with a maximum zero

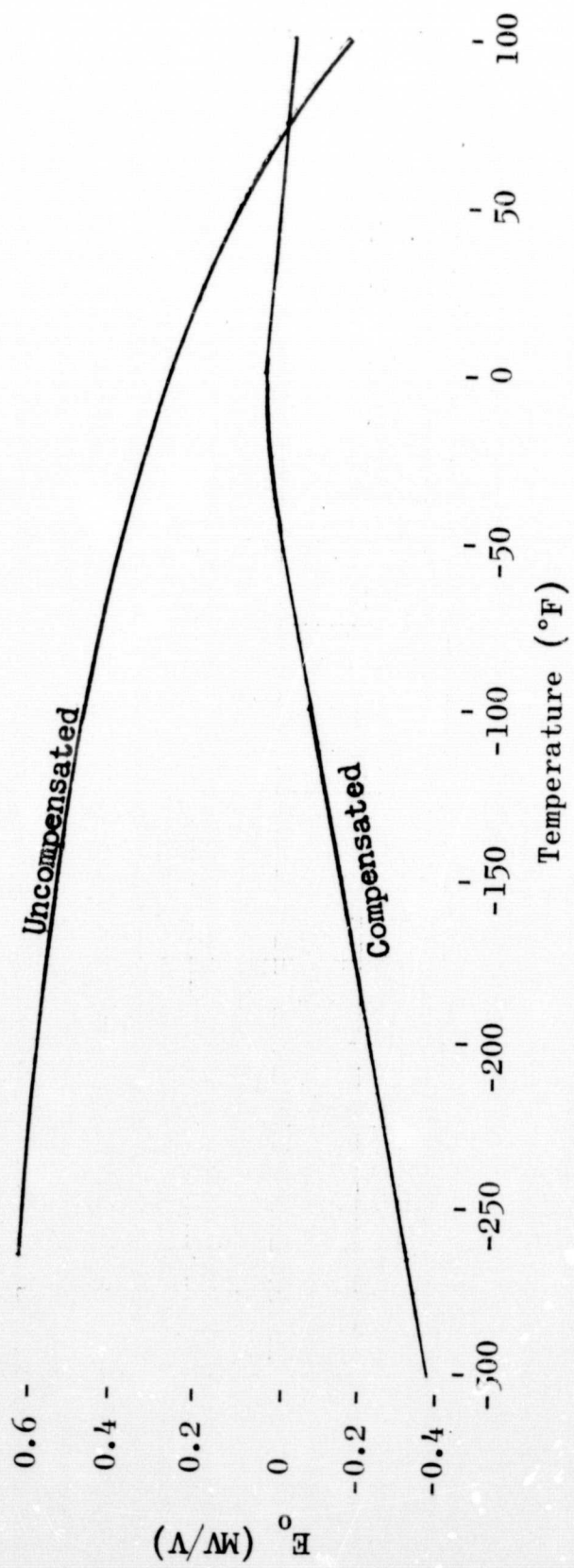


Figure 5. Zero Balance Characteristics of S/N 9

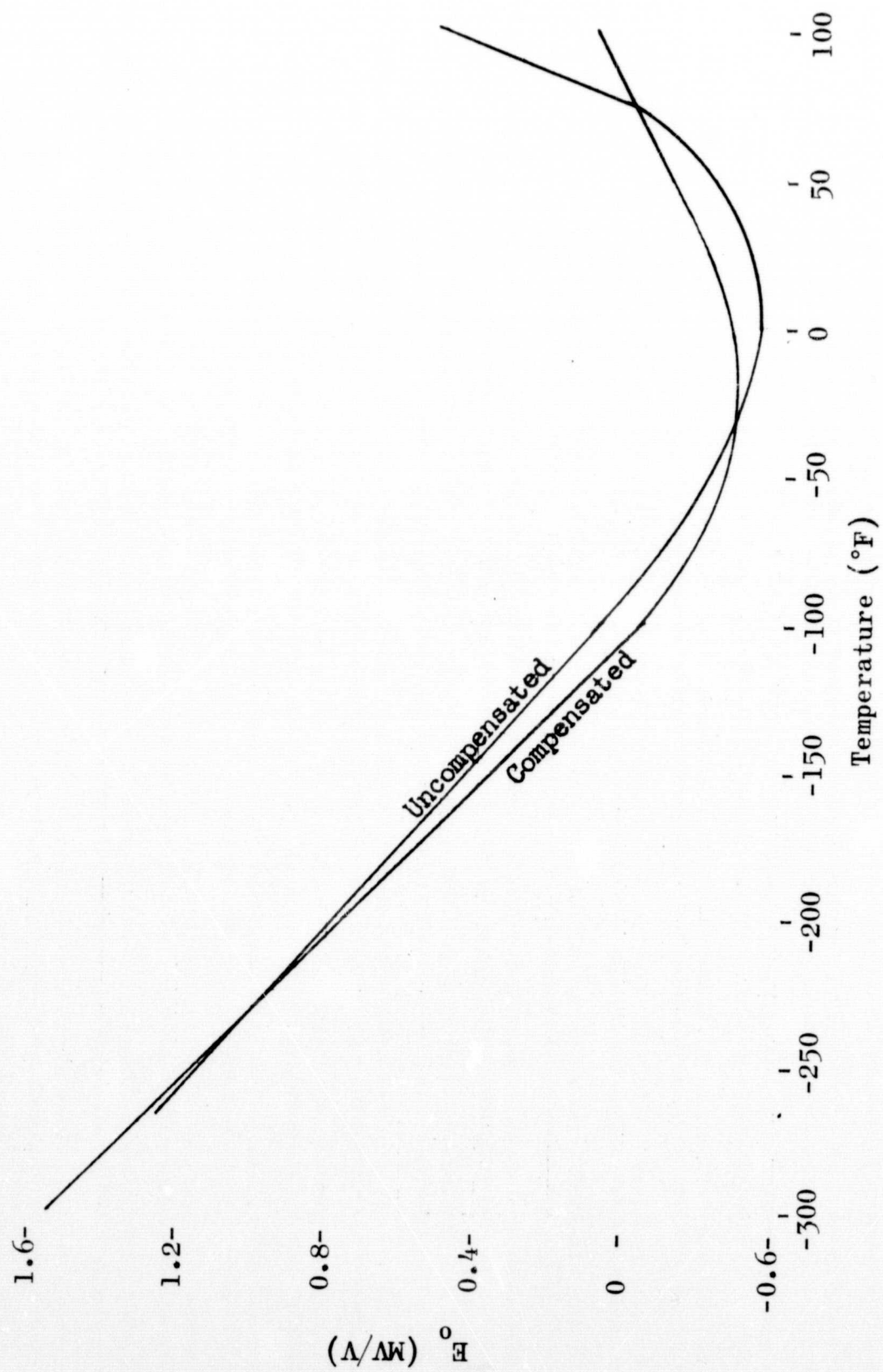


Figure 6. Zero Balance Characteristics of S/N 10

shift of $\pm 1.14\%$ of full scale output per 100°F . This compares with a target value of $\pm 1\%$ of F.S./ 100°F and a required value of $\pm 5\%$ of F.S./ 100°F .

