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MARCH, 1965

INSTRUMENTATION DESIGN STUDY FOR TESTING A HYPERSONIC RAMJET ENGINE ON THE X-15 A-2

Volume 3

CONCEPTUAL DESIGN OF MEASUREMENT SYSTEMS

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PREPARED UNDER CONTRACT NO. NAS 4-715

For

NATIONAL AERONAUTICS & SPACE ADMINISTRATION

ADVANCED ENGINE AND TECHNOLOGY DEPARTMENT

GENERAL ELECTRIC

CINCINNATI, OHIO 45215

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1. INTRODUCTION

Considerable interest exists within the Government in research programs aimed at developing safe, reliable and efficient hypersonic air-breathing engines. A previous feasibility and preliminary design study (reference 1) showed it was feasible to flight test experimental ramjet engines on the X-15 airplane. To aid in such an experimental ramjet test program, a list of desired flight test measurements was identified by the NASA Flight Research Center, (reference 2). In September, 1964, the General Electric Company was awarded a four month contract, NAS4-715, to evaluate these measurements and to specifically:

a. provide a conceptual design of a thrust/drag measuring device;
b. define and provide conceptual designs of other advanced instrumentation requiring development;
c. identify commercially available components; and
d. formulate an overall plan to provide the flight instrumentation for ramjet tests.

The results of this program are reported in three volumes: Volume 1, "Summary, Costs, and Schedules", Volume 2, "Preliminary Design of In-Flight Thrust/Drag Measuring Device", and Volume 3, "Conceptual Design of Measurement Systems".

This report includes a technical discussion of instrumentation systems and techniques, applicable for fuel, static pressure, structure and exhaust gas measurements with conclusions and recommendations.

2. SUMMARY

A four month program NAS4-715 to study the instrumentation requirements for an experimental hypersonic ramjet to be flight tested on the X-15 A-2 airplane has been completed.

In conducting the study, major guidelines were provided by the NASA Flight Research Center and included the following:

a. A desired measurements list identifying engine variables, number of measurements of each, possible engine location of sensor and desired accuracy. (Table 1)

b. A weight limitation of fifty pounds for engine mounted instrumentation.

c. Minimum and maximum altitude trajectories of the proposed X-15A-2 flights and corresponding environmental conditions.

d. Current on-board recording capability of the X-15 airplane.

TABLE 1 - DESIRED MEASUREMENTS

Description	Overall Range	Measurement Range Low	Measurement Range High	Accuracy Low	Accuracy High	Dynamic Response of Measured Quantity
Thrust/Drag Measuring Device	-6000 to +6000 lb.	±500 lb	±6000 lb.	±10 lb	±120 lb.	100 cps 100 cps
Inlet, forward of throat	0.1 - 60 psia	0.1 - 60 psia		±.01 psia	±.5 psia	0-10 cps
Upper inlet ramp	1.0 - 120 psia	5.0 - 120 psia		±.05 psia	± 1 psia	100 cps
Inlet throat	1.0 - 250 psia	8.0 - 250 psia		±.1 psia	±3 psia	0-10 cps
Combustor	1.0 - 250 psia	4.0 - 250 psia		±.05 psia	±3 psia	2 taps 0-3 cps 1 tap 0-200 cps 1 tap 0-2000 cps
Nozzle	1 - 250 psia	4.0 - 250 psia		±.05 psia	±3 psia	0-10 cps
2 rakes - four taps each	1.5 - 80 psia	10 - 80 psia		±.1 psia	±1 psia	0-10 cps
1 rake - upper inlet ramp	1.0 - 120 psia	10 - 120 psia		±.1 psia	±1 psia	0-10 cps
1 rake - combustor	1.0 - 250 psia	4.0 - 250 psia		±.05 psia	±3 psia	0-10 cps
Inlet ramp and throat	390 - 2500°R	390-2500°R		±5°R	±25°R	0-3 cps
Combustor and nozzle	390 - 2500°R	1000 - 2500°R		±10°R	±25°R	0-3 cps
Combustor	390 - 6500°R	700 - 6500°R		±20°R	±200°R	Not specified
Engine Vibration 1 - 3 axis	0-200 g 200 - 2500 cps	0 - 50 g 200 - 2500 cps		±2.5 g ±25 cps	±2.5 g ±25 cps	200 - 2500 cps
External Surfaces	0.1 - 45 psia	0.1 - 45 psia		±.01 psia	±.5 psia	0 - 3 cps
External Structural temperatures	390 - 2500 °R	1000 - 2500 °R		±10 °R	±25 °R	0-3 cps

Table I - Desired Measurements - cont'd

Description	Overall Range	Measurement Range Low High	Accuracy Low	Accuracy High	Dynamic Response of Measured Quantity
Rosette Strain gages	Ultimate design strain microinches/ inch	Yield design strain microinches/ inch	±5% (of maximum strain)	±5%	0-10 cps
Temperature or enthalpy of Exhaust gases	600 - 6500 °R	600 - 6500 °R	±20 °R	±200 °R	Not specified
Composition of exhaust gases	Note 1	Note 1	±10% (major species)		Not specified
Hydrogen pressure in cooling jacket	300 - 500 psia	300 - 500 psia	± 5 psia	±5 psia	0-3 cps
Pyrophoric fuel tank internal pressure	14.7 - 500 psia	250 - 400 psia	± 5 psia	± 5 psia	0-3 cps
Liquid Hydrogen Tank Wall Temperature	36 - 630 °R	36 - 60 °R	±1 °R	±1 °R	0-3 cps
Hydrogen Temperature in Cooling Jacket	36 - 2000 °R	200 - 1800 °R	±2 °R	±20 °R	0-3 cps
Hydrogen Flow Rate	0-5 lb/sec	0-5 lb/sec	±.05 lb/sec	±.05 lb/sec	0-10 cps
Pyrophoric Fuel Flow Rate	0-5 lb/sec	0-5 lb/sec	±.05 lb/sec	±.05 lb/sec	0-10 cps

NOTE: Products of H_2 and Air Combustion

3. TECHNICAL DISCUSSION OF INSTRUMENTATION SYSTEMS AND TECHNIQUES

3.1.0 Fuel Measurements

3.1.1 LH_2 Fuel Flow

3.1.1.1 Requirements

It is expected that the mass flow measurement of liquid hydrogen will play an important part in the determination of ramjet performance during flight test. For this reason, considerable effort was directed toward identifying meter requirements and calibration procedures. In order to satisfy accuracy and dependability requirements for the flow measurement, the flowmeter selected should meet the following specifications.

a. Adaptable to the existing 1½ inch, vacuum-jacketed line.
b. Vacuum-jacketed to prevent heat leakage.
c. Volume not to exceed 5 inches in diameter and 16 inches in length, including vacuum jacket.
d. Overall range of 0-5#/sec. with repeatability of ±.05#/sec.
e. Dynamic frequency response of 0-10 cps.
f. 0-5V DC output or signal compatible with TM.
g. Capable of installation upstream of shutoff and refill valves in X-15.
h. Capable of passing 1-phase, 2-phase, or slug flow either direction without damage.
i. Minimum operational life of six hours over a 2-year period.
j. Require low pressure drop.
k. Capable of retaining calibration for a 6-month period.
l. Withstand ±60 mils amplitude vibration 10-55 cps.
m. Withstand ±10 "G" acceleration 55-2000 cps.
n. Suitable for flight test application.
o. Operate from either 2-phase 115V (±1.1V) 400 cycles ±4 cycles or 28V DC unregulated.
p. Operate with up to 450 psig pressure.
q. Capable of being removed and replaced or repaired and calibrated and reinstalled within a 2-week period.
r. Lightweight.

3.1.1.2 Meter Selection

There are two problems associated with liquid hydrogen flow metering which make it difficult to provide accurate measurements:

a. Compressibility
b. Two phase flow.

Liquid hydrogen is a highly compressible liquid whose density varies considerably with both temperature and pressure. Average measurements of liquid hydrogen density across the fuel pipe are extremely difficult because of the existing profiles.

Since the LH_2 in the X-15 will be pressurized at 330 psig and vacuum-jacketed throughout, very little if any 2-phase flow will be present during flight. However, during the refueling, purging, or cool-down operation, some 2-phase flow can and probably will exist. This flow can be non-homogeneous and can be present as slug flow, annular flow, or in an indiscrimate flow mixture of liquid and vapor. These conditions could cause high velocity gas flow in both directions and high, short duration, pressure surges. The flowmeter selected must be ruggedly built and not susceptible to overspeed or damage due to high velocity gas flow in either direction. It must produce reliable output readings even though some 2-phase flow does exist. It is suspected that 2-phase flow can be caused by certain levels of vibration although this seems highly improbable with the high operating pressure.

A fairly extensive review of flow meters is included in references 3 and 4. Reference 5 provides information dealing specifically with cryogenic instrumentation.

Three principal types of meters were selected for consideration in the program.

Volumetric Flowmeters (differential - pressure meter)

Orifices and venturies have been investigated for use as cryogenic flow meters (references 6 and 7). In considering the requirements as identified in section 3.1.1.1. there are several disadvantages which cannot be overcome.

a. Flow rate is proportional to the square root of pressure drop. Consequently a flow range of ten would result in a corresponding pressure drop variation of one hundred.

b. Orifices are relatively inefficient in that they dissipate relatively large amounts of energy.

Volumetric Flowmeters (differential-pressure meter) cont'd

c. Flow must be single phase. Liquid to gas conversion can occur if velocity is high enough through the meter.

d. Mass flow measurement requires complex measurement of hydrogen pressure and temperature for density compensation.

Volumetric Flowmeters (Turbine Type)

Turbine type flowmeters were considered during the study; however, they are susceptible to damage due to high velocity gas flow, and both temperature and pressure must be sensed very accurately in order to calculate mass flow rate. Magnetic braking devices and bypass valve systems have been used in certain applications to prevent rotor overspeed, but the general concensus of opinion of the participants of the 1963 Cryogenics Engineering Conference Seminar on Flow Measurements (see Reference 8) was that magnetic brakes and other overspeed protective means were inadequate. Greater complexity with reduced reliability as well as potential errors have caused people to avoid these methods whenever possible. Figures 1 and 2 are plots of probable errors in the conversion of volumetric flow to mass flow due to temperature and pressure errors. Inaccuracies of this magnitude are not tolerable on this program.

Mass Flow Meters

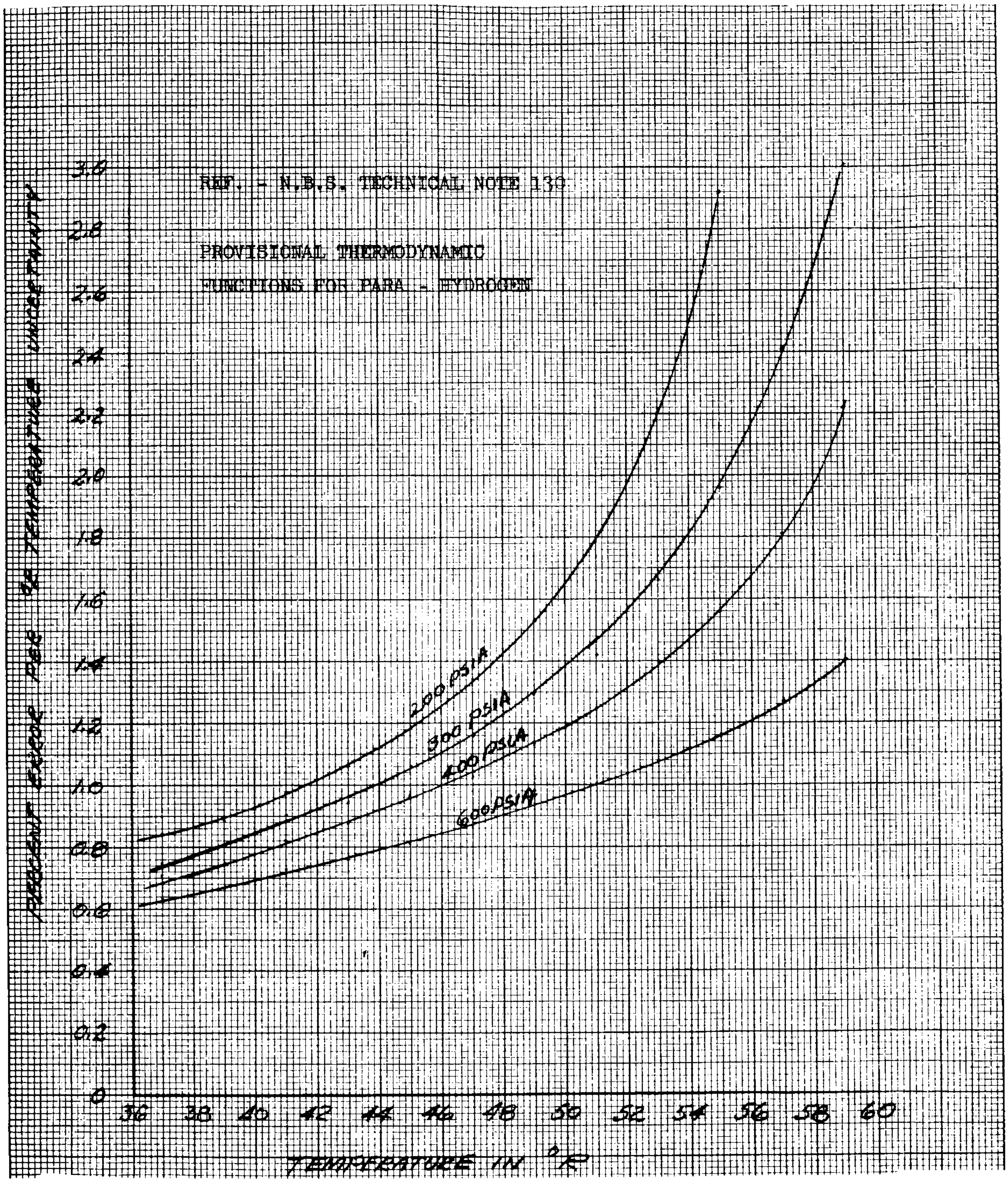
The state of the art in mass flowmeters has advanced to the point where they are practical and should be used on this program. (See table 2) Mass flow of liquid hydrogen can be measured directly to a high degree of accuracy without the necessity of recording temperature and pressure. They are of a size and weight which is not prohibitive even with the required vacuum jacket and can be made to have a 0-5V DC output voltage which is compatible with the data acquisition equipment that is going to be used. Dynamic flow calibrations have not been made on these instruments at this time, and therefore frequency response can only be estimated.

Four manufacturers build liquid hydrogen mass flowmeters that could possibily be used in this system. The General Electric Company, Potter Aeronautical Corporation, Waugh-Foxboro, and Bendix-Pioneer all have LH_2 mass flowmeters in various stages of development. The liquid hydrogen range of one to five pounds per second is apparently within the current state of the art and possibly one-half to five pounds per second, with a repeatability of better than the ±1% requirement, even with some 2-phase flow. The 330 psig operating pressure is not a problem nor is the requirement to permit filling through the same line (reverse flow through meter).

TABLE 2

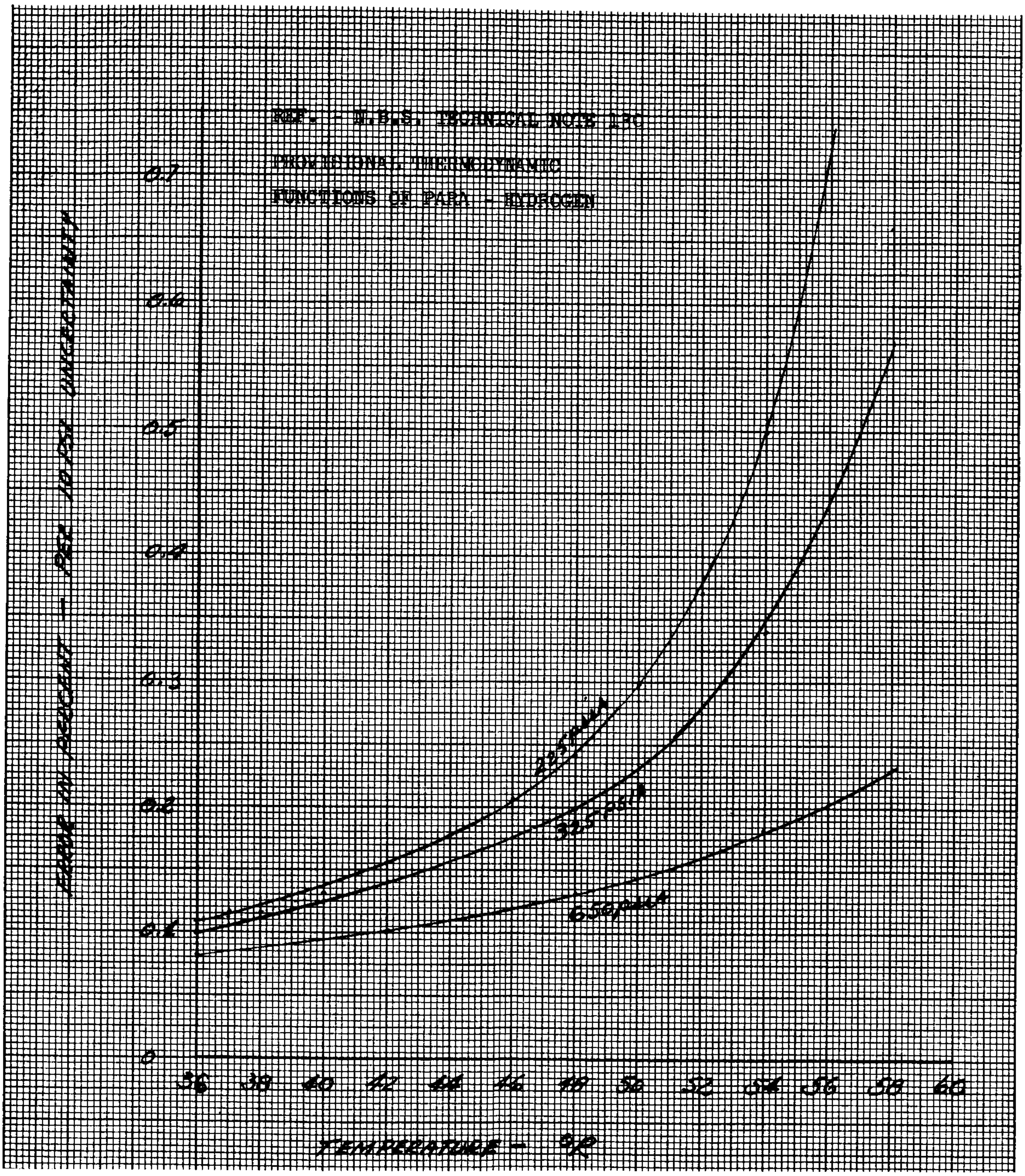
LIQUID HYDROGEN FLOWMETER SUMMARY

	DESIGN CRITERIA	BENDIX	G. E.	POTTER	WAUGH
1.	Adaptable to 1-1/2 inch vacuum jacketed line	yes	yes	yes	yes
2.	Designed within a volume less than 5" dia. & 16" long including vacuum jacket.	yes	yes	yes	yes
3	Range of 0-5 #/sec. LH_2	yes	1-5	1-5	1-5
4.	Repeatability of ±.05 #/sec.	yes	yes	yes	yes
5.	Dynamic frequency response of 0-10 cps	yes	no	no	no
6.	Passing 1-phase, 2-phase, or slug flow either direction without damage.	yes	yes	no	no
7	Min. operational life of 2 hrs. over 2 year span.	yes	yes	yes	yes
8.	Compatible input power requirements	yes	yes	yes	yes
9.	Compatible output signal	yes	yes	yes	yes
10.	Low pressure drop	yes	yes	yes	yes
11.	Able to hold calibration for 6 months	yes	yes	yes	yes
12.	Withstand ±60 mils amp vib. 10-55 cps ±10 "G" accel. 55-2000 cps.	?	yes	?	?
13.	Constructed as aircraft hardware	?	yes	?	?
14.	Operate with up to 450 psig pressure	yes	yes	yes	yes
15.	Vac. jacketing	yes	yes	yes	yes



Conversion Error for Volume to Mass
Flow Calculations per Degree Fluid
Temperature Uncertainty (Para - hydrogen)

Figure 1



Conversion Error for Volume to Mass
Flow Calculations per 10 psi Fluid
Pressure Undertainty (Para - hydrogen)

Figure 2

However, they indicate that more work with vibration and 2-phase flow is necessary before most of them will commit themselves as to how their instruments will perform under these conditions. Little has been done to vacuum-jacket these units, but it is possible to do this and still be of a size and weight compatible with the X-15.

Figures 3, 4, 5a and 5b are basic outline sketches of these meters.

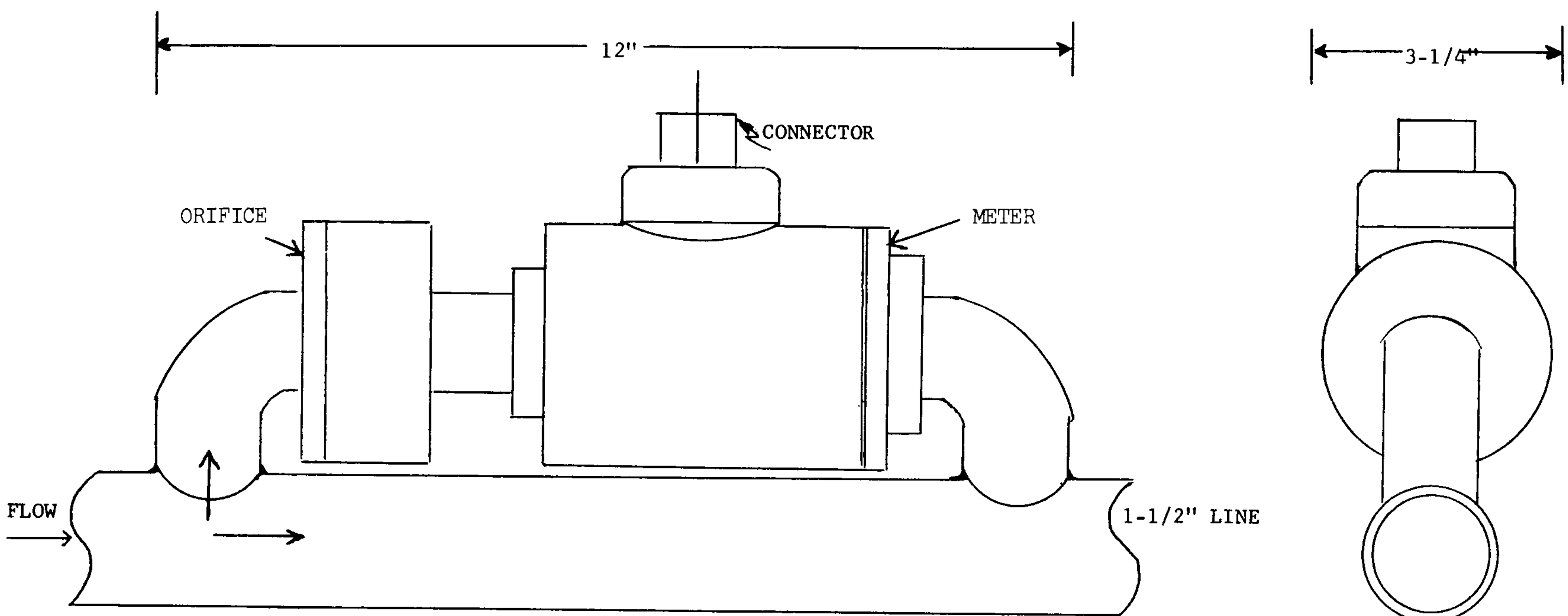
Figure 3 is the GE angular-momentum true mass flowmeter with bypass. This unit was originally designed for reading hydrocarbon mass fuel flow in jet aircraft and has been flown with considerable success on the B-47, B-52, KC-135, and many other aircraft. It works on the angular-momentum principle and responds directly to true mass rate of flow. No auxiliary equipment is required to measure and compensate for temperature and pressure. No amount of 2-phase flow will damage this meter in any way even though the design flow rate is greatly exceeded.

For the ranges desired, a bypass element is used with this flowmeter. It is a conventional orifice plate in the main pipeline which diverts a fixed fraction of the total flow from the sensor. Major design emphasis is placed on maximum reliability to eliminate hazards to the installation, in addition to ensuring long maintenance free life. Factors contributing to the utility of design include small physical dimensions, materials' compatibility, and low pressure drop.

The flow sensor is the primary detector of this liquid hydrogen measurement system. Its function is to develop a voltage signal proportional to total mass rate of flow. A predetermined but fixed fraction of total flow passes through the sensor.

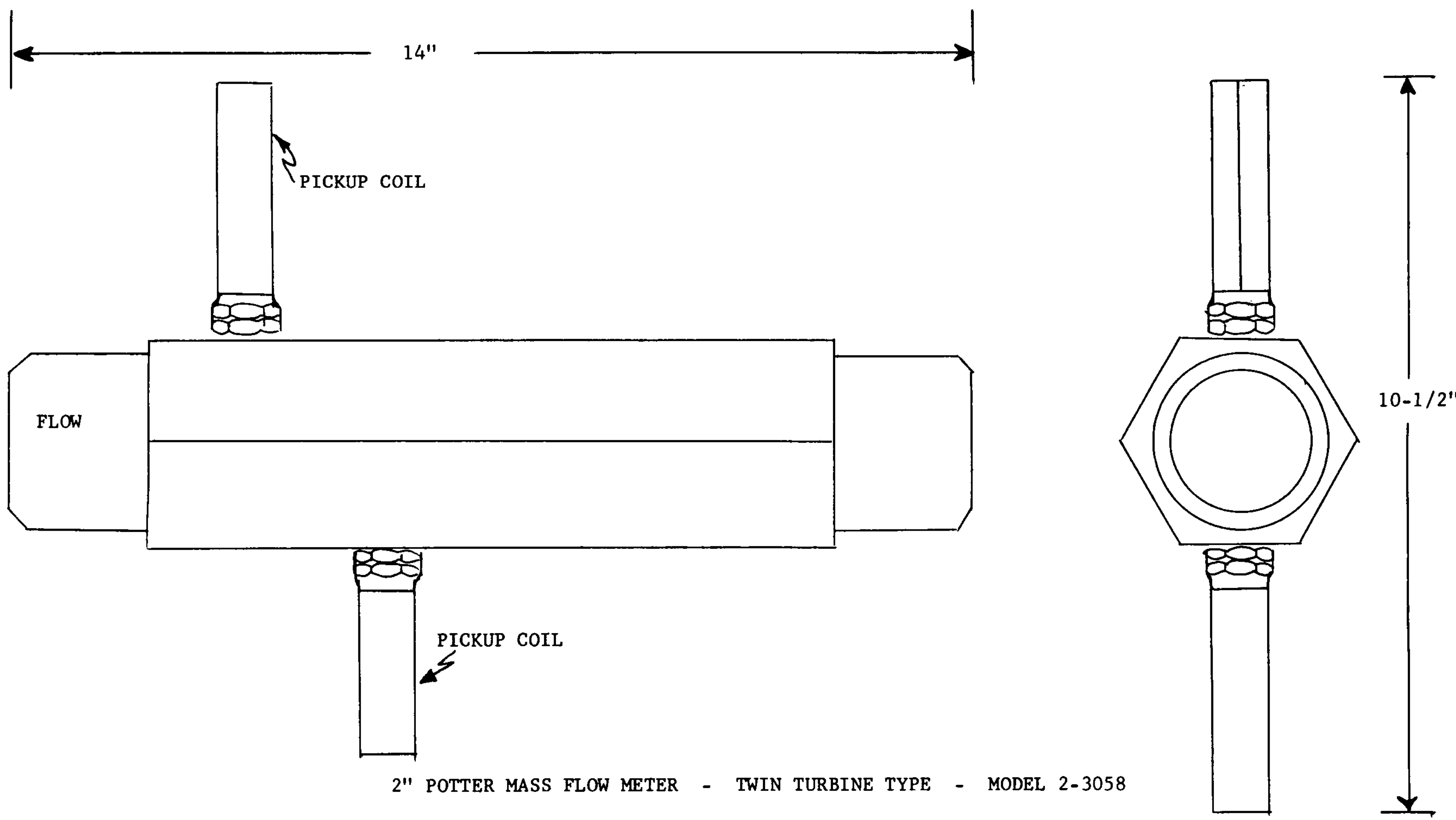
The flow sensor comprises five basic elements: an impeller, a turbine, a turbine-restraining element, an electromechanical transducer element, and an impeller drive mechanism. (see Fig. 6)

The primary hydraulic flow-sensing elements are the impeller and turbine. They are similar rotors placed coaxially end to end with small axial spacing, the impeller being disposed upstream of the turbine. Each rotor consists of a pair of concentric cylinders with radial vanes and/or thin-walled tubes dividing the annular space between them into a number of parallel flow passages. These rotors are enclosed in a common cylindrical housing. Radial clearances are small enough to prevent appreciable fluid flow around them. The impeller and turbine are rotatably supported through ball bearings on a common shaft. High quality ball bearings are selected on the basis of service-proven operating characteristics under cryogenic environmental conditions.



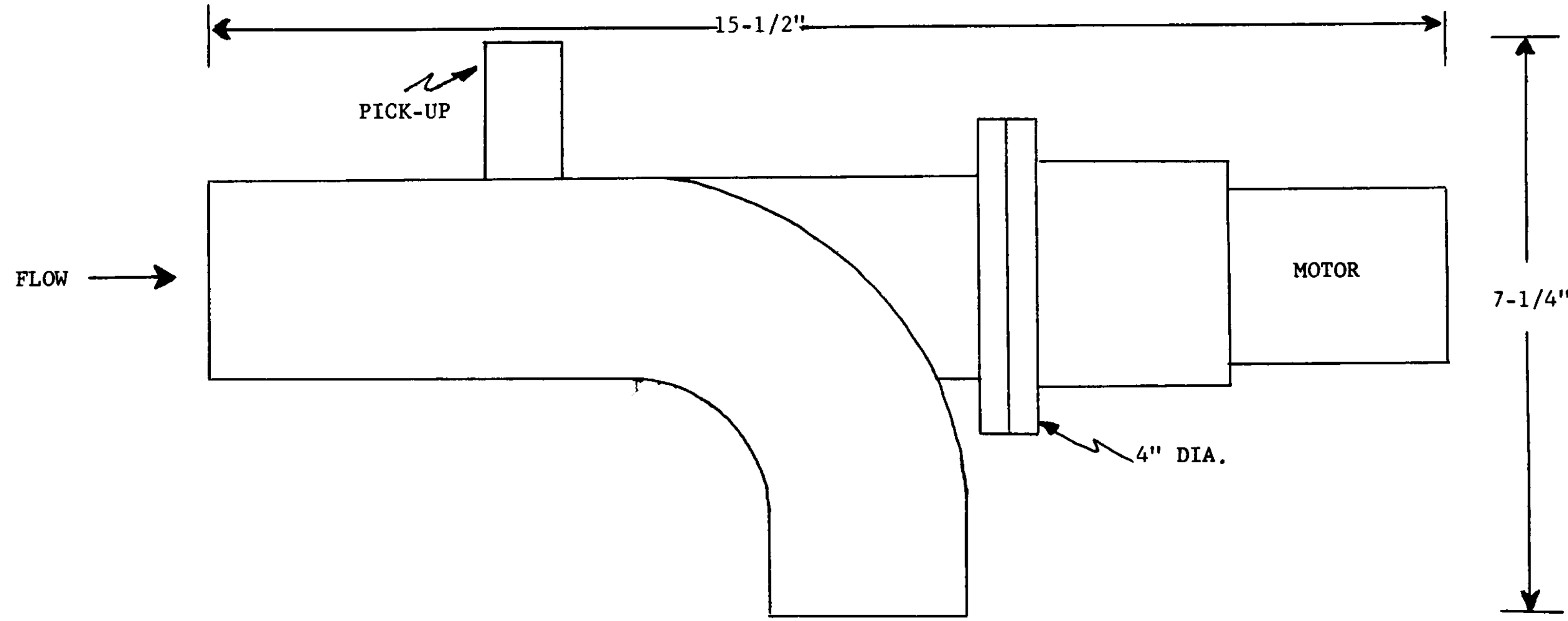
GENERAL ELECTRIC ANGULAR MOMENTUM MASS FLOW METER, MODEL TJ85 WITH BY-PASS

Figure 3



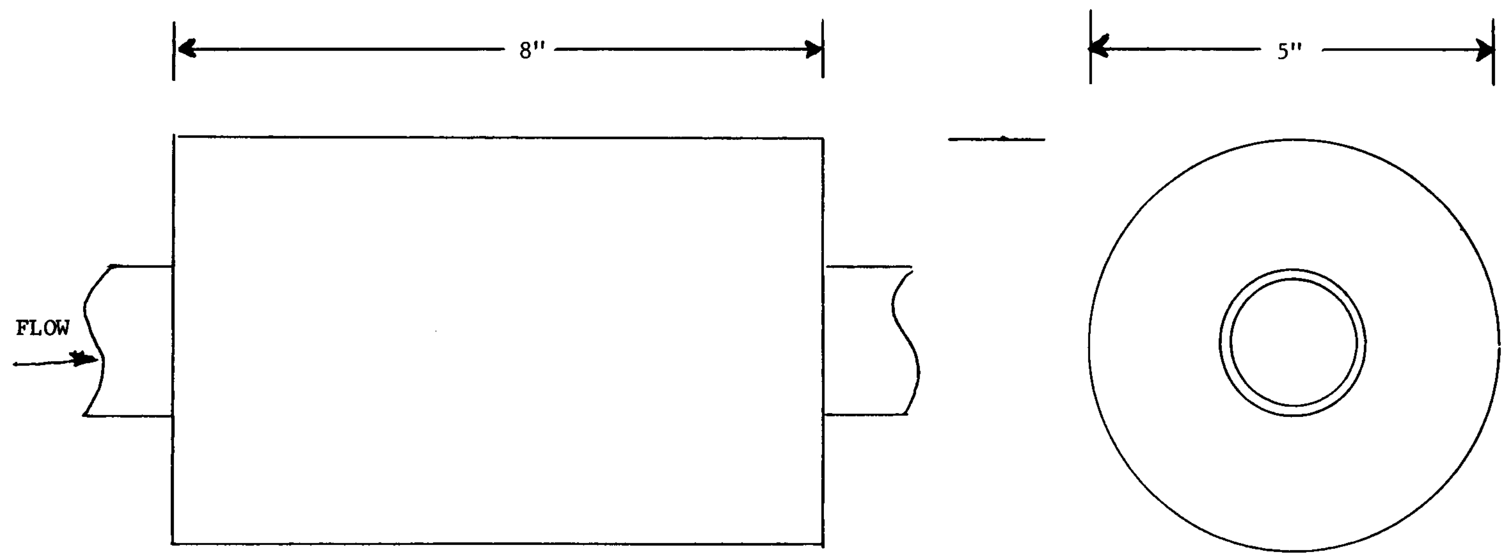
2" POTTER MASS FLOW METER - TWIN TURBINE TYPE - MODEL 2-3058