Flowmeter S/N 10 had an uncompensated characteristic with a serious inflection point at approximately 0°F . Temperature compensation was more difficult to achieve in that two shunt resistors were required, $800\ \Omega$ across one gage only in one leg and $4\text{K}\Omega$ across both gages of the other leg. Maximum zero shift for S/N 10 is $\pm 3.6\%$ of full scale per 100°F which occurs in the range of -100°F to -300°F .

There are two possible reasons for the rather large zero shift: (1) the strain gages were not a matched set, even though they were packaged and sold as such, and (2) the more likely possibility that gage characteristics were changed by the electron beam welding process, which is used to attach the sensor to the housing.

Because of this latter possibility, the electron beam welding technique has been modified to give a lower weld penetration so that, in future units, the strain gages will be more protected from an over-temperature condition during the welding process.

TEMPERATURE COMPENSATION FOR SPAN

Span compensation, if required, for semi-conductor strain gages is usually accomplished by placing a passive resistor in series with the constant voltage power supply which excites the bridge. This is done to offset the gage factor

change which varies inversely with temperature. Since gage resistance varies directly with temperature, the series resistor results in a bridge excitation variation with temperature. The series resistor value is selected so that bridge excitation change and gage factor change cancel each other.

For the subject flowmeters, load tests throughout the temperature range were conducted by hanging a 500 gram weight at the center of the drag-body (target). The results of these tests are depicted in Fig. 7.

Although output sensitivity did not remain constant throughout the temperature range, the values of $\pm 0.26\%$ and $\pm 0.46\%$ of full scale per 100°F for meters S/N 9 and S/N 10, respectively, are within the target specification of $\pm 1\%$.

THERMAL GRADIENT EFFECTS

A thermal gradient between the strain gages on the upstream and downstream sides of the bending beam would result in an erroneous output which could not be resolved by temperature compensation techniques. Therefore, this possible effect must be eliminated by a design approach which minimizes the possibility of thermal gradients.

For the subject meters, a design approach was considered which would insulate or shield the bending beam from the direct gas flow. This would tend to create heat transfer conditions which were equal for both upstream and downstream sides of the beam.