Figure 4



2" WAUGH-FOXBORO MASS FLOW METER - SINGLE TURBINE DRIVEN AT A CONSTANT TORQUE

FIGURE 5a



BENDIX 1-1/2" MASS FLOW METER - CAPACITANCE TYPE

FIGURE 5b

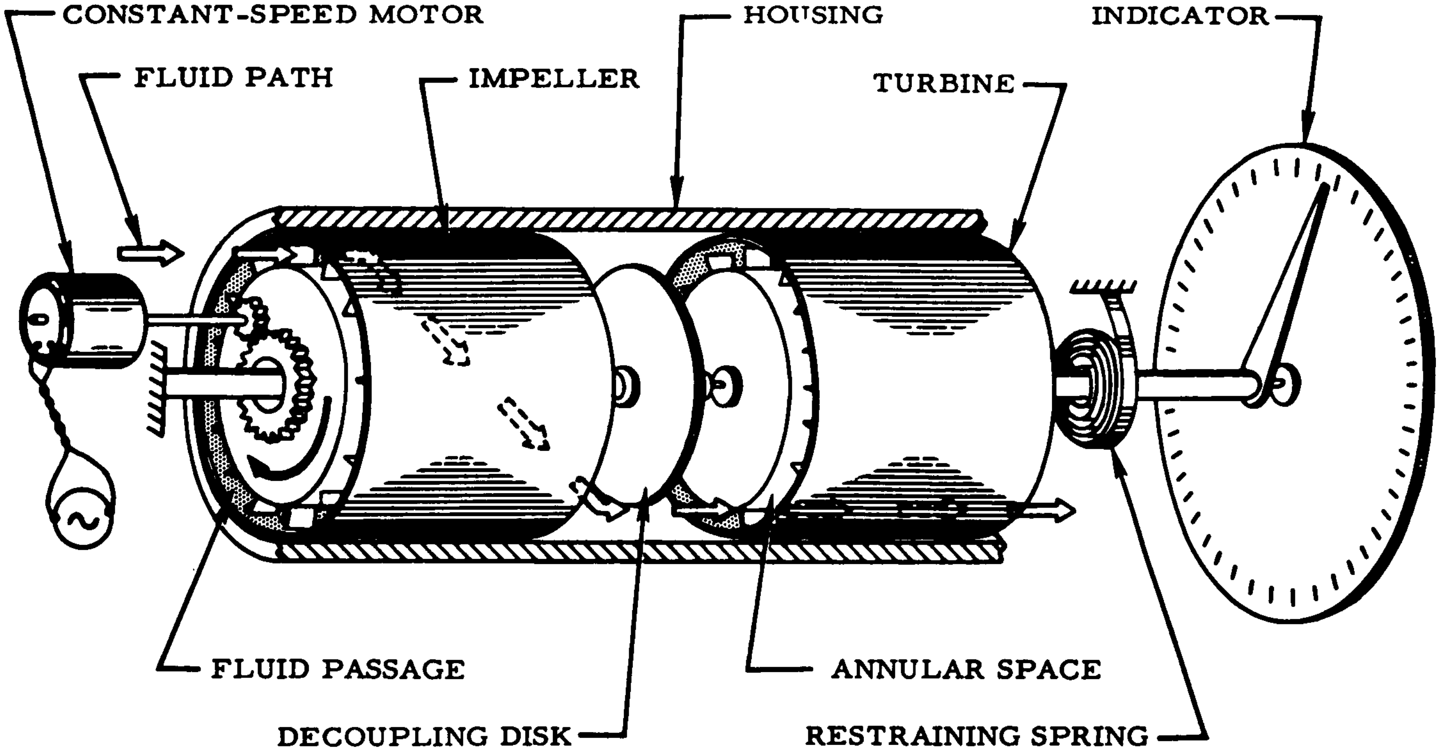


FIGURE 6 Pictorial Diagram of General Electric Mass Flowmeter

The basic simplicity of design is a major factor contributing to precise concentricity and axial alignment of the critical flow sensing elements. In addition, this approach effectively minimizes the influences of bearing friction, viscosity, and upstream disturbances of the fluid flow pattern. Experience has shown that such design considerations are highly significant in ensuring maximum accuracy, reliability, and long maintenance-free life. (Reference 9)

The turbine restraining element is a spiral spring of essentially conventional mechanical design. Materials are selected for compatibility with cryogenic environments in addition to the stringent operational requirements always imposed on such elements. A substantial reduction in criticalness is realized through use of a telemetering transducer that requires only moderate angular deflection in conjunction with a high turbine torque. These factors permit a relatively stiff spring, resulting in maximum resistance to the mechanical abuse associated with high levels of vibration and shock.

The electromechanical transducer is a brushless position -to-voltage type pickoff. Features of this element include extreme simplicity in both electrical and mechanical design, elimination not only of sliding electrical contacts (brushes and sliprings), but also removal of all electrical connections and conductors to regions entirely outside the fluid flow passages, incorporation of the rotating member as an integral part of the turbine structure, and ease of adjustment, maintenance, and serviceability. Such characteristics greatly enhance flexibility, accuracy, and reliability.

The impeller is driven by a permanent magnet-type synchronous motor energized by 2-phase, low-frequency AC electrical power. The entire impeller-drive mechanism comprises only the 4-pole motor stator and the rotor. The stator assembly is mounted outside the sensor housing, similar to that of the telemetering element. The rotor is simply a hollow cylindrical permanent magnet, diametrically magnetized and mounted as an integral part of the impeller.

Extreme simplicity is the outstanding characteristic of this design. All electric connections and wiring are isolated from the fluid without recourse to auxiliary means for motion transmission such as flexible diaphragms, rotating seals, or magnetic couplings. The basic arrangement of electrical components eliminates the need for fluid seals except for those otherwise associated with assembly or pipe connection procedures. There is no gearing either external to, or immersed in, the fluid and there are only four bearings, two for each rotor, of a design service-proven in cryogenic environments. The unique impeller drive-motor design has been in production in the General Electric mass flowmeter transmitter. Although designed for conventional hydrocarbon fuels, this transmitter has recently been subjected to flow tests with liquid nitrogen and liquid hydrogen. (Reference 9)

Relative to accuracy, the performance was precisely that to be expected under comparable hydraulic flow conditions with ordinary fuels. A shift due to thermoelastic spring properties was observed, as expected, but the cryogenic environment has no observable influence on hydraulic characteristics. The shift observed is a systematic error that is eliminated in the LH_2 calibration factor. During more than 40 hours accumulated operating time, the unit functioned without failure of any kind and no deterioration was observed upon completion of tests.

The impeller motor is energized by a precision frequency controlled power source to maintain constant speed. Each unit mass of fluid in transit emerges from the impeller flow passage and enters the turbine flow passage with constant angular momentum. In passing through the turbine this fluid momentum is reduced to zero. In consequence of Newton's Law, the fluid exerts on the turbine a mechanical torque proportional to mass flow rate independently of physical properties of the fluid such as viscosity, density, and environmental conditions.

The turbine is restrained by the spring to deflect through an angle proportional to fluid momentum torque. The pickoff develops a voltage proportional to deflection, and therefore proportional to mass flow rate as required. This unit is designed to maintain turbulent flow conditions in the sensor and bypass over the operating range, thus does not require a straightening section of line in front of it. The General Electric mass flowmeter will meet all of the requirements for steady state conditions which last for periods of .5 to 1 sec. duration but fails to meet the frequency response required. This unit could be used if the required frequency response was of the order of from one to two cps rather than 10 cps. Units of this type have been in production and have much background from the viewpoint of application and testing. Little if any improvement in frequency response characteristics of this meter are possible.

Figure 4 is a 2-inch Pottermeter, Series 3000, which has been designed for liquid hydrogen with a range of 99 to 505 GPM (1-5 lbs./sec.). This meter incorporates a rotor having two sets of turbine blades with different blade angles coupled by a spring and capable of relative angular motion with respect to each other. As a result of the blade angle difference, the two sets of blades tend to rotate at different speeds but cannot because of the spring coupling. Thus, they take an angular displacement with respect to each other, the magnitude of which is proportional to the flow momentum. However, the rotor assembly considered as a unit functions as a volumetric turbine meter, rotating at a speed proportional to the average fluid velocity.

Thus, by measuring the elapsed time taken for the phase-angle displacement to traverse a reference point as sensed by the two magnetic pickoffs, a direct measure of mass flow rate is effected. Both of the signals would have to be telemetered, received, and discriminated before any intelligence could be obtained from them or an airborne converter could easily be developed with a 0-5V DC output.

This meter would be approximately 15 inches long and 5 inches in diameter, with an offset for the two sensors of about 3 to 4 inches. The above dimensions include a vacuum jacket. The weight would be in the neighborhood of 25 pounds. The manufacturer does not claim operation of this unit at flow rates lower than 99 G.P.M.

This unit has been tested at Wyle Laboratories in Norco, California, with good results (Reference 10) when up to 11% of gaseous helium was introduced to simulate two-phase flow. Pressure drop is 1.2 p.s.i.d. Meter design requires a 2" diameter section to meet flow requirements and in addition, a 30" straight section of pipe is required ahead of the meter in order to maintain accuracy. In the current X-15 installation, this would require removal of the left wing.

Figure 5a is a basic outline of a 2 inch Waugh-Foxboro constant torque mass flowmeter, Model FM 32-400. This meter utilizes a single turbine which is driven with a constant torque. The turbine then turns at a speed proportional to mass rate of flow of the fluid passing through it. This signal is sensed by a conventional magnetic pickup coil and can be converted with equipment already developed for airborne use such as Foxboro Converter, Model FR-320, with 0-5V DC output. This flowmeter was designed originally for fuel truck use rather than aircraft. It is a rugged instrument that is not susceptible to overspeed.

Figure 5b is a Bendix mass flowmeter which operates on a null balance capacitance principle. Bendix feels that they can make this unit to be the size indicated, which includes a vacuum jacket. The only unit made so far was for NASA-Huntsville on Contract NAS 8-5218, as a prototype for ground use only. This was a 3-inch meter, 8 inches in diameter, and 11 inches long. It is claimed to have excellent response time, high accuracy and not to be affected by any amount of 2-phase flow. It uses a wire screen sensing element supported by a system of levers and diaphragms which eliminate all sliding or rotating friction. A null-detecting element is used which permits null error correction to be initiated within microseconds after the element departs from its null position. Thus, this flowmeter has a basic design which solves the frequency response-limiting characteristics of the rotating element type flowmeters.

The system measures flow rate by making two separate measurements on the fluid passing through a pipe (a) density of the fluid, and (b) integrated force the fluid exerts upon a screen placed in the flow stream.

These separate analogs are multiplied together to obtain an analog of mass flow rate. This analog is later integrated with time to obtain a total flow indication. The attractive features of these system elements are that they:

a. Are unaffected by 2-phase flow.
b. Require only microseconds to detect small errors.
c. Are not subject to overspeed or damage.

This unit also incorporates a counter-balance so that the transducer is to a large degree insensitive to the intensity, frequency, or orientation of body acceleration forces. As originally designed, the prototype meter was intended for ground use, with further study and design needed to meet the requirements for flight. Design goals are .1% full scale accuracy, better than 100 cps frequency response and reduced size for airborne use.

No airborne signal conversion equipment has been developed but could be with a compatible 0-5V DC output.

The Bendix-Pioneer central mass flowmeter appears to be the only meter capable of meeting all requirements for liquid hydrogen flow as identified in Section 3.1.1.

3.1.1.3 Installation

The liquid hydrogen flow sensor can be mounted in the fuselage on the left side of the X-15 between the leading and trailing edge of the left wing. Signal conditioning or power supply can be mounted in the instrumentation bay.

3.1.1.4 Calibration

W. J. Alspach and T. M. Flynn of the National Bureau of Standards (ref. 8) indicate that predictable water/cryogen correlation of calibration is highly improbable. Therefore it is recommended that the calibration of the LH_2 sensor be made using LH_2 and a mockup of the fuel plumbing system in which it will be used. A 15 point calibration should be made every six months.

Wyle Laboratories have an excellent liquid hydrogen facility for meter calibration with accuracies on the order of .1%. They have been performing steady state flow calibrations and tests for some time at 50 psig. The pressure used in the X-15 LH_2 system will be 330 psig. It is unknown at this time whether it will be necessary to calibrate this unit at its operating pressure. A description of the Wyle facilities is included in Appendix 1.

3.1.2 Pyrophoric Fuel Flow

3.1.2.1 Meter Selection

A true mass flow meter could also be made for a pyrophoric fuel such as pentaborane with the range and accuracies necessary and eliminate the need for recording temperature and pressure of this fuel. To determine the mass rate of flow, true mass flow rate would be sensed by this unit and recorded on one data channel; however, a volumetric meter would certainly satisfy the accuracy requirements and be much less expensive. Cox, Potter, Waugh, and many others make volumetric flowmeters which could be used with pentaborane.

3.1.2.2 Calibration

Calibration of this unit with the pyrophoric fuel selected will be possible with ±2% of point accuracy on the flow stand presently under construction at Edwards Air Force Rocket site.

Some development work to obtain compatible materials and some testing to determine what bearings should be used will probably be necessary. Many precautions will have to be taken for ground handling of pyrophoric fuels because it is a highly toxic and volatile liquid.

3.1.3 Hydrogen Pressure Measurement

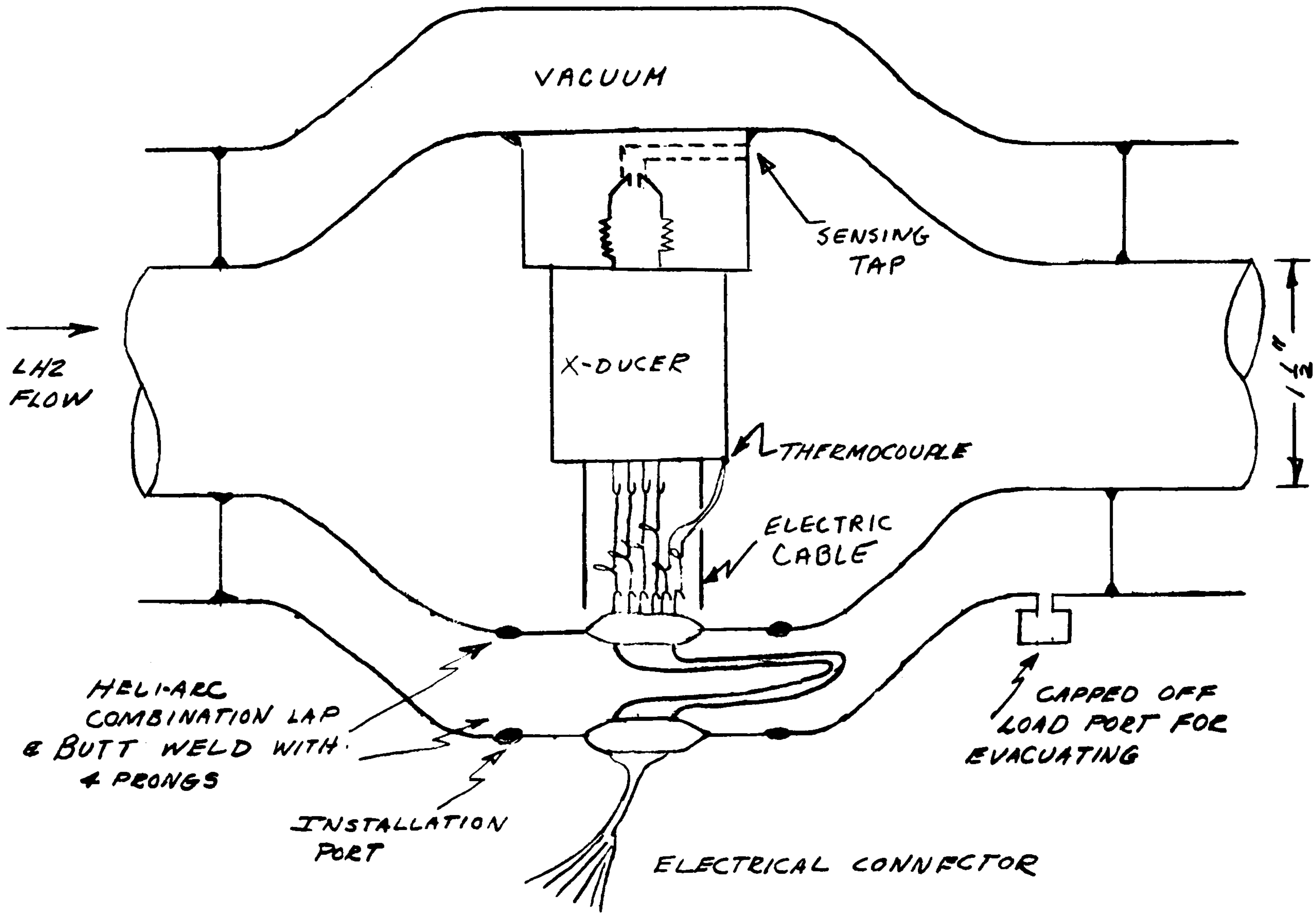
Measurement of liquid hydrogen pressure is a requirement for hypersonic ramjet testing, primarily to determine hydrogen thermodynamic conditions and fuel system performance. The anticipated requirements are:

a. Range 300 - 500 psia
b. Accuracy ±5 psia
c. Frequency 0-3 cps

These objectives are feasible if certain constraints are placed on the instrumentation particularly with respect to location of the transducer.