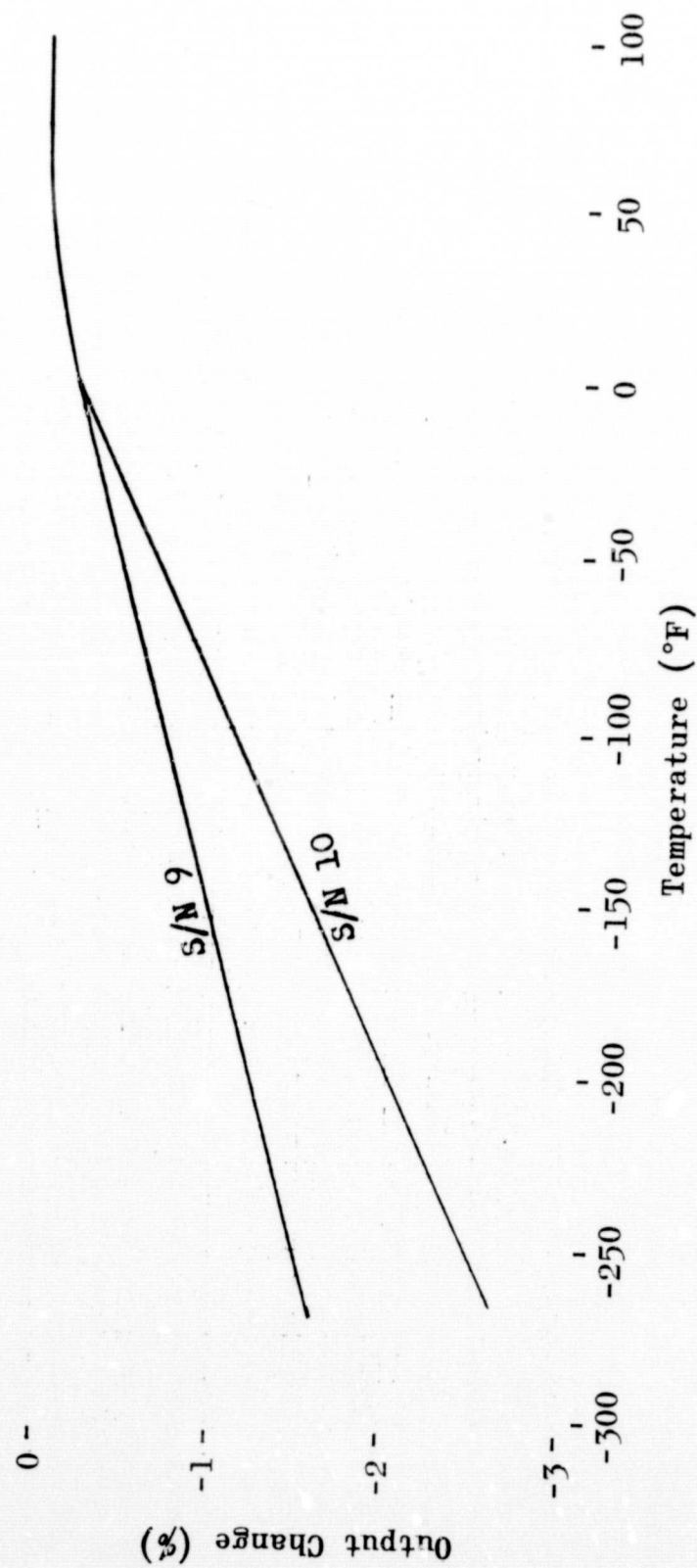


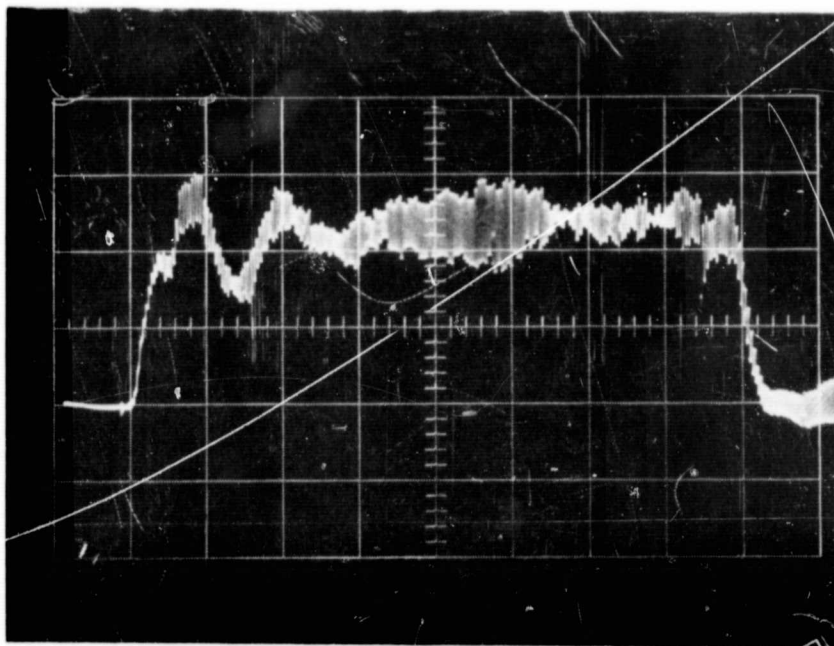
Figure 7. Output Temperature Sensitivity

Experiments were conducted with an existing prototype flowmeter developed previously for liquid application. This prototype was chosen because its beam thickness (0.004") was smaller than that which had been calculated for the NASA, MSC meters (0.007"), thereby enhancing the possible thermal insulation effects.

Pulsed GN_2 flows of approximately 50% of the meter's full scale output were used for the evaluation since the possible thermal gradient effect is transient in nature, in that under steady flows, the hardware becomes thermally soaked, thus eliminating gradients. Gas temperature was 40°F lower than the meter.

The meter was first exposed without insulating the beam, Fig. 8. The beam was then insulated by gluing 0.006" thick paper tape strips to both upstream and downstream sides of the beam. Figure 9 is the flowmeter's response to the gas pulse with the beam insulated. It is obvious that output characteristics during the transient part of the flow are essentially the same for both the insulated and uninsulated beam. The paper tape evidently increased the damping of the meter's natural frequency, as indicated by the lower resonance conditions of Fig. 8, but no other measurable differences were observed. Increasing tape thickness also had no effect.

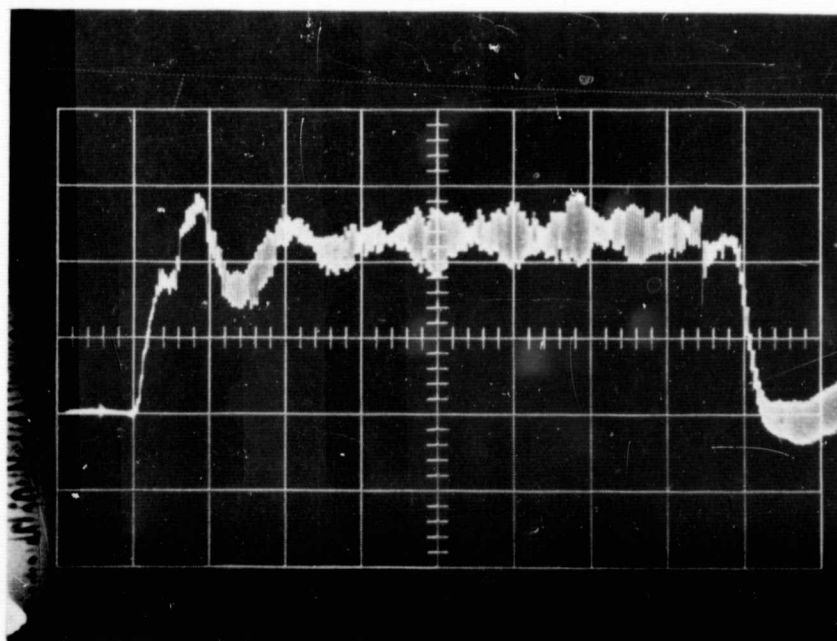
It was therefore concluded that the beam geometry selected for the subject flowmeters was adequate.



Sweep Rate = 10 ms/cm

Pulse Amplitude =
~80% Full Scale

Figure 8. Thermal Gradient Response (No Insulation)



Sweep Rate = 10 ms/cm

Pulse Amplitude =
80% Full Scale

Figure 9. Thermal Gradient Response (Beam Insulated)

FREQUENCY RESPONSE

Previous work on liquid and gaseous flowmeters had established that an undamped natural frequency of 3K Hz or greater would result in a frequency response of at least 1000 Hz. This is true because, under flowing conditions, the meter is significantly damped.

As indicated previously, 4000 to 5000 Hz was selected as the undamped resonance range which would produce a frequency response of greater than 1000 Hz. The calculations for this undamped resonance are as follows:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K}{M}}$$

where K = spring constant of beam $\left(\frac{3EI}{Pl^3} \text{ \#/in.} \right)$

E = Young's Modulus (30×10^6 psi)

I = Moment of Inertia of Beam ($84 \times 10^{-8} \text{ in.}^4$)

l = length of beam (0.34 in.)

P = force at target (1#)

M = lumped mass of target and beam $\left(2.19 \times 10^{-6} \frac{\text{\#-sec}^2}{\text{in.}} \right)$

Sample Calculation:

$$K = \frac{3(30 \times 10^6)(84 \times 10^{-8})}{1(0.35)^3} = 1762 \text{ \#/in.}$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{1762}{2.19 \times 10^{-6}}} = 4500 \text{ Hz}$$

Figures 10 and 11 show the response of the meters to an impulse excitation in free air (undamped). S/N 9 has an undamped natural frequency of approximately 4000 Hz while the f_n of S/N 10 is approximately 4500 Hz.

Flowmeter S/N 9 has a lower resonance because of a slightly different beam geometry due to machining tolerances.

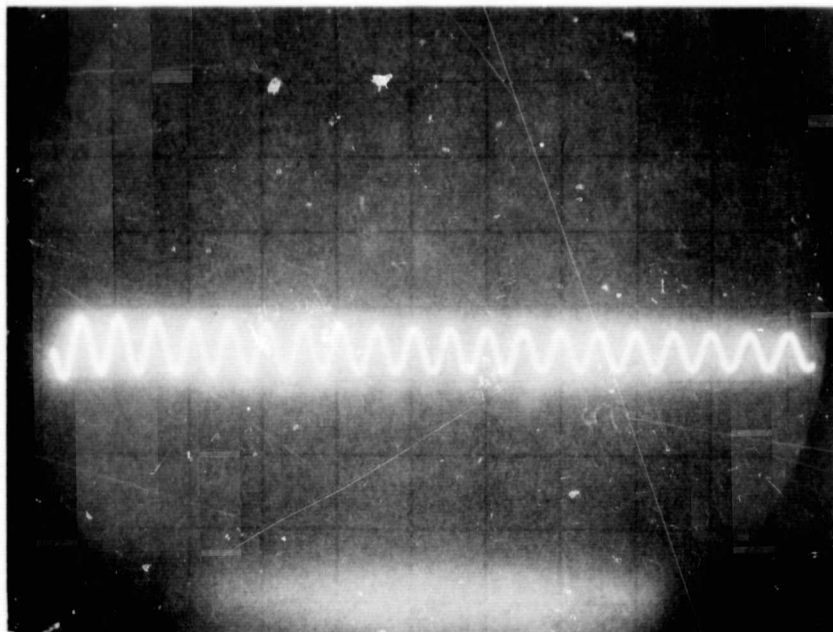
The flowmeter's response to ambient gaseous nitrogen pulses is shown in Fig. 12. From Fig. 12 it is obvious that the pneumatic feed system has a 50 Hz dynamic characteristic, and therefore is the limiting response factor.

In a further attempt to prove that the meter's dynamic response approaches 1000 Hz, the meter was mechanically excited in a ramp-unloading condition. Figures 13 and 14 demonstrate that both meters responded to the ramp in less than one millisecond.

A review of previous work with gaseous feed systems revealed that even for systems having much smaller feed system volumes (3/8" diameter line), resonances were on the order of 50 to 100 Hz (see Fig. 15). It was therefore concluded that the meter's response is at least an order of magnitude greater than that of most pneumatic feed systems such as the one employed in this effort.

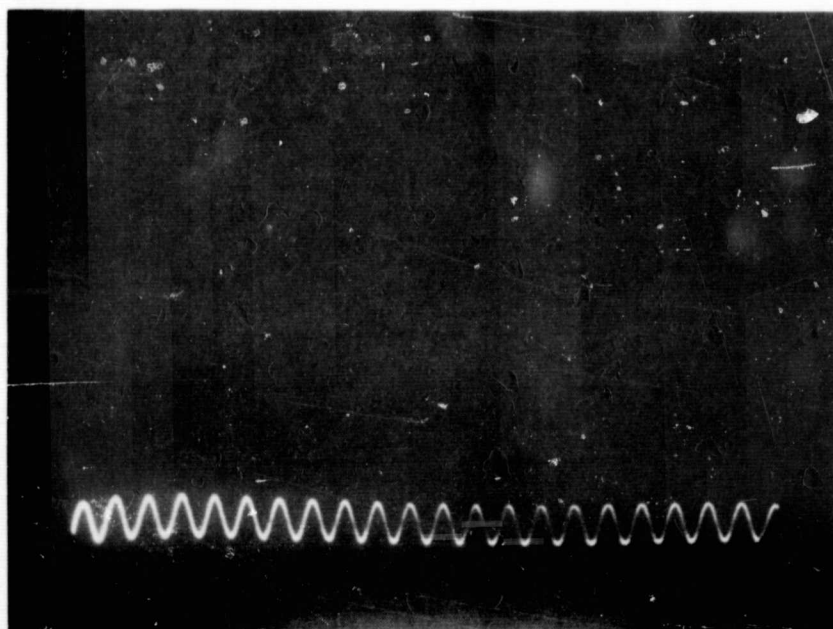
CRYOGENIC GAS APPLICATION

The test set-up of Fig. 16 was utilized to test the meters under both ambient and cryogenic pulse conditions. This same set-up was also utilized for the ambient gas calibrations.



Sweep Rate = 0.5 ms/cm

Figure 10. Undamped Natural Frequency of S/N 9

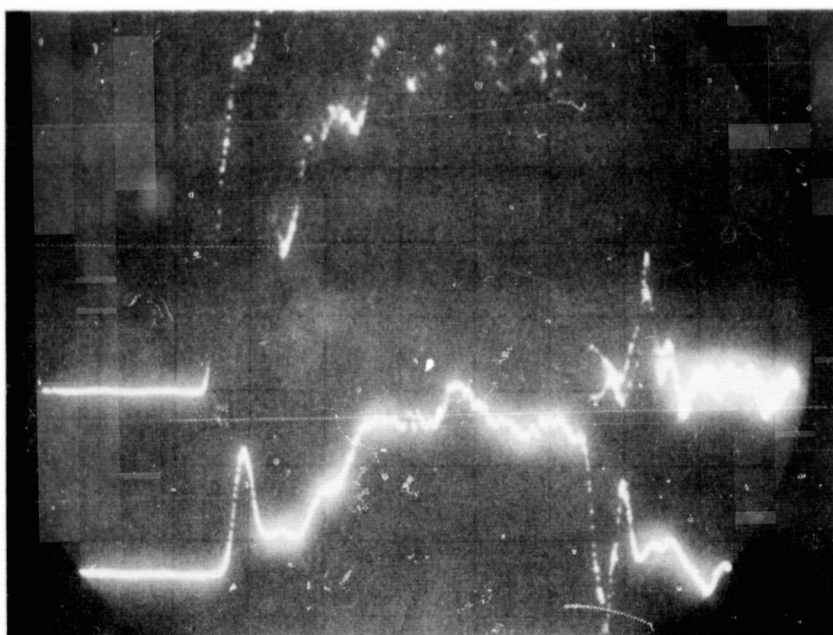


Sweep Rate = 0.5 ms/cm

Figure 11. Undamped Natural Frequency of S/N 10

S/N 9

S/N 10



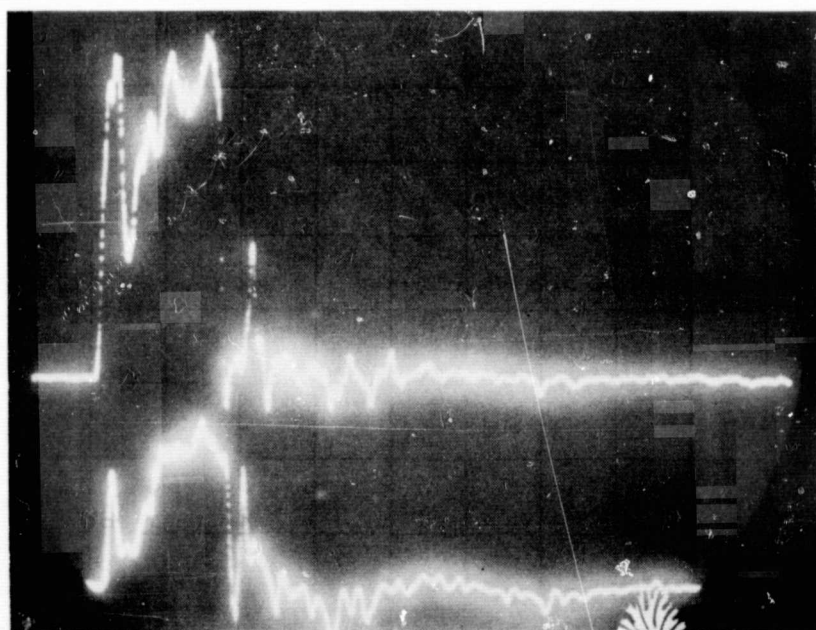
Pulse Amplitude =
~100% F.S.