The measurement may be accomplished by locating the transducer in one of three ways:

a. Immersing it in the hydrogen transfer line in the X-15 or ramjet. (Figure 7)
b. Boss-mounting on the ramjet line. (Figure 8)
c. Remote mounting in the ramjet thermally-lagged instrumentation package.



CONCEPTUAL INSTALLATION OF PRESSURE TRANSDUCER IN LH2 LINE

FIGURE 7

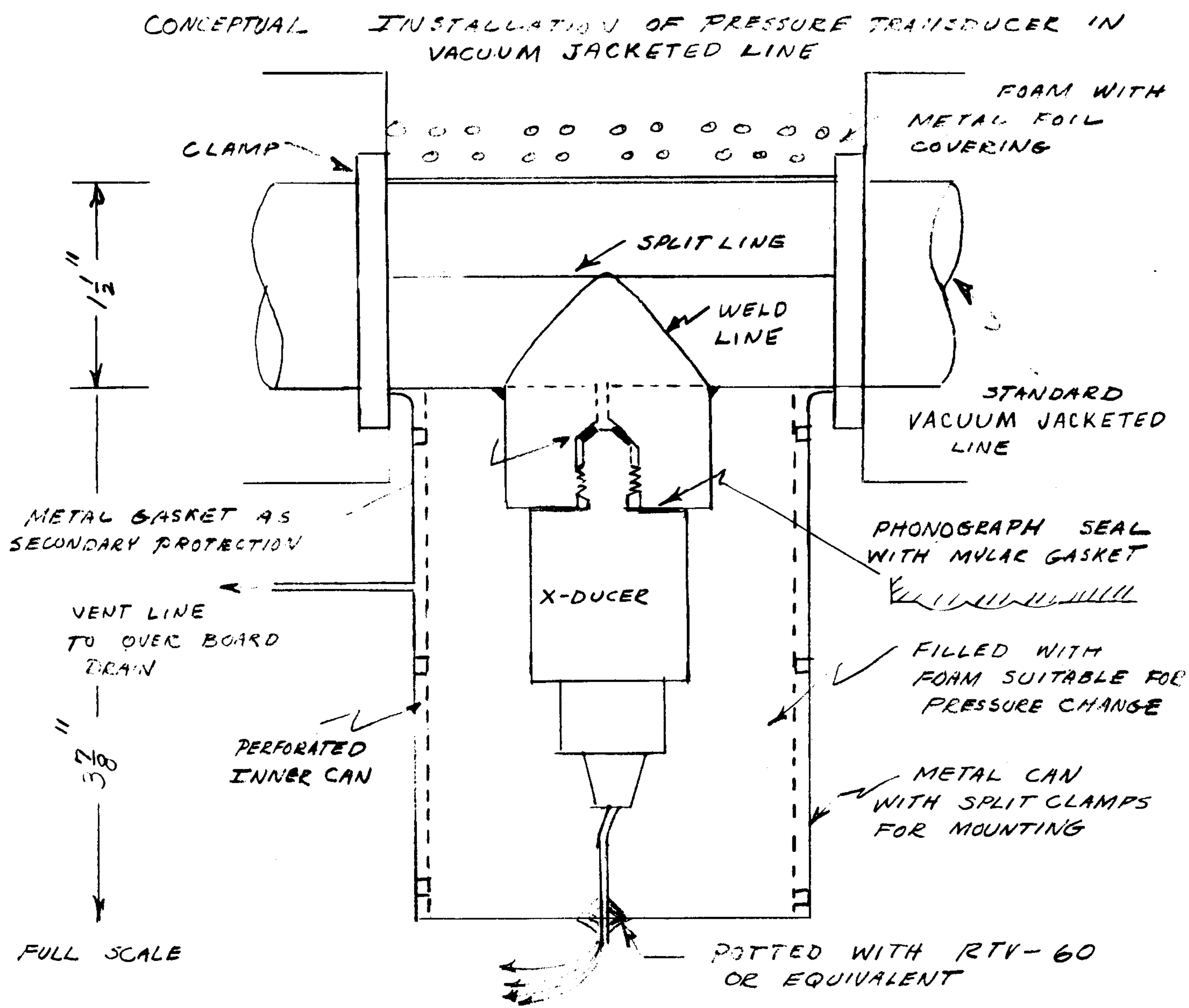

CONCEPTUAL INSTALLATION OF PRESSURE TRANSDUCER IN
VACUUM JACKETED LINE
CLAMP
FOAM WITH
METAL FOIL
COVERING
SPLIT LINE
WELD
LINE
STANDARD
VACUUM JACKETED
LINE
METAL GASKET AS
SECONDARY PROTECTION
PHONOGRAPH SEAL
WITH MYLAR GASKET
X-DUCER
VENT LINE
TO OVER BOARD
DRAIN
FILLED WITH
FOAM SUITABLE FOR
PRESSURE CHANGE
PERFORATED
INNER CAN
METAL CAN
WITH SPLIT CLAMPS
FOR MOUNTING
FULL SCALE
POTTED WITH RTV-60
OR EQUIVALENT

Figure 8.

3.1.3.1 Sensor Immersion

Liquid hydrogen will provide an exceptionally stable environment for an immersed transducer (Ref. 12). The only requirement is to supply a transducer that has a known calibration at this temperature. Electro-mechanical compensation is available that would provide nearly the same zero and sensitivity levels at both room temperature and LH_2 temperatures. A relatively large error of repeatability on multiple thermal shocks between room temperature and LH_2 has been observed. The Bureau of Standards (ref. 13) reports errors in the order of 1% from this cause. Apparently there is appreciable mechanical or electrical unstability within the normal transducer. An expected error analysis for this type environment, assuming laboratory calibration of LH_2 temperature and computer correction of the calibration follows:

Source	Error (%F.S.)
Lab calibration errors	±0.1
Aircraft installation unknown	±0.9
Thermal Shift-10°R	±0.1
Hysteresis	±0.25
Vibration - 10 G	±0.27
Non-repeatability(multiple thermal shock)	±1.0
PCM Drift	±1.0
Non-linearity	±0.5
Single thermal shock	Nil

While this transducer location poses an installation problem, it is the recommended way to obtain hydrogen thermodynamic state.

Another requirement on the ramjet is the measurement of the pressure after the fuel control to evaluate control and surge problems, and thermodynamic state of hydrogen. To simplify installation and weight in the ramjet, either a boss-mounted transducer or a remote mounted unit is possible.

3.1.3.2 Remote Mounting

While the remote mounted transducer is more accurate, it imposes surge oscillation, safety, and weight problems which are not acceptable. Additional lines in the liquid hydrogen flow system should be looked at with care before installation for possible leakage at couplings and for fatigue failure. If negative and positive "G" occur, surges will appear because of LH_2 vaporization as the liquid-gas interface is displaced.

3.1.3.3 Boss Mounter

The practical solution to transient pressure measurements in the liquid hydrogen line is utilization of the transducer mounted on a boss. This will provide good data as long as sufficient cooling time exists before the ramjet operation to insure thermal stability. Thermal transients can cause large errors.

3.1.3.3. Boss Mounter - cont'd

A thermal step from roomtemperature to LN_2 with the state of the art transducers resulted in errors as high as 12% of full scale at a test conducted by the National Bureau of Standards. (ref. 13) Foam insulation sprayed on the transducer after installation would decrease this problem. Some data available from the National Bureau of Standards (ref. 13) indicates transducer response times in the order of two seconds, but the test conditions were different enough to question its application to the ramjet. Temperature monitoring of the transducer would reduce the uncertainty by establishing that steady state temperature conditions are present. When this is established, errors of less than 4% of full scale can be surmised from the manufacturer's bulletin without corrections from temperature information.

Transducers when purchased should specify calibration at room and LH_2 temperatures with at least three temperature cycles to establish stability. Calibration curves should be supplied at room temperature and LH_2 temperatures. Some vendors have utilized GHe to temperature compensate and extrapolated the calibration curves to 36°R.

Calibration of cryogenic transducers should be periodically made at room temperature in the calibration laboratory. Any deviation from its previous value above 1% F.S. should require recalibration at cryogenic temperatures.

3.1.4 Hydrogen Temperature Measurements

3.1.4.1 Requirements (36°R - 60°R)

Measurement of liquid hydrogen temperature in the environment of the X-15 and the ramjet greatly restricts the choice of thermometers. For measurements in the liquid state, the requirements include:

Measurement range:	36°R to 60°R
Accuracy:	±1°R
Frequency Response:	0-3 cps
Maximum velocity of hydrogen:	90-100 ft./sec.
Diameter of cryogenic line:	1-1/2"
Weight:	At a minimum

3.1.4.2 Types of Sensors

Some types of thermometers considered to accomplish these requirements are:

a. Gas thermometers
b. Vapor-pressure thermometers
c. Magnetic thermometers
d. Thermoelectric thermometers
e. Quartz crystal thermometers
f. Resistance thermometers.

Types of sensors - cont'd

a. Gas Thermometers

This approach uses knowledge of the gas state to measure temperature. A known volume of gas at cold temperature is contained in a closed system. The pressure is measured and temperature is calculated, knowing the particular gas characteristics along with pressure and volume. It is suitable for long time static measurements and achieves an accuracy of ±0.09K. It is quite useful as a secondary standard over a range of 75°R - 162°R. using helium gas.

b. Vapor Pressure Thermometers

Vapor pressure thermometers consist of a bulb partly filled with a liquid or solid, with vapor in equilibrium with the condensed phase connected to a pressure measuring instrument. This is an excellent secondary standard using the physical properties of the material to establish boiling point temperature. It is suitable for calibrating thermocouples and platinum resistance thermometers over limited ranges of temperature. For instance the liquid He vapor pressure thermometer is used between 3°R - 7.5°R.

c. Magnetic Thermometers

This approach is utilized primarily for temperatures below 1.8°R, which is near the lower limit for a vapor pressure thermometer using the gas. These low temperatures are determined by measuring the magnetic susceptibility of a para-magnetic salt. This requires a very elaborate system and is used for work to determine temperatures close to absolute zero.

d. Thermoelectric Thermometers

Of the many ways to measure cryogenic temperatures, thermocouples are the simplest, disturb the stream the least, and have the fastest response. Unfortunately thermocouples do have shortcomings that limit their use for making cryogenic temperatures and the greatest one is the low microvolt per degree output. Several thermocouples have been calibrated from 5°R up to the values reported in NBS circular 561. Typical output range from 3-15 microvolts per degree R in the 36°R-60°R range. This low output per degree makes it imperative that the wire be homogeneous over its entire length and prohibits the use of plugs, connections, or any substitution of one wire for another.

Thermoelectric Thermometers - cont'd

Small changes in temperature of the reference junction also affects the accuracy. For instance, for a 492°R reference the microvolts per degree of chromel/alumel is approximately 22 microvolts/1°R. At 36°R, the value is 2.2 microvolts/1°R. For every .1°R error of the reference junction a 1°R error would be observed in the final temperature determination.

Thermopiles (several thermocouples in series) can be used to a good advantage to measure differential temperatures. However, it is important to know the reference temperature very accurately and the non-linearity of the thermocouples add problems to this method of measurement.

e. Quartz Crystal Thermometers

A quartz crystal applied in a resonant circuit can result in a rather linear light weight temperature sensitive probe in the cryogenic region. The signal conditioning can be provided in an output format that would be suitable to the X-15 data system, requiring a single tape track to record the temperature sensitive frequency signal along with the use of an accurately timed clock track to process the data.

In the present designs the crystal is enclosed in a gas filled envelope and the crystal must be brought to the cryogenic temperature. This results in a long time constant instrument. Its typical characteristics are:

Type:	Quartz crystal temperature sensor
Temperature range:	36°R to 765°R
Resolution:	36°R to 90°R ±.018°R
	90°R to 765°R±.0063°R
Linearity:	±0.2°K nonlinearity 135°R to 162°R
Repeatability:	.036°R
Response time:	3-5 seconds
Probe power consumption:	Less than 20 MW
Output power:	1/2 watt minimum
Output impedance:	50 ohms
Weight: sensor	4 ounces
Signal conditioner	16 ounces - Instrumentation compartment

f. Resistance Thermometer

The property of variable resistivity in materials with temperature can result in some rather rugged, sensitive and accurate thermometers. The suitability of a particular material to provide a satisfactory measurement in flight depends upon many factors:

a. Resistivity that is reasonably linear with temperature.
b. Resistivity stability.
c. High sensitivity.
d. Insensitivity to environment
e. Mechanical suitability.

No one material exhibits all these characteristics over the entire temperature range. Materials that can be used as resistance thermometers can be divided into pure metals, alloys, and compounds that are semi-conductors. Pure metals and alloys usually exhibit a positive temperature coefficient of resistance and become less sensitive at lower temperatures. Pb, In, Pt, Cu, Au-Ag have and are being used by different experimentors. Lead and Indium have been used to 13°R and 6°R (ref.15) but must have special handling. Platinum has exhibited the best properties above 18°R and is used in the standards, calorimetry and missile fields. The semi-conductors usually have a negative temperature coefficient and have excellent sensitivity over very short temperature ranges. Carbon resistors and thermistors are available that have temperature coefficients of 1000 MV/1°R in specified ranges. Temperature range of this family of detectors is from 7°R - 200°R. (ref.16) Problems have been experienced such as reproducibility with thermal cycling and atmospheric exposure. A recent development in this field has been the doped germanium crystal. It has been used successfully from 2°R - 200°R. (ref.17)

3.1.4.3 Sensor Selection

In evaluating the different sensors for the application of measuring hydrogen temperatures in the range of 36°R-60°R, the following factors were considered:

a. Simplicity.
b. Response time.
c. Compatibility with the PCM recording system.
d. Accuracy.

Gas, vapor pressure, and magnetic thermometers involve complicated systems that are more applicable to special laboratory problems such as standard laboratories than to missile applications. The slow time response eliminated the quartz crystal for this application.

Sensor Selection - cont'd

For the final analysis, three systems were considered. One, a stable and reproducible commercially available semiconductor, a doped germanium crystal. Two, a platinum-resistor thermometer with a 1000 ohms resistance at 492°R. Three, a thermocouple system using either the most sensitive gold-cobalt thermocouple or the more conventional chromel-alumel thermocouple.

All systems were normalized for use on the X-15 Pulse Code Modulation system. The output of all systems were limited to ±15 millivolts in the 36°R-60°R range. This was done by reducing the current flowing through the detectors so that the maximum signal did not exceed ±15 millivolts.

The three systems are plotted on figure 9. It is obvious if a least count of 60 microvolts for thePCM is used as one of the criteria that none of the thermocouple systems are sensitive enough to meet the 1°R accuracy.

The platinum resistance thermometer has more sensitivity above 45°R and less sensitivity below 45°R than the germanium resistor. For the 30°R-60°R range, the lowest sensitivity for the Pt resistance thermometer is 250 Mμ/1°R and 100 Mμ/1°R for the germanium resistor.

The most probable working range for the pumping system would fix the critical temperature measurements to be in the 40°R-59°R range. The platinum resistance thermometer is equal, or superior to, the germanium crystal in this range. The platinum resistance thermometer is recommended for this application.

3.1.4.4 Error Analysis

The error analysis for a selected commercial platinum resistance thermometer is summarized below for a 36°R measurement. A temperature of 36°R will result in the largest error.

Error Source	Dynamic Error °R	Random Error °R	Systematic Error
Sensor Calibration		±0.05	
Interpolation		±0.10	
Repeatability		±0.18	
Frequency - 3 cps	±0.17		
System Calibration		0.016	
Interchangability		1.50	
Recovery		± .005	-0.01
Stem Conduction			+0.03
Power Supply		± .02	
Signal Conditioning		± .01	

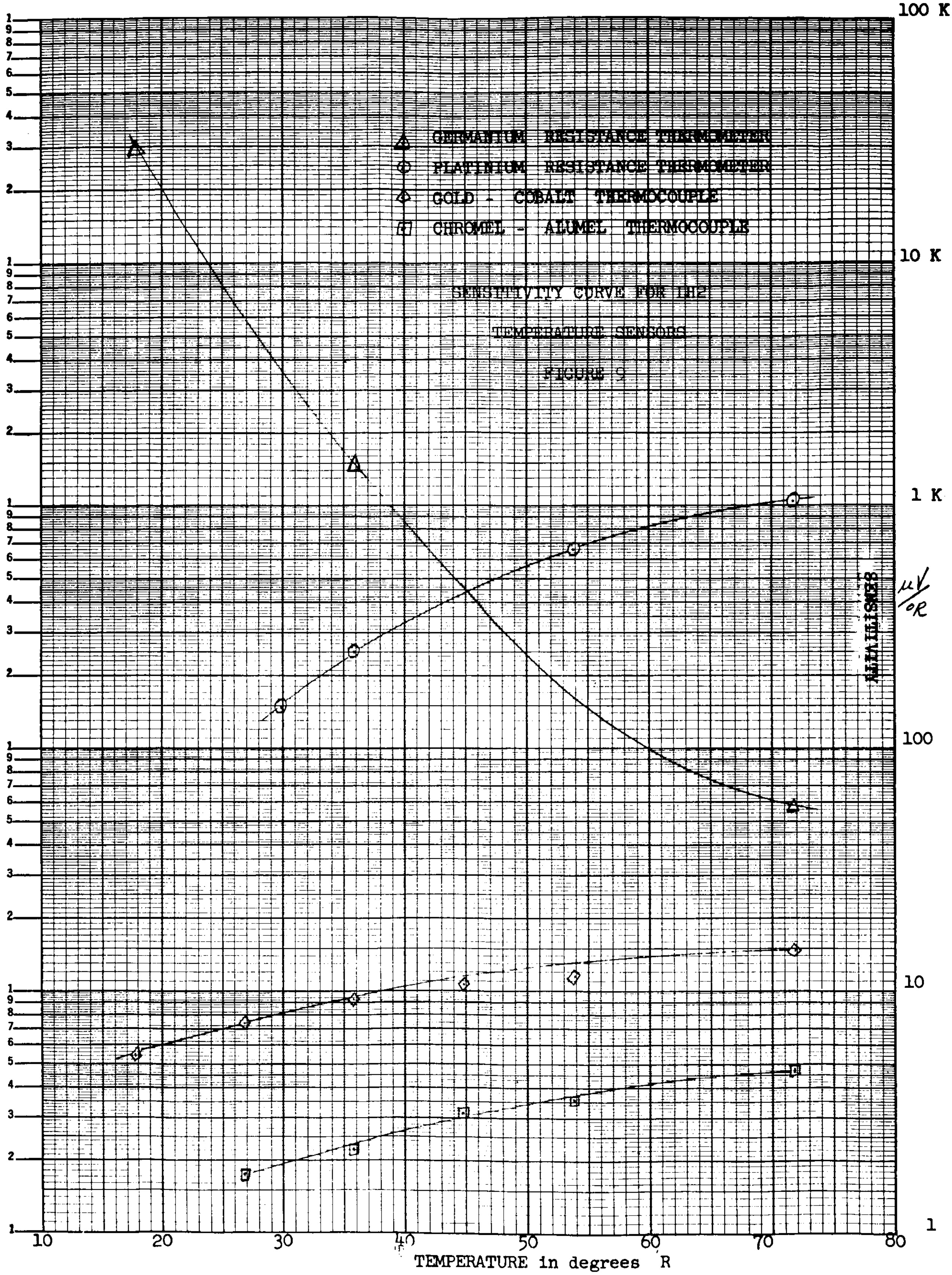

GERMANIUM RESISTANCE THERMOMETER
PLATINIUM RESISTANCE THERMOMETER
GOLD - COBALT THERMOCOUPLE
CHROMEL - ALUMEL THERMOCOUPLE
SENSITIVITY CURVE FOR LH2
TEMPERATURE SENSORS
FIGURE 9
SENSITIVITY
100 K
10 K
1 K
100
10
1
10
20
30
40
50
60
70
80
TEMPERATURE in degrees R

Figure 9.

The root mean square value of the random and dynamic error is ±0.31°R. This is well within the requirements of the system of ±1°R. It should be pointed out that there is no way to insure that the probe will measure the average temperature of the hydrogen in the pipe. If the temperature profile in the pipe is large, the error could be greater than 1°R.

Calibration and Interpolation Error

Calibration of the probe should be conducted at 491°R, 139°R, and 7.29°R accurate to 0.04°R. The low temperature points are in addition to the normal specifications. Vendors will supply computer printout on interpolated data in groups of 20 points which are accurate to ±0.1°R, which can be charged as random error. In view of the range required, the 20 resistance temperature points should be from 35°R in 2° increments to 73°R. This information will permit a resistance box to substitute in the calibration of the aircraft PCM system.

Recovery Error

Frictional heating effect in a moving liquid can result in a temperature rise on a probe. The theory has been investigated in detail for only a few specialized cases. Flow parallel to a flat plate in laminar conditions is well described. Using the conditions of LH_2 at 90.6 ft./sec., an estimate heat rise of .01°R can be calculated. While this cannot be applied directly to the configuration of a round probe with a high Reynolds number, a rough idea of the magnitude is obtained. The use of a velocity guard to decrease this type of error will result in a degraded frequency response.

Stem Conduction Error

In this application the magnitude of stem conduction error for a probe in LH_2 at 36°R primarily depends on the heat transfer resistance between the external stem and the surrounding atmospheric medium. The error has been estimated for the Rosemount #150MA6 probe in air at 5 ft./sec. and ambient pressure. It is a systematic error in the order of +.03°R. The solution requires insulated coating to eliminate cryogenic pumping. A light coat of rigid foam will be sufficient to acheive these conditions. The error will decrease with altitude to an insignificant value under test conditions.

Power Supply and Signal Conditioning Error

The signal conditioning with a single resistor as previously discussed provides a minimum error. The X-15 instrumentation power supply can contribute error. A variation of 0.1% F.S. in the supply will contribute a random error in the order of 0.02°R.

3.1.4.4 Error Analysis - cont'd

Power Supply and Signal Conditioning Error - cont'd

Selection of the resistor material requires a near zero temperature coefficient material to make error from this cause small. For example, the use of manganin wire varied over 72°F results in a temperature uncertainty of approximately 0.01°R.

Insulation and Shunting Error

Any resistance shunting the probe will have an effect of decreasing sensitivity and will result in a systematic error which can be largely eliminated by system calibration. The specification of input impedance on the PCM system is 200,000 ohms. An uncertainty in impedance of this value will result in an error of .005°R.

Repeatability Error

Repeatability of platinum probes over repeated cycling of temperature is as good as 0.18°R. This is a random error.

Frequency Response Error

The time constant for a typical probe in LH_2 flowing at 91.6 feet/second is 0.016 seconds. This gives a frequency response.

$$F = \frac{1}{2\pi T} = 10 \text{ cps (3 db down)}$$

Assuming a single time constant which is the worst possible case for a heat transfer, the attenuation is at 3 cps.

$$A = \frac{1}{1 + J\ f/F} = .957$$

Making the assumption of a 10% fluctuation of temperature at 40°R, the error due to time delay is 0.17°R.

This value is based on a Rosemont 150 MA sensor. The calculations are derived from Rosemont Bulletin 106017, entitled "Time Constant and Self Heating Effects for Temperature Sensors in a Moving Fluid", and Bulletin 7619 entitled "Methods of Measuring Temperature Sensor Time Constant and Self Heat."

System Calibration Errors

Calibration of the platinum resistance measuring system is most easily accomplished by placing a decade resistance bridge in place of a platinum probe, adjusting the resistance to the calibration resistance for a specific temperature on a 10-20 point schedule. This eliminates many systematic errors. In calibration the accuracy of the resistance decade box should be determined and recalibrated periodically. The errors from this source are rather small with a good decade box. Assuming a ±0.15% resistance standard, the temperature error is ±0.016°R at 36°R to ±0.029°R at 60°R. This is a random error.

3.1.4.4 Error Analysis - cont'd

System Calibration Errors - cont'd

Interchangability

Interchangability of probes is of interest when a unit has failed. At 60°R interchangability is excellent, in the order of ±0.2°R; but at 40°R, interchangability between probes results in errors of about ±1.50°R. In view of the accuracy requirements of better than ±1°R, any change of probes will require recalibration of the system and a change in the data reduction program.

Self Heating Error

Specification of the selected probe results in a 1.8°R error for 360 microwatt dissipation. The selected current of 0.5 MA is approximately .2 microwatts at 36°R to 7.5 microwatts power dissipation at 60°R. This results in negligible error.

Recording System

The PCM recording system (low level) was selected for this measurement. Low level accuracy for the environmental conditions without individual channel calibration should be approximately 1% of full scale if major dropout errors are excluded. With individual channel calibration the expected errors might be 0.5 to 0.6%.

3.1.4.5 Requirements (200-R - 1800°R)

The requirements for the measurement of temperature rise of the hydrogen in the cooling tubes are specified as follows:

Measurement Range	200°R - 1800°R
Accuracy	2° at 200, 20° at 1800°
Frequency response	0-3 cps.

3.1.4.6 Types of Sensors

A sensor that has a linear output whose signal is recorded on the PCM recording system will have an average sensitivity of 3.2°R per count.

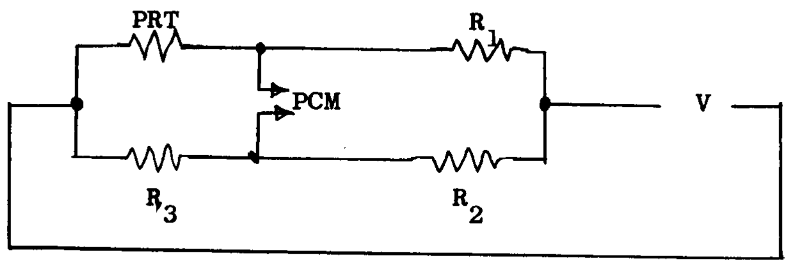
Based upon the general discussion of methods for measuring hydrogen temperature, only two systems were considered. One, the platinum resistance thermometer, and the other the swaged ceramic insulated chromel alumel thermocouples.

3.1.4.6 Types of Sensors - cont'd

a. The platinum resistance thermometer (PRT)

The platinum resistance thermometer can be purchased as off the shelf items to measure gas temperatures in the range of 25°R-1950°R. One of the advantages of this sensor is that it can be placed in a non-linear bridge and read out on the PCM system and meet the quoted accuracy.

A typical platinum resistance thermometer for this application would change its resistance from 160Ω to 1800Ω over the range from 200° - 1800°R. A non linear bridge can be made as follows:



The voltage across the bridge and the values of R_1, R_2, and R_3, are chosen such that the full scale of 30 MV will equal the range of 200-1800°R, and the change in MV/1°R is greater at 200°R than it is at 1800°R.

A platinum resistance thermometer that is rugged enough to stand a 200°R-1800°R range is usually large and has a slow response time. However, the time response could be increased by not using a protective wall and exposing the probe directly to the stream.

Great care must be exercised to make certain that the sensor is the same temperature as the gas. The sensor should not disturb the stream by creating a large pressure drop and the sensor must be insulated to make certain that it is not affected by its environment. This could prove to be a very serious problem for the task of measuring the temperature in the cooling tubes.

The error analysis would include all of the items covered in the discussion of the platinum resistance thermometers, plus an allowance for uncertainty in the change in resistance of the leads on the thermometer and the sensitivity of the bridge at different temperature levels. No difficulty should be encountered measuring the sensor temperature to ±2°R at 200°R and 2% over the entire range.

b. Thermocouples

Thermocouples have a great advantage in measuring the temperature of gases flowing in small tubes. They can be made very small, (an overall diameter of .010 is possible), and they measure the temperature in very small zones with a minimum amount of disturbance.

3.1.4.6 Types of Sensors - cont'd

b. Thermocouples - cont'd

The thermocouple considered for this application would be a small swaged thermocouple assembly with a sealed end and an insulated measuring junction. This thermocouple is explained in detail in the section dealing with structural measurements. A sealed thermocouple would be preferred because of its non-vulnerability to problems caused by hydrogen and assembly.

At cryogenic temperatures chromel and alumel should not be subjected to hydrogen because of embrittlement (ref. 18) however, at temperatures above 1500°R, direct exposure is possible. It is often advantageous to fabricate parts with the thermocouples installed. This can be accomplished by sealing both ends of the swaged thermocouple sheath for the brazing cycle and terminating the lead end after fabrication. Although it is possible to send sheathed thermocouples through a brazing cycle it is recommended whenever possible, that guide tubes be brazed into place during fabrication and the thermocouples installed in these guide tubes later at a sacrifice in accuracy.

Thermocouples can be used to indicate temperatures without disturbing the stream at different locations on the tube bundle by merely fastening the thermocouples to the outside of the tubes and insulating the thermocouples and the tube for minimum heat loss. When thermocouples are used to measure the temperature of gas in tubes the thermocouples should be inserted so that several diameters are exposed parallel to the stream. This minimizes the error due to radiation and conduction.

3.1.4.7 Sensor Selection

The final selection of sensors for measuring hydrogen temperature on the ramjet engine to determine thermodynamic state will depend primarily on how many are required, and how much space can be provided for installation. Where a small number of sensors are required, the platinum resistance thermometer represents the most accurate measurement system.. For a large number of measurements and inaccessible locations, the sheathed chromel/alumel capped thermocouple is recommended. The trade-off is basically convenience for accuracy.

If one type of thermocouple is used to cover the requested, wide range, chromel/alumel is a recommended selection. Because the thermocouple has an output voltage of approximately twice the PCM system at 1800°R an attenuator is required. The stability of the PCM system is 1%; this represents 150 micro volts at the gate input or 300 micro volts at the attenuator input. Since this is a large value relative to the typical CA sensitivity of 23 micro volt/°R, it is evident that individual calibration of each thermocouple channel is required to achieve the desired accuracy. The expected improvement in accuracy is .6% full scale or 180 microvolts uncertainty at the input to the attenuator.

The chromel alumel thermocouple changes its sensitivity with absolute temperature. A comparison of the expected error, including this effect, is given below along with the desired system accuracy.

Temperature	PCM Error	Desired Accuracy
1800	7.8°R	36°R
500	8.2°R	10°R
200	15.0°R	4°R

3.2 Static Pressure

Static Pressure is defined as the actual pressure existing in a flowing gas also sometimes referred to as stream pressure (Ref. 19). In order to measure engine internal performance it will be necessary to measure static pressures at various points throughout the engine. Errors can be introduced at several points in the measuring system and are generally identified with (a). Pressure taps, (b). Dynamics of pressure lines, and (c). Pressure readout systems.

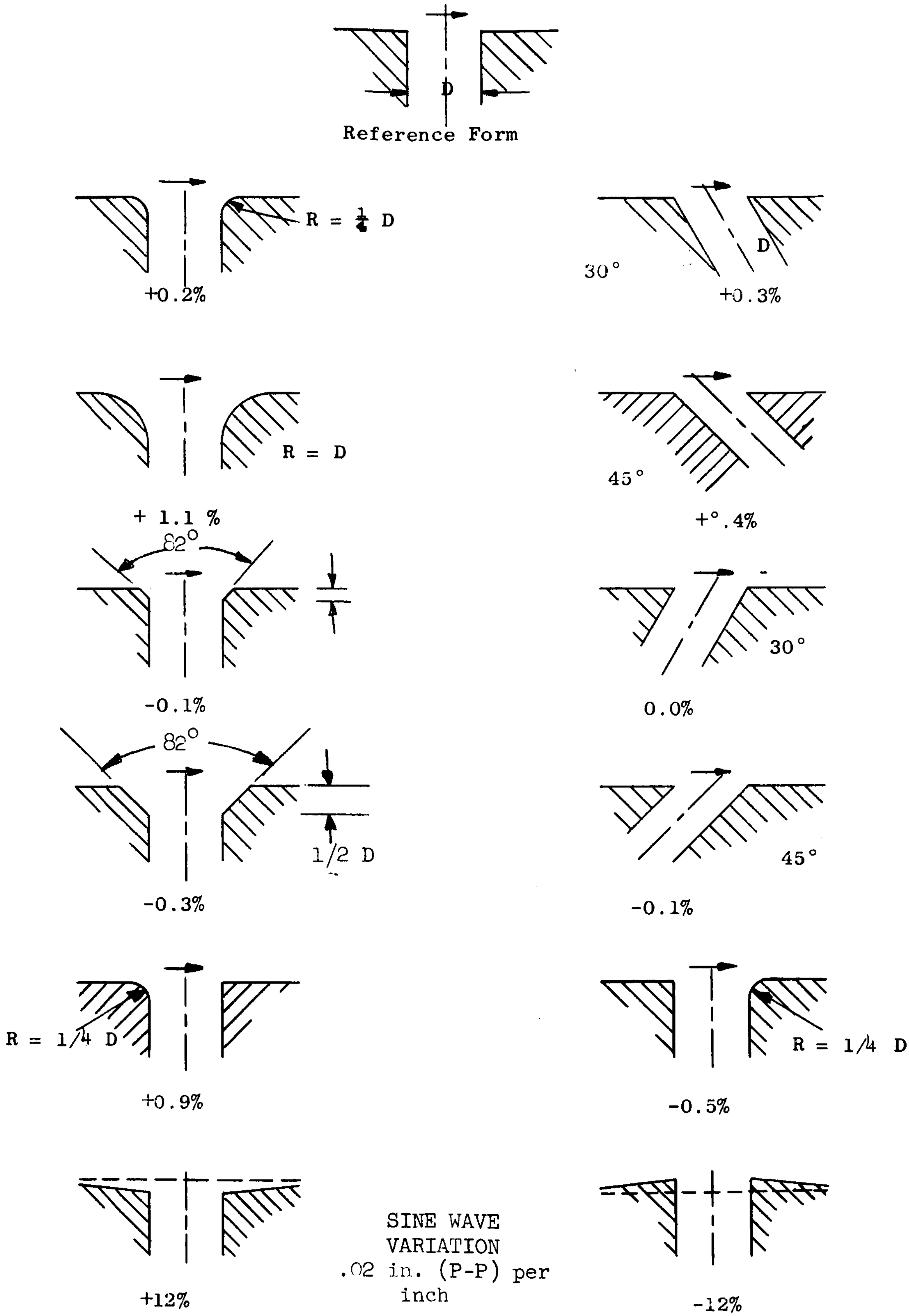
3.2.1. Pressure Taps

An ideal small hole in a flat surface which does not disturb the flow along the surface could be used to measure the static pressure without error. Anything that disturbs the flow will change the static pressure, therefore, a real hole in a real surface will be in error if: (a) the hole is large enough or the edges are shaped to disturb the flow, or (b) the surface is wavy or irregular. The amount that the pressure indicated at a real hole differs from the true free stream pressure is defined as static tap error.