Pulse Amplitude =
~50% F.S.

Sweep Rate = 20 ms/cm

S/N 9

S/N 10



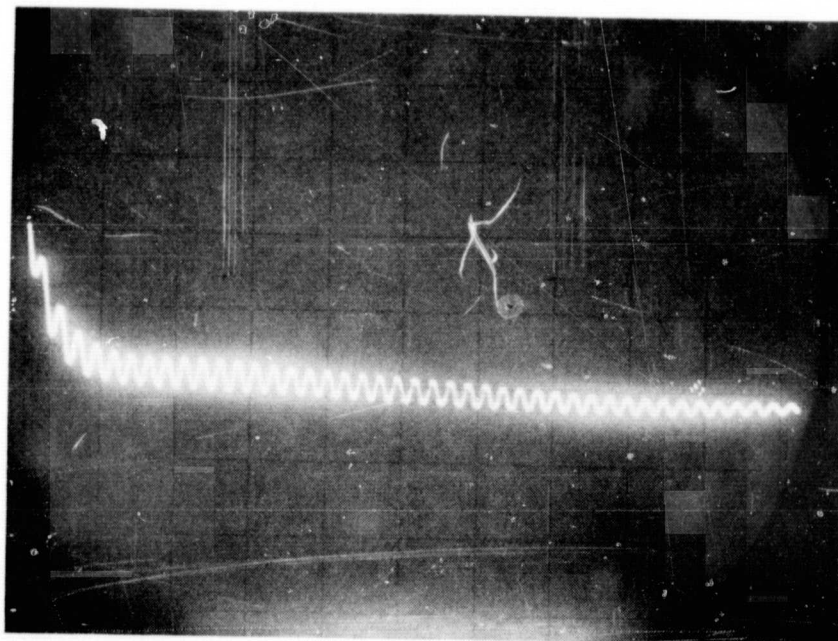
Pulse Amplitude =
~100% F.S.

Pulse Amplitude =
~50% F.S.

Sweep Rate = 50 ms/cm

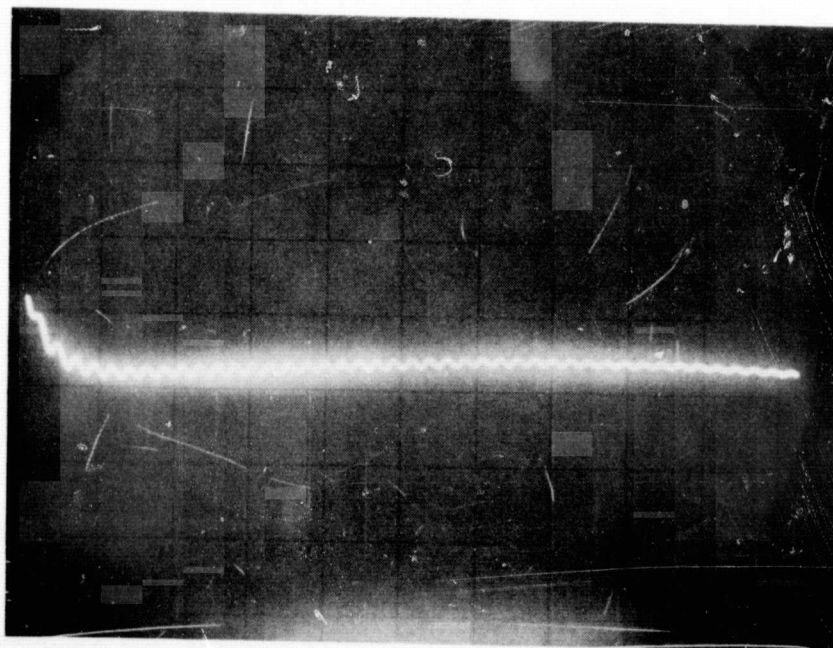
Figure 12. Response to Ambient GN_2 Pulses

R-8702



Sweep Rate = 1.0 ms/cm

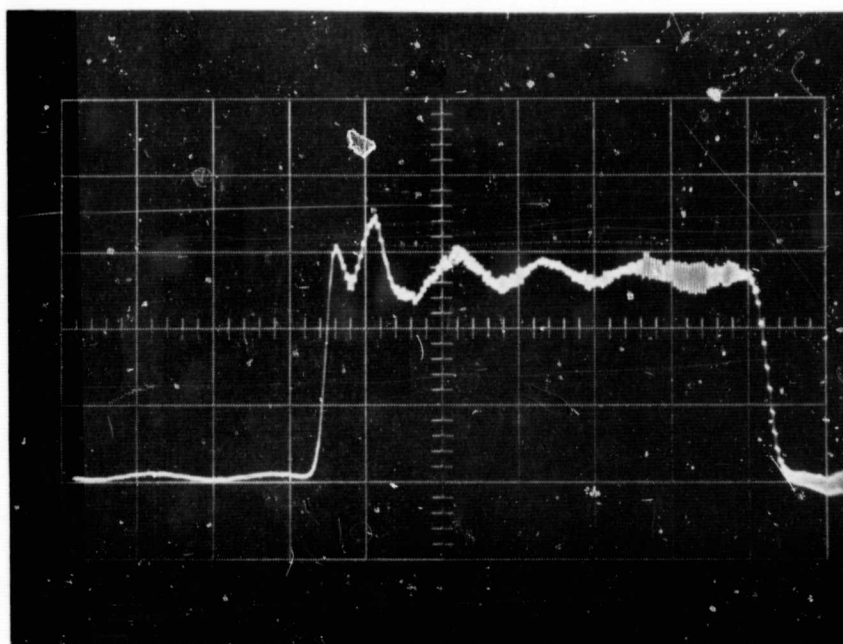
Figure 13. Response to Ramp-Unload - S/N 9