If a surface is curved or wavy, the pressure at the surface will vary above and below free stream pressure. The pressure at the peaks of the waves will be lower than free stream and the pressure at the low points will be above free stream. (Ref.20). If the surface is intentionally curved, there will be a real, expected difference between surface and stream pressure and the tap will read surface pressure. If the surface is accidentally curved, as it might be if a local spot is polished slightly down into an otherwise smooth surface, the difference will be an unexpected error.

There will be an impasse between required static tap geometry to obtain the desired pressure accuracy of static measurements and the desired engine design. The accuracies desired will require that the engine walls be absolutely smooth perhaps even polished and certainly nonablative.

Rayle's thesis is an early and quite often quoted work on static hole errors. (Ref.20 and21). Figure 10is based on his ASME paper, and shows the effect of small variations in the static tap edge. All available data has been taken with subsonic flow velocities, with a static hole that is small compared to the boundary layer thickness. The error is probably best computed based on a mean dynamic pressure a short distance out into the boundary layer as was done in Ref. 22. An accurate evaluation of the errors to be expected in supersonic flow is badly needed. Until such data is available, the errors can be best estimated by using Rayle's indicated errors based on an average dynamic pressure near the wall as a guide.



STATIC TAP ERROR (% DYNAMIC HEAD)

FIGURE 10

3.2.1 Pressure Taps - cont'd

In discussions with individuals involved in nose cone measurements, the best current practice on regenerative cooled or ablative protected surfaces seems to be static pressure measurements which are estimated to be within 10%. There are special cases where the accuracy is much better than this, but very careful precautions must be taken to better this accuracy. The author of reference 22 points out: "In common with many previous investigations, it has been noted that even a very slight burr on the edge of the hole, or a small quantity of dirt inside it can have a very significant effect on the reading given by a static pressure hole." This kind of care will be extremely difficult to achieve in a ramjet environment. Figure 11 is a test coupon typical of a regeneratively cooled surface and similar to those which will exist in a cooled wall engine. Figure 12 is typical of an ablatively protected surface. Neither of these surfaces would be even remotely acceptable for accurate static pressure measurements.

An error which is calibratable and known and can be corrected is seldom a problem. Neither the regenerative nor the ablative surface will produce this kind of an error. On the regenerative surface the error can be expected to be extremely sensitive to flow direction. With flow parallel to the tubes of Figure 11, the error could be quite small. With the flow across the tubes the tap down between the tubes could read nearer total than static. In order to attempt to correct the error in this case the flow direction would have to be accurately known. If by local heating and cooling the surface distorts this will cause an error which could be large and either positive or negative. This kind of error has been noted even in the small changes in countour of an airplane when it is pressurized. (Reference 23).

Accurate measurements are possible on ablation surfaces before the onset of erosion. Unfortunately, as the surface ablates the local disturbance of the hole causes a somewhat higher ablation rate with an attendant change in the local surface. About all that can be said for a static tap error in this case is that it will become larger with time. There may not even be any possibility of predicting whether the error will be positive or negative. The only hope for useable statics in an ablative surface is to use the pressure readings before the ablation has gone far enough to produce too large an error. So far all modifications of an ablative surface to attempt to improve the situation have only made it worse. If the ablative material in the region around the hole is changed in any way at all it will either ablate faster or slower than the surrounding material. In either case it will produce an error.

The only possible method of producing static taps which will have acceptably small errors appears to be by maintaining the engine surfaces absolutely smooth with very small sharp edged taps (or chamfered per Rayle's recommendations). If the engine designer cannot provide this kind of surface, large uncertainties in static pressure measurement can be expected.

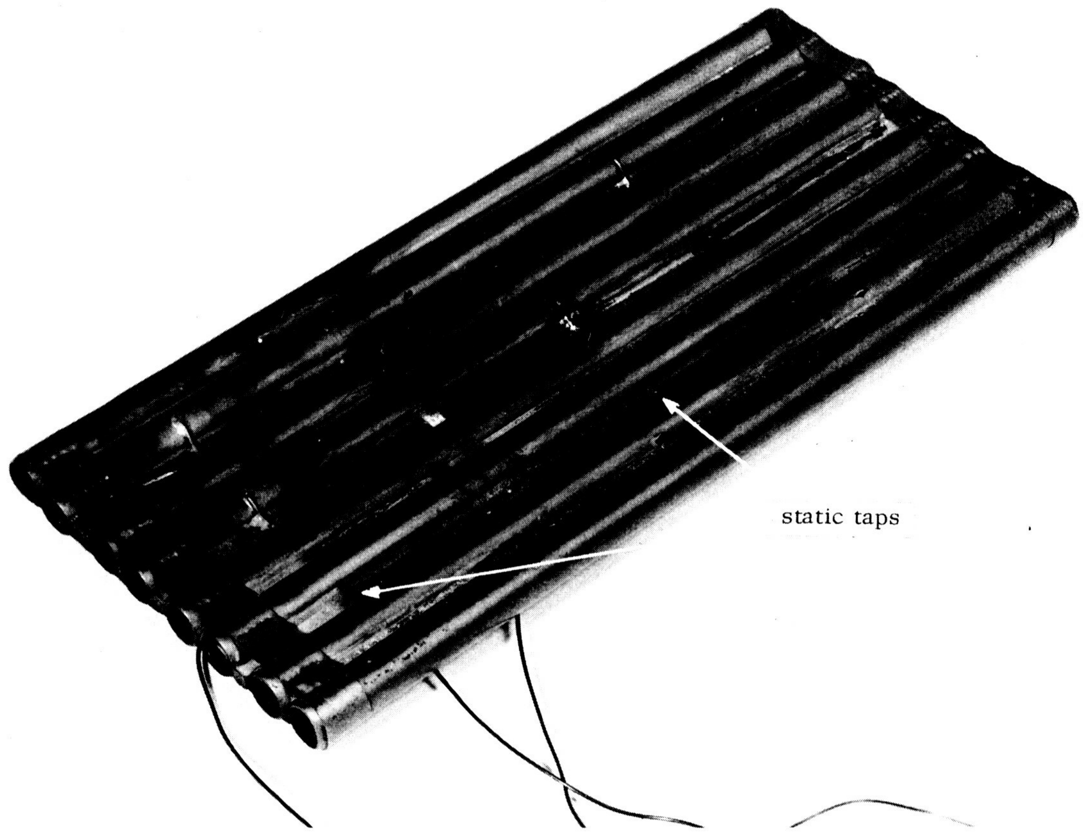
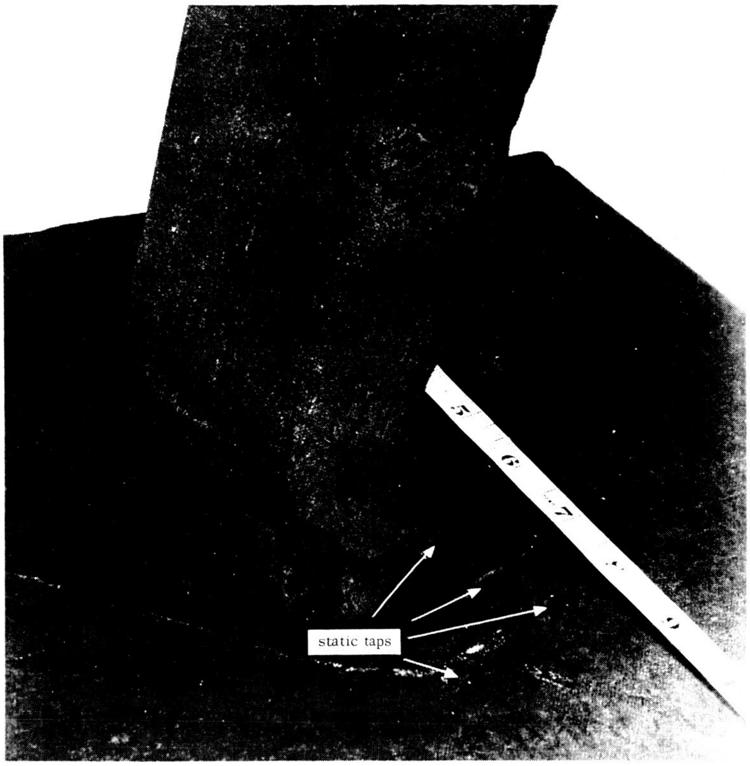
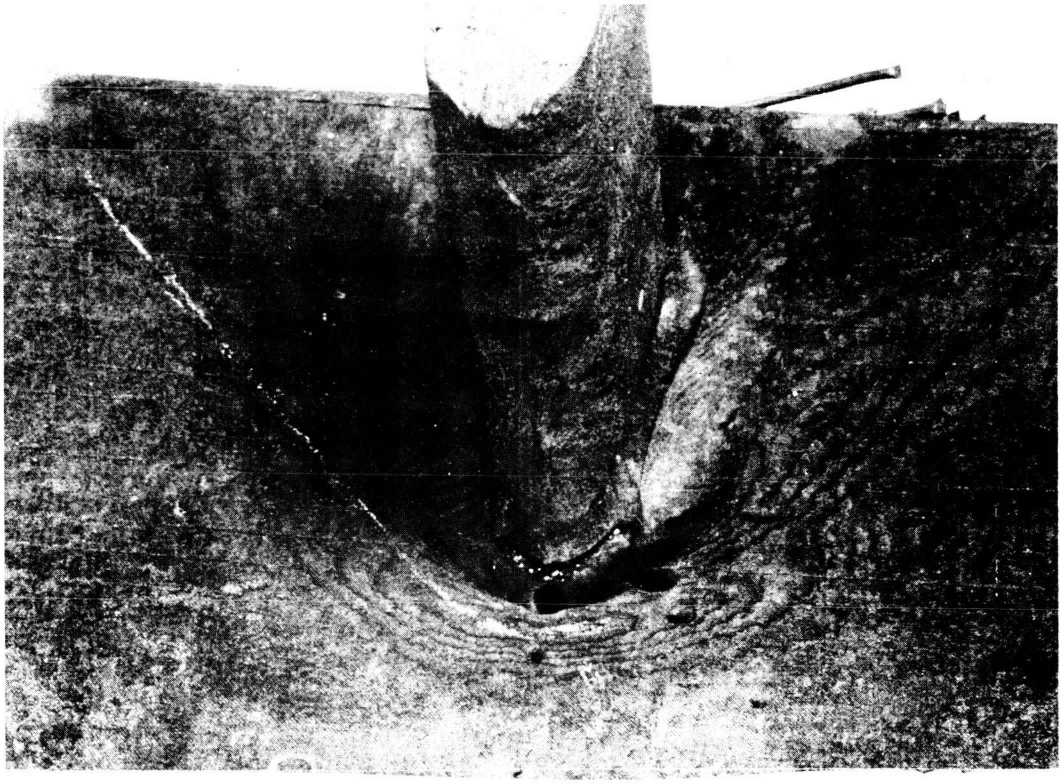


Figure 11 Typical Regeneratively Cooled Surface



a. View Showing Static Tap Errosion



b. View Showing Shock Wave Errosion

Figure 12 Typical Ablatively Protected Surface

3.2.1 Pressure Taps - cont'd

As a further note, the small taps required for steady state accuracy by the considerations above will be inconsistent with the large holes required for dynamic response. (See section 3.2.2).

3.2.2 Dynamics of Pressure Systems.

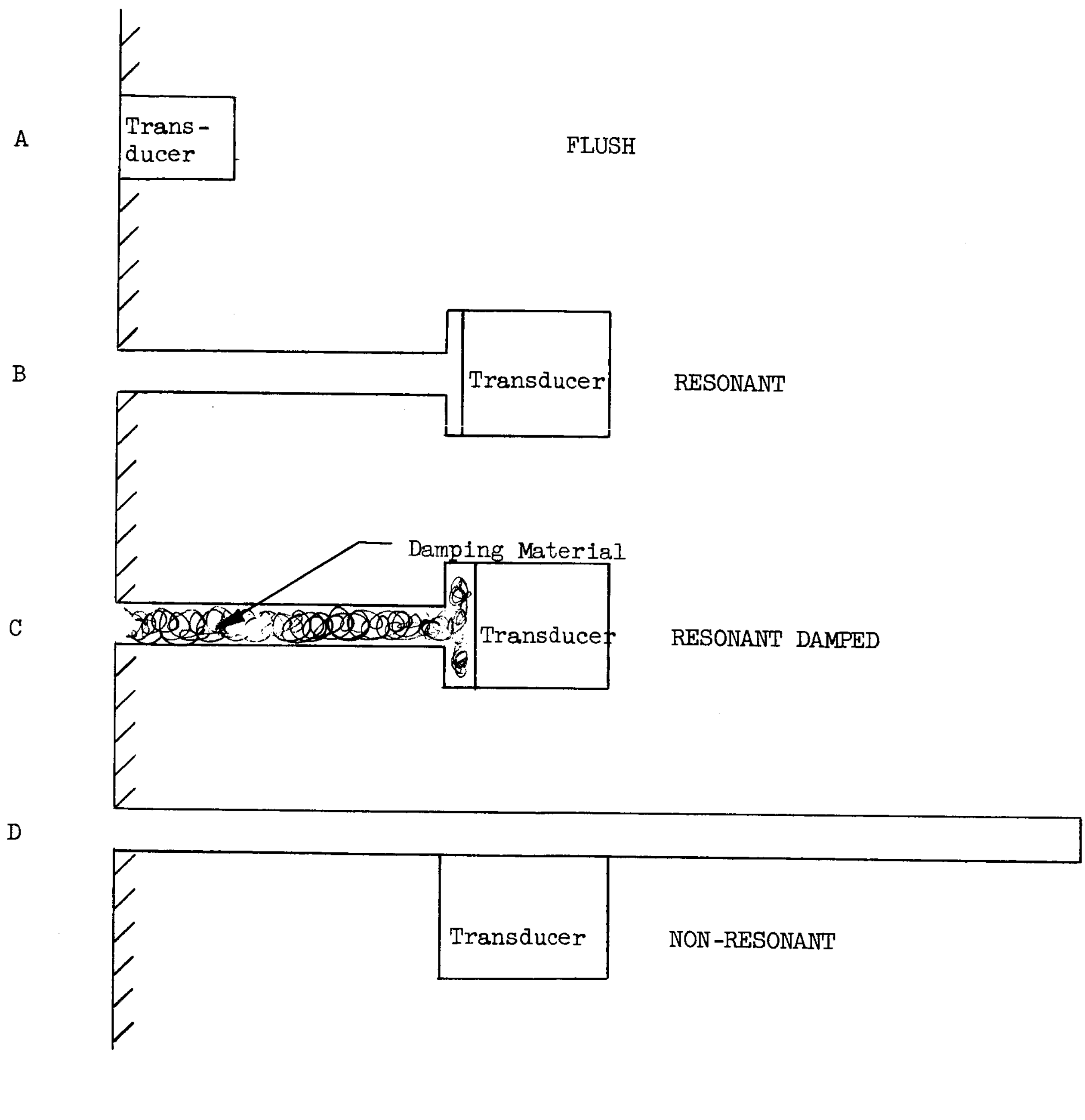
In order to measure engine performance it will be necessary to make some continuous measurements of fluctuating pressure since engine operation is expected to be transient in nature. There may also be pressure fluctuations due to burner instabilities or inlet unstarts which will require a wide range of frequency response on a few special transducers. Transient pressures may be recorded by several systems as shown schematically in figure 13. These may be broken down into:

a. Flush diaphragm systems.
b. Resonant tube and transducer systems.
c. Damped resonant tube and transducer system.
d. Tube connected non resonant systems.

Each system has specific advantages and limitations which will be discussed briefly. Each of the systems may be used at some points on the engine.

3.2.2.1 Flush Diaphragm

The flush diaphragm system is of course the simplest as far as error analysis. If, as is ideally possible, the transducer diaphragm is absolutely flush with the wall of a chamber and does not disturb the airflow, there will be no "tap errors" or "tube errors" as there will be with the other systems. The indicated pressure will be the same as the wall pressure up to the limits imposed by the transducer itself. A limit of 10% of the resonant frequency of the transducer is considered adequate in standard practice. If the transducer is specially damped and properly calibrated specifically for high frequency use, it may be useable to approximately 50% of the natural frequency. A flush diaphragm system is limited to stream conditions which will not overheat the diaphragm and usually requires a rather large area on the wall. This system is frequently used as the standard during laboratory calibration for checking errors of other systems.



PRESSURE SENSING SYSTEMS

FIGURE 13

3.2.2.2 Pressure Tubing and Transducer

The most commonly used pressure transducer system uses a tube from the pressure port to the transducer sometimes with a volume at the transducer, as at fig. 13(b&c). For steady state pressures this method is ideal. The volume at the transducer can even be made fairly large to deliberately average out pressure fluctuations, as is frequently done. The manometer so often used in the lab is this kind of a system. For fast response the tube must be kept short with a minimum volume provided at the transducer. In some cases damping may be added as shown at Figure 13c. The response time (or frequency response) of this class of system has been very thoroughly investigated both theoretically and empirically. See references 24 through 54 .

Iberall (reference 24) is widely quoted and represents the most complete theoretical analysis of a simple tube and volume system with a variable amount of damping.

With very small or no volume at the end, a smooth constant area pipe, and low damping,the system has a resonant frequency, often called the organ pipe resonance, corresponding to a wavelength four times the tube length. The curve marked 1/4 wave in figure14 represents the frequency length relationship. If the volume is not neglibible the curves marked S/V which is the tube area divided by the end volume may be used to determine the resonant frequency. These curves are based on the well known helmholtz resonator frequency formula. For either case as the damping varies the error will vary as shown in figure 15. There will also be a phase shift which depends on frequency as shown in Figure 16. At frequencies which approach resonance close enough to produce large amplitude errors it is possible to add damping either in the form of small diameter tubing or by stuffing the inside of the tube with some material such as steel wool to improve the amplitude error. (References25 and 54.) This is done at the expense of phase shift. Some experimentors have even carried this method to frequencies well above resonance (reference 44,54). Because of the large phase shifts produced these systems would only be useable at a single (sine wave) frequency. Any wave shape other than a sine wave would be severely distorted. If this type system is used at frequencies below 10% of the acoustic resonant frequency and the damping is kept below critical the error due to resonance will be below 10%. Above this the error can be estimated from Iberall or figure 15.

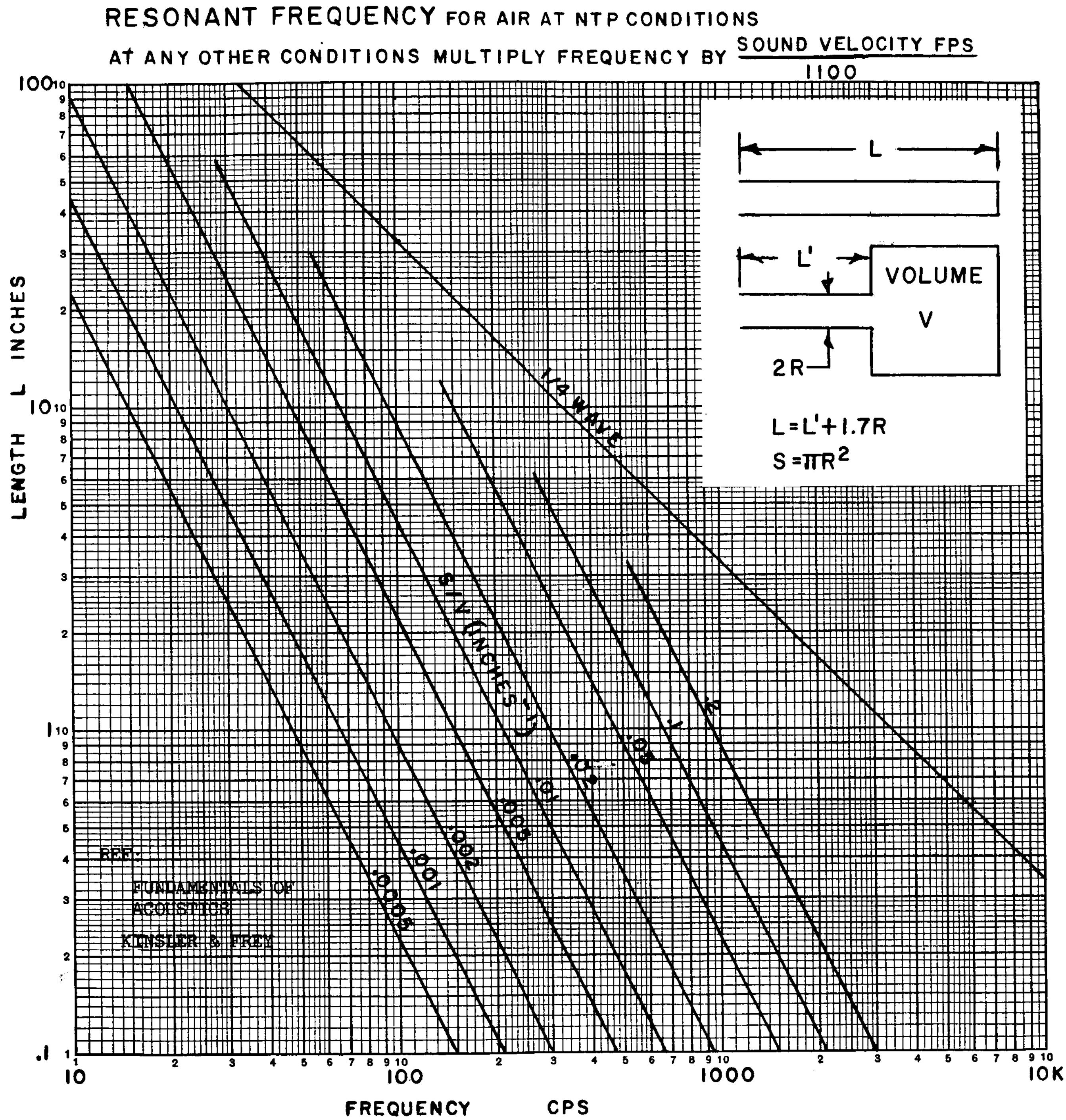
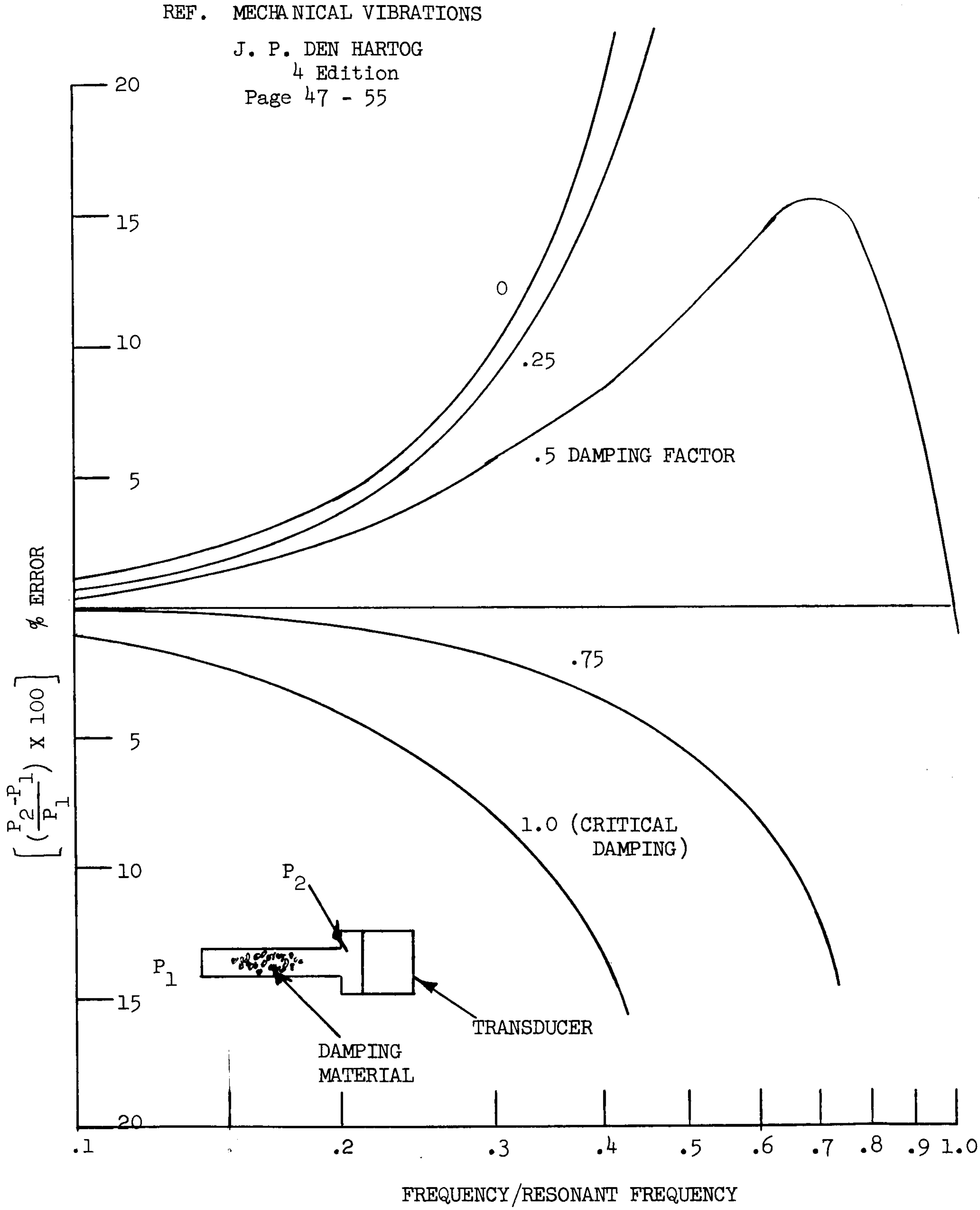
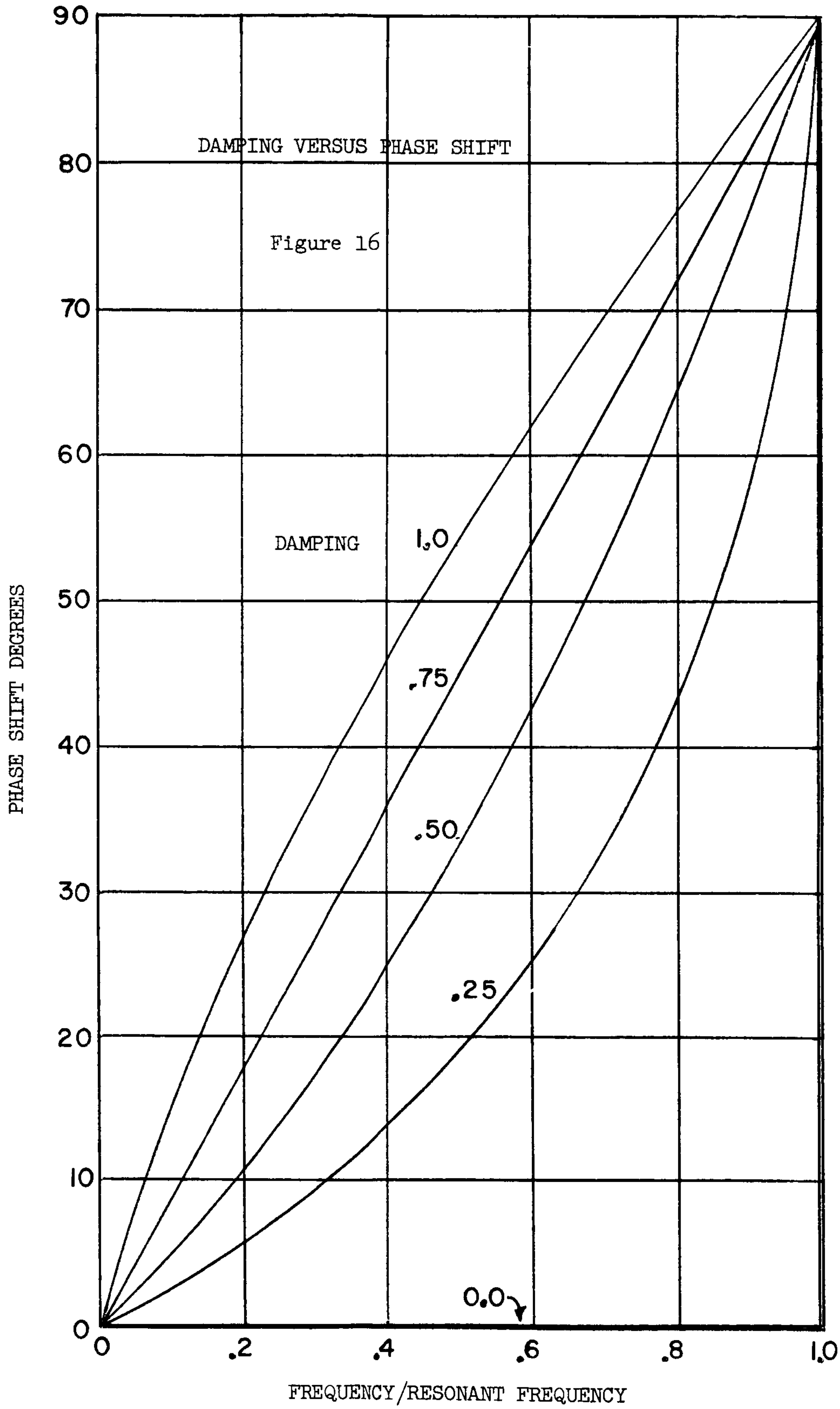

RESONANT FREQUENCY FOR AIR AT NTP CONDITIONS
AT ANY OTHER CONDITIONS MULTIPLY FREQUENCY BY SOUND VELOCITY FPS / 1100
L
L'
VOLUME
V
2R
L=L'+1.7R
S=πR²
1/4 WAVE
S/V (INCHES⁻¹)
.0005
.001
.002
.005
.01
.02
.05
.1
.2
LENGTH L INCHES
100
10
1
.1
10
100
1000
10K
FREQUENCY CPS
REF:
FUNDAMENTALS OF ACOUSTICS
KINSLER & FREY

Figure 14.



DAMPING VERSUS PRESSURE ERROR

Figure 15



DAMPING VERSUS PHASE SHIFT
Figure 16
DAMPING
1.0
.75
.50
.25
0.0
PHASE SHIFT DEGREES
FREQUENCY/RESONANT FREQUENCY
90
80
70
60
50
40
30
20
10
0
0
.2
.4
.6
.8
1.0

Figure 16

3.2.2.3 Non Resonant Probe Tube

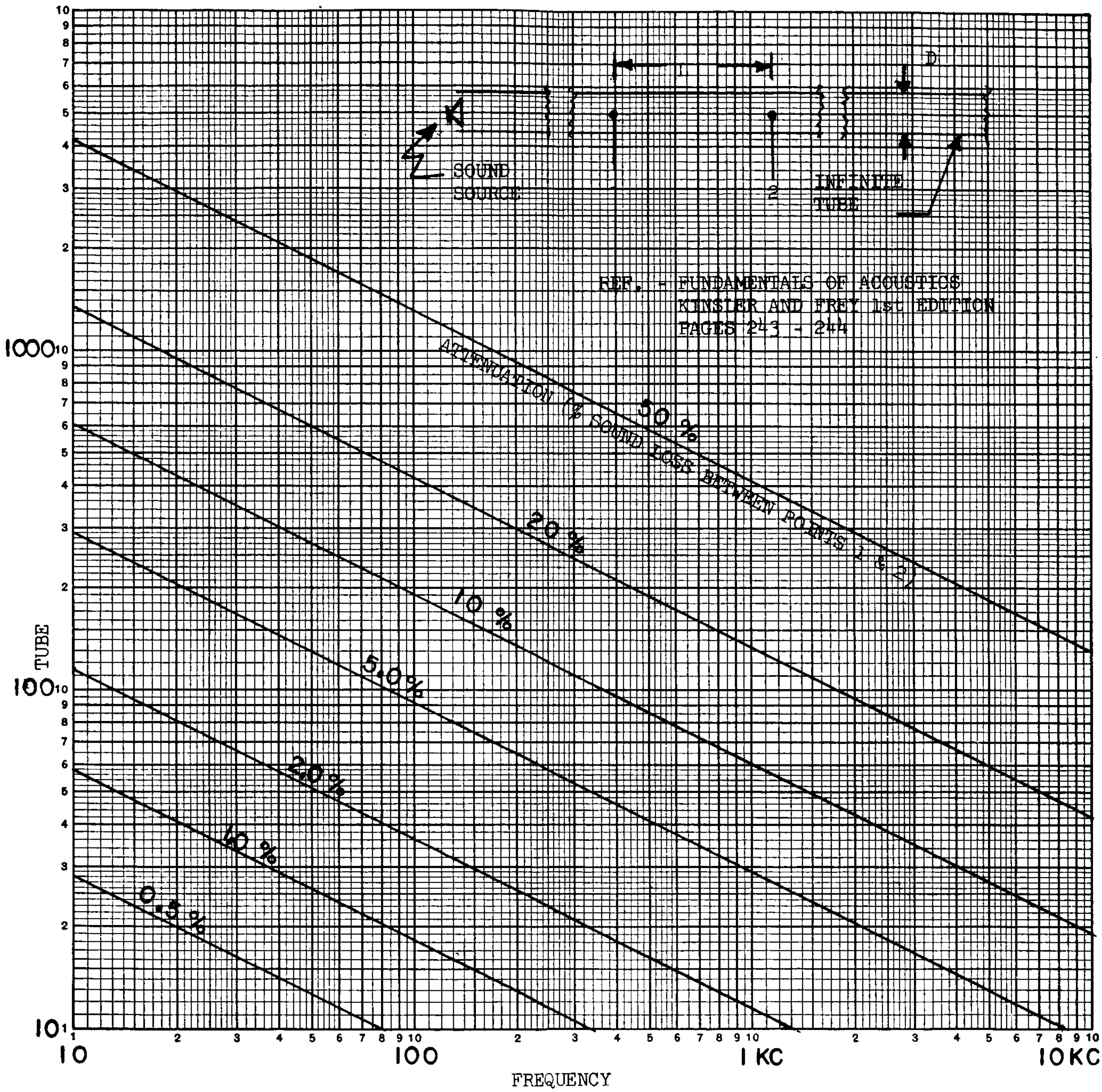
If the error due to resonance becomes larger than desired a non resonant system as shown at Figure 13d should be considered.

The resonance problems on the fig. 13b type system occur when a pressure wave enters the tube, travels to the transducer, is reflected back down the tube, and continues to echo back and forth in the tube. Resonance can be prevented as at fig. 13d by providing a constant area tube extending beyond the transducer. If the tube were infinitely long there could be no resonance as the pressure pulse entering the tube would continue traveling forever. If the attenuation is sufficiently high in a tube it can be capped off at a selected length and the reflected wave will be attenuated sufficiently to eliminate error due to resonance. This system has been used for making sound measurements under conditions where the microphone could not be placed at the point where the measurement is required (reference 55) but seems to have been little used in pressure measurement.

If the tube area is held exactly constant from the sensing point to a point beyond the transducer where the attenuation is quite high, there will be no errors due to resonance. There will be some attenuation of the wave as it travels through the tube, due to air nonlinearity effects, (reference 56) and a time delay due to the transmission time, but these errors will always be less than the errors which would be caused by resonance if the tube were terminated at the transducer. Fig. 17 may be used to estimate the attenuation in a tube at any frequency. The attenuation from the sensing port to the transducer will be an error. The attenuation from the transducer to the capped end of the tube must be high enough to prevent an appreciable echo from returning to the transducer. Any echo which returns to the transducer will be an error signal. The attenuation can be increased by adding damping material (reference 55) by tapering the tube or by making part of the tube of sound absorbing material. Care must be taken that the sound absorbing material does not cause reflections large enough to produce appreciable errors in the data. Air nonlinearity errors which are a function of dynamic signal level can be estimated from Figure 18 (reference 56). There will be a time delay due to the transmission time which can be estimated from figure 19.

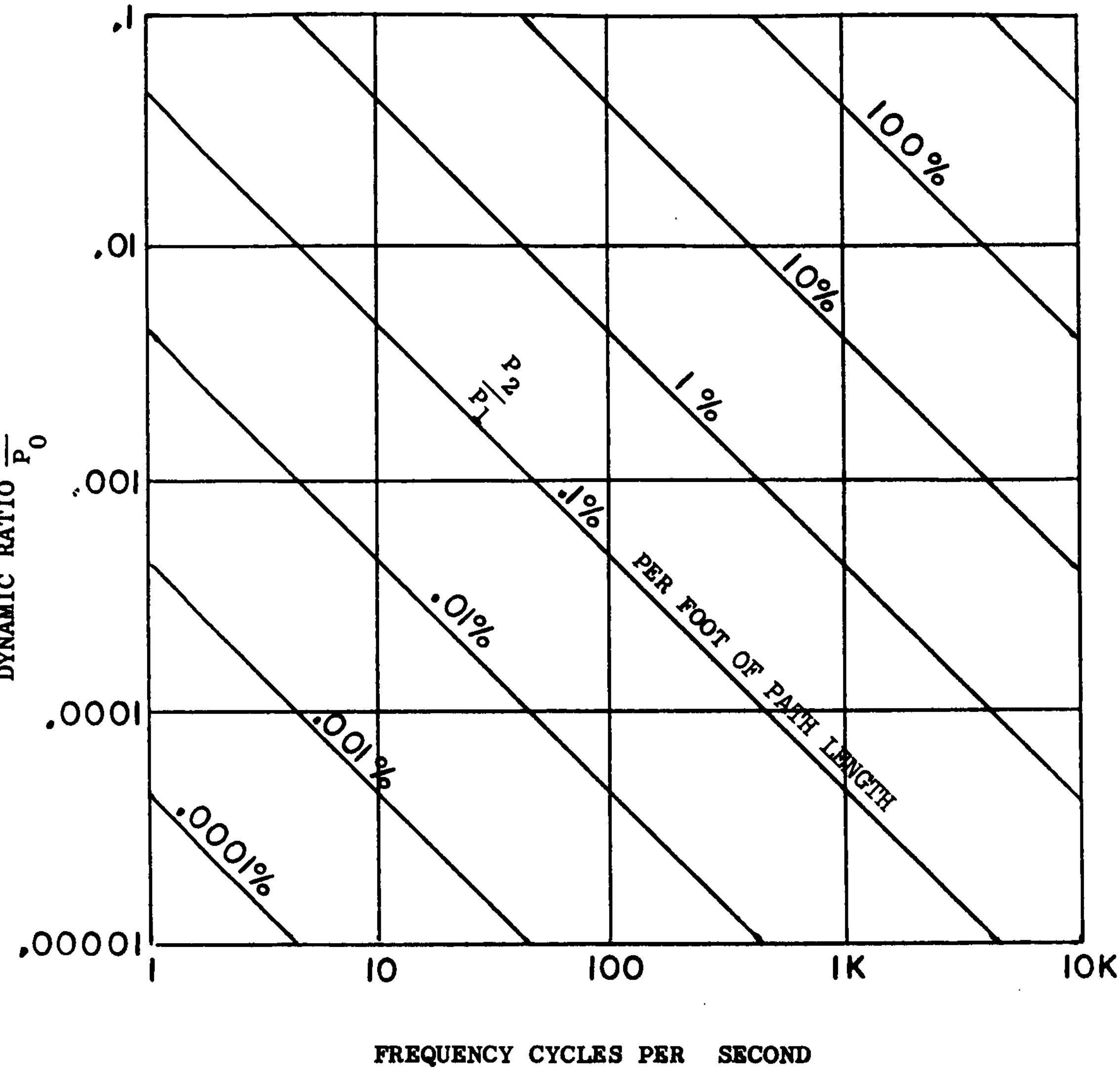
The total error for this type of system will be approximately the sum of the errors due to attenuation, reflection from the closed end of the tube and air nonlinearity. There will also be a time delay which must be considered if the data is to be compared from two or more transducers.

Non resonant transducer systems are recommended for all pressures where response higher than 100 cps is required. All pressures for which response over 1 cps is desired should be checked by the engine manufacturer to determine errors when final line size and length has been determined.



Attenuation of Sound in A Tube

Figure 17



Second Harmonic Distortion for air at 518.4°R and $\gamma = 1.4$

At any other temperature T°R multiply $\frac{P_2}{P_1}$ by $(518.4/T)^{.5}$

At $\gamma = 1.3$ multiply $\frac{P_2}{P_1}$ by 1.07

At $\gamma = 1.2$ multiply $\frac{P_2}{P_1}$ by 1.16

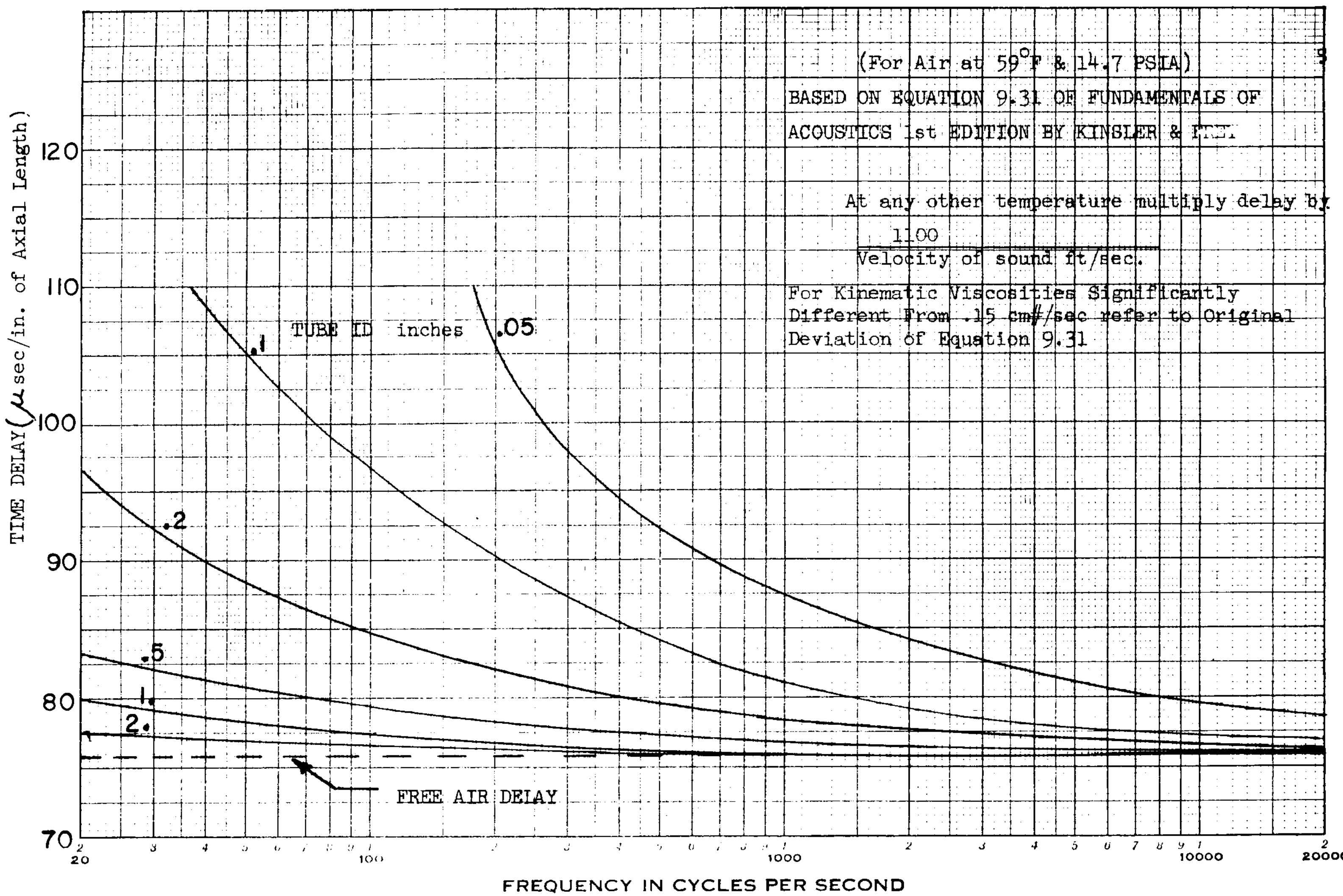
P_0 - Free Stream Static Pressure

P_1 - Pressure Fluctuation (Fundamental)

P_2 - Pressure Fluctuation (Second Harmonic)

AIR NON-LINEARITY EFFECTS

Figure 18



Time Delay vs. Tube Diameter and Frequency

Figure 19

3.2.2.4 Comparison of Resonant and Non Resonant Transducers

Fluctuating pressures can be measured with any one of the systems shown in Figure 13. Theoretical analysis and calibrations to establish probe resonances by comparing relative input and output at various frequencies have shown the non resonant system to be superior to the resonant configurations. A direct comparison of the two tube connected systems with a flush system was made as shown in Figure 20. The three types of systems were connected to a small chamber which was driven with a Bruel and Kjaer (B & K) mod. 4216 artificial mouth. The driving signal was a square wave at approximately 100 cps. The amplifier speaker chamber combination distorted the signal to that shown at fig. 21a as measured on the chamber monitor transducer. Fig. 21b is the same signal as measured on the resonant transducers. The superimposed "sine-wave" corresponds to the 1/4 wave resonance frequency for the connecting tube. The conditions were chosen deliberately where the resonant frequency was far above the measured frequency. At conditions above about 1/4 of resonance the measured frequency wave form became completely unrecognizable. Fig. 21c shows the same input wave form measured with the same 2½" tube connection to the signal chamber but with a non resonant termination (approximately 20 feet of ¼ inch tubing).

3.2.3 Pressure Readout System

In studying the requirements for accurate pressure readout, several important conclusions evolved:

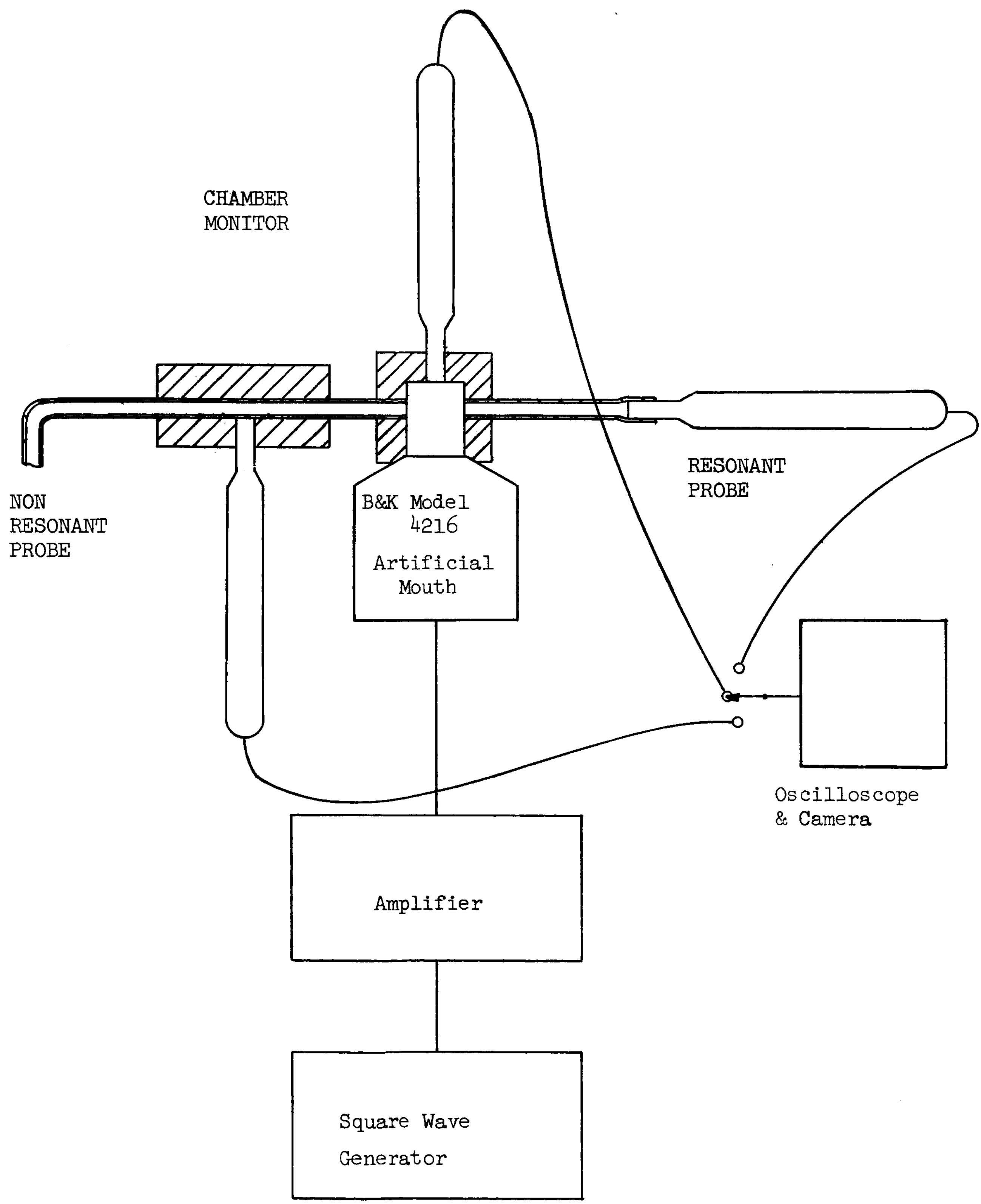
a. A single transducer will not cover the desired pressure ranges with sufficient accuracy.
b. In order to provide reasonable accuracy and reliability, pressure instrumentation should be centrally located with provisions for thermal and vibration protection.
c. Several system concepts are available and application will depend upon final selection of engine pressures to be measured.

These conclusions are discussed in detail in the following sections.

3.2.3.1. Transducer

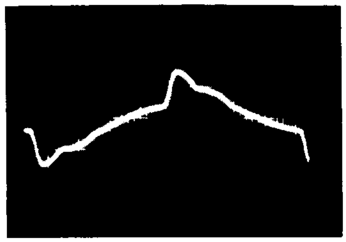
3.2.3.1.1 Types of Transducers

A pressure transducer is an electromechanical device through which an input pressure signal is converted to an output electrical signal. In most cases the pressure results in a displacement of a spring in presumed accordance with Hooke's law. The displacement produces a change in some electrical property which is measured in an appropriate manner. The transducer's maximum frequency response is limited by the mass-spring relationship in the unit, but in application is most frequently determined by viscous fluid flow within the instrumentation lines.

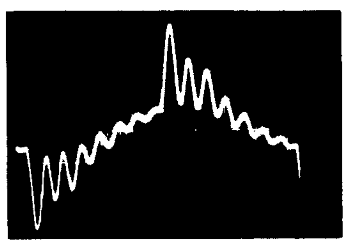


TEST SETUP FOR COMPARISON OF PROBE SYSTEMS

FIGURE 20



100 CPS Chamber
Monitor Transducer



Resonant Transducer

Non Resonant Transducer

Figure 21 Comparison of Probe System Responses

3.2.3.1.1 Types of transducers - cont'd

Some of the types of pressure transducers manufactured by the industry are categorized according to the electrical property utilized in detecting displacement.

a. Strain gage - bonded
b. Strain gage - unbonded
c. Semiconductor strain gage
d Potentiometric
e. Variable reluctance
f. Capacitance
g. Strain oscillators
h. force balance
i. Piezoelectric
j. Digital

Each type has its particular area of application. Some are automatically eliminated from this specific application by the limitations of the environment. The work statement places a restriction of 50 pounds for the instrumentation package in the ramjet. If we make a reasonable assumption that one half of the weight be allotted to other than the pressure transducers, the average weight is:

$$\frac{25\#}{67 \text{ measurements}} = .37\# = 5.9 \text{ oz./transducer + accessories}$$

A survey was made of the different types of pressure transducers, considering the weight, accuracy, stability, temperature range, applicability to the PCM system, and many other factors concerned with the expected environment of the ramjet testing. Some of the salient points are evident in Table I .

TABLE I

Pressure Transducers

Type	Accuracy	Comments
Strain gage-bonded	good	350° max.
Strain gage-unbonded	good	700° max - good stability
Strain gage-semiconductor	fair	high temperature coefficient
Potentiometric	fair	high hysteresis
Variable reluctance	very good	medium temp. coefficient and signal cond. problem.
Capacitance	poor	highest temp. capability signal cond. problems
Strain oscillators