Sweep Rate = 1.0 ms/cm

Figure 14. Response to Ramp-Unload - S/N 10

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Sweep Rate = 10 ms/cm

Figure 15. Small Volume Feed System Resonance

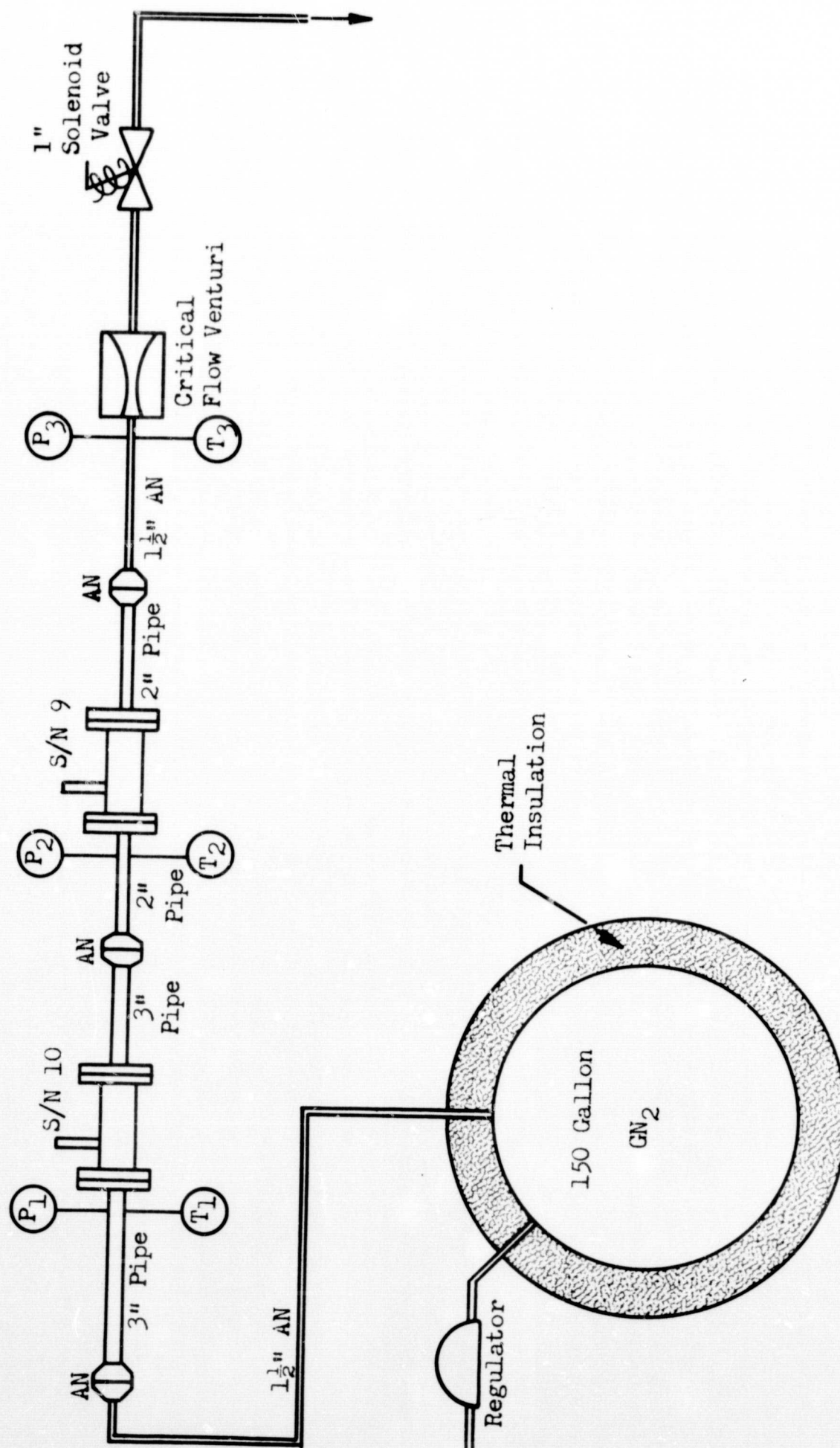


Figure 16. Flow Bench Schematic

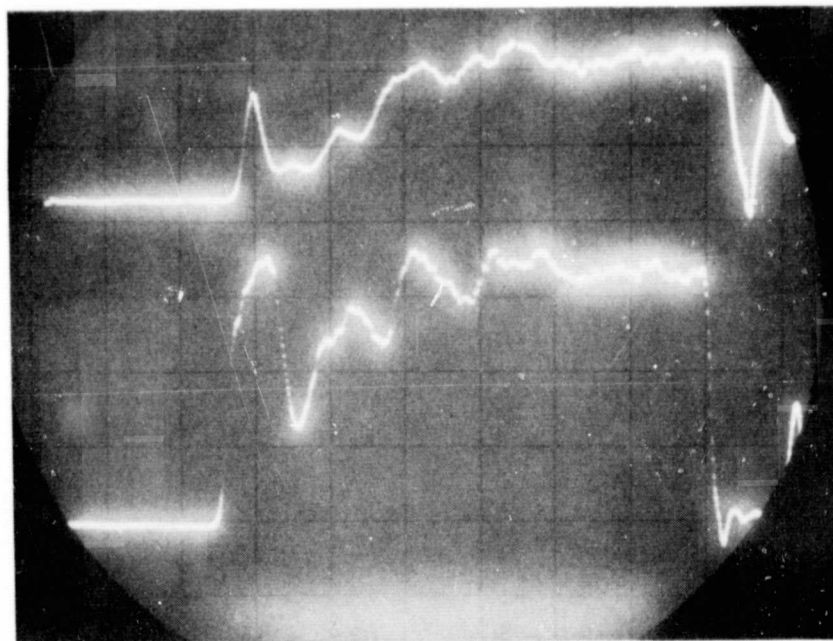
For cryogenic gas pulses, the GN_2 supply tank was pre-chilled overnight with liquid nitrogen. Since the line to the meters was not thermally insulated, a pre-pulse, steady-state flow was used to pre-chill both meter and line. The cryogenic gas pulse immediately followed this pre-chill flow. Figure 17 represents both meters' response to cryogenic gas pulses. Figure 12 represents both meters' response to ambient pulses. These results demonstrate the meters' insensitivity to thermal gradients.

CALIBRATION

Calibrations using ambient temperature (20° to 60°) gaseous nitrogen were performed with both meters in series in the test set-up of Fig. 16. Three different critical flow venturies were utilized as transfer standards. Figures 18 and 19 represent the flow coefficient curves, plotted from the data of Table I, for each of the two meters with a constant voltage excitation of 2.000V. The GO_2 and GH_2 curves represent ideal gas extrapolations from the GN_2 data. An ideal gas assumption is valid since pressures were no greater than 500 psia and temperatures were between 20°F to 60°F .

Each of the three different velocity points are shown as circled points on the GN_2 curves. For each velocity condition, mass flow rate was varied by changing the pressure and thus the density of the calibrating gas. Variations at each velocity point for at least four different mass flow rates were within $\pm 1\%$ of the depicted curve values.

S/N 10



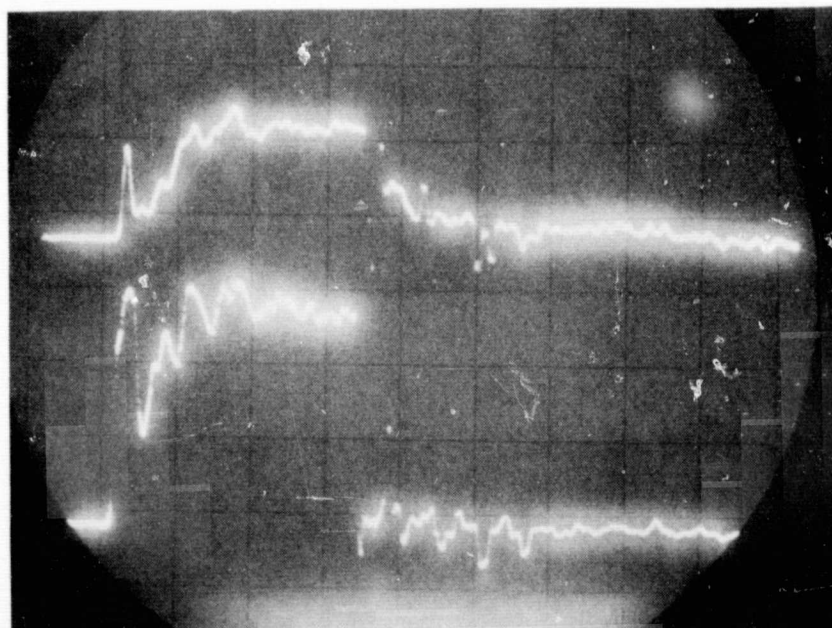
Pulse Amplitude =
~40% F.S.

S/N 9

Pulse Amplitude =
~80% F.S.

Sweep Rate = 20 ms/cm
Temperature = -146°F

S/N 10



Pulse Amplitude =
~40% F.S.

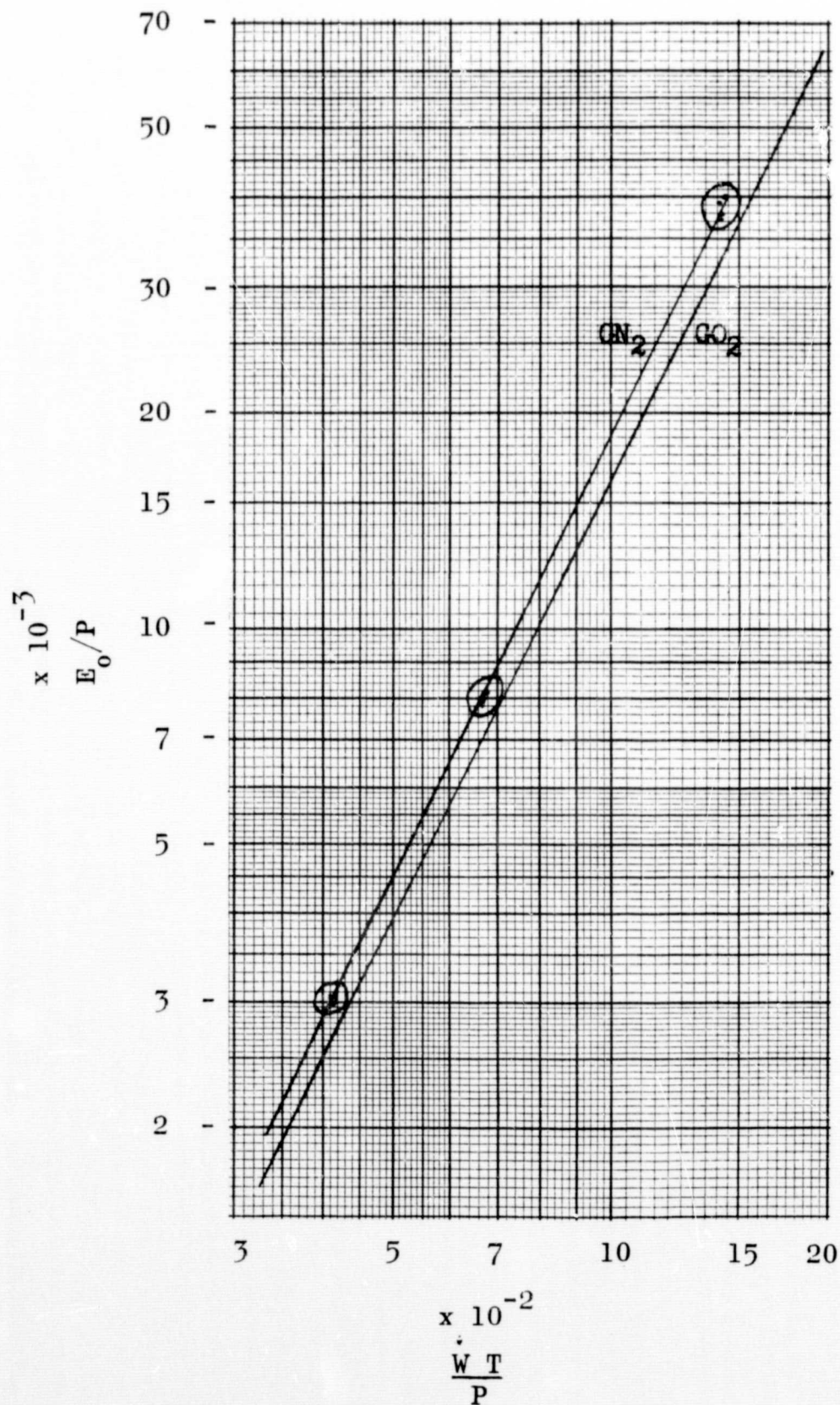
S/N 9

Pulse Amplitude =
~80% F.S.

Sweep Rate = 50 ms/cm
Temperature = -243°F

Figure 17. Response to Cryogenic GN_2 Pulses

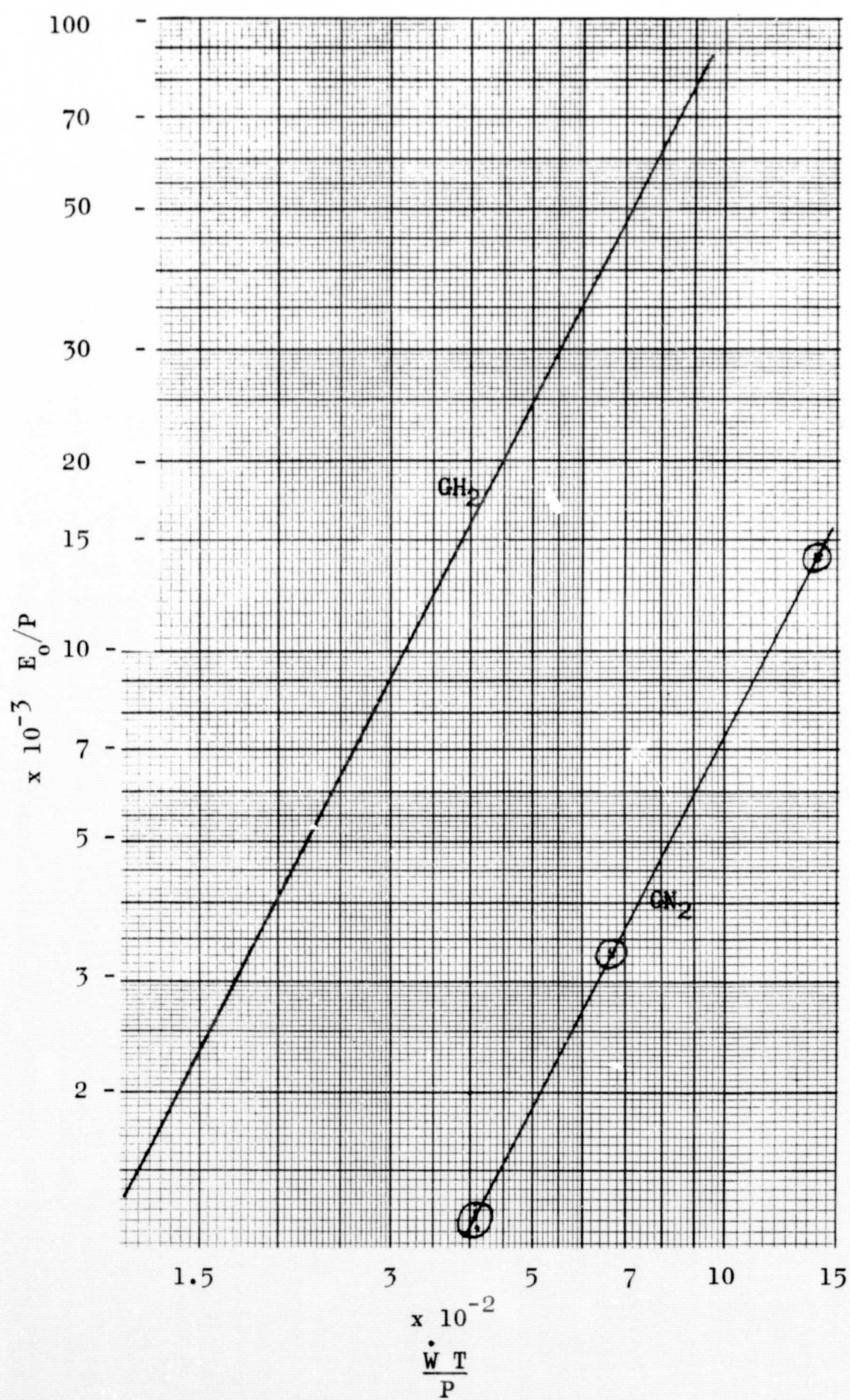
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$$\dot{W} = \frac{K P}{T}$$

$\dot{W}$ = Mass Flowrate (#/sec)
 P = Gas Pressure (psia)
 T = Gas Temperature (°R)
 E_o = Meter Output (millivolts)

Figure 18. Flow Coefficient Curve for S/N 9



$$\dot{W} = \frac{K P}{T}$$

$\dot{W}$ = Mass Flowrate (#/sec)

P = Gas Pressure (psia)

T = Gas Temperature ($^{\circ}R$)

E_0 = Meter Output (millivolts)

Figure 19. Flow Coefficient Curve for S/N 10

TABLE I

CALIBRATION DATA

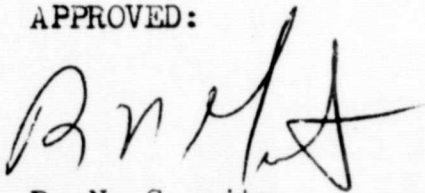
Run No.	S/N 9						S/N 10						$\dot{W}$ lb/sec	Venturi Diam. (in)
	$E_{in}(V)$	$E_{out}(MV)$	P (psia)	T(°R)	E_o/P	$\dot{W}\sqrt{T/P}$	$E_{in}(V)$	$E_{out}(MV)$	P (psia)	T(°R)	E_o/P	$\dot{W}\sqrt{T/P}$		
1	1.999	5.73	144	496	39.8×10^{-3}	14.4×10^{-2}	1.999	2.06	148	492	13.9×10^{-3}	13.9×10^{-2}	0.930	0.598
2	1.999	10.80	275	510	39.3×10^{-3}	14.3×10^{-2}	1.999	3.95	282	507	14.0×10^{-3}	13.9×10^{-2}	1.74	0.598
3	1.999	14.80	398	511	37.2×10^{-3}	14.2×10^{-2}	1.999	5.64	404	510	14.0×10^{-3}	14.0×10^{-2}	2.50	0.598
4	1.999	18.40	494	503	37.2×10^{-3}	14.3×10^{-2}	1.999	7.07	504	502	14.0×10^{-3}	14.1×10^{-2}	3.16	0.598
5	1.999	1.57	196	499	8.01×10^{-3}	6.76×10^{-2}	1.999	0.65	197	491	3.30×10^{-3}	6.67×10^{-2}	0.593	0.408
6	1.999	3.00	364	491	8.24×10^{-3}	6.76×10^{-2}	1.999	1.22	367	482	3.32×10^{-3}	6.64×10^{-2}	1.11	0.408
7	1.999	3.67	452	485	8.12×10^{-3}	6.72×10^{-2}	1.999	1.54	457	480	3.34×10^{-3}	6.62×10^{-2}	1.38	0.408
8	1.999	4.15	531	482	7.82×10^{-3}	6.69×10^{-2}	1.999	1.76	538	478	3.27×10^{-3}	6.58×10^{-2}	1.62	0.408
9	1.999	0.56	187	499	2.99×10^{-3}	4.15×10^{-2}	1.999	0.18	187	496	0.96×10^{-3}	4.14×10^{-2}	0.348	0.320
10	1.999	1.14	381	503	2.99×10^{-3}	4.14×10^{-2}	1.999	0.46	382	501	1.21×10^{-3}	4.12×10^{-2}	0.704	0.320
11	1.999	1.73	568	500	3.04×10^{-3}	4.09×10^{-2}	1.999	0.72	571	500	1.26×10^{-3}	4.07×10^{-2}	1.04	0.320
12	1.999	1.78	579	498	3.07×10^{-3}	4.12×10^{-2}	1.999	0.75	582	494	1.29×10^{-3}	4.08×10^{-2}	1.07	0.320

CONCLUSIONS

It was demonstrated that the two high-response, cryogenic gas flowmeters are capable of measuring pulse gas flows throughout a temperature range of -300°F to $+100^{\circ}\text{F}$ and the flow rate range of interest, 3.2 #/sec of GN_2 extrapolated to 2 #/sec of GO_2 for S/N 9 and 1 #/sec of GH_2 for S/N 10. It was further demonstrated that the frequency response of the meters approaches 1000 Hz.

Although the temperature sensitivity of S/N 10 was greater than the target value ($\pm 1\%$ F.S. per 100°F), an improved electron beam welding technique should overcome that problem.

APPROVED:



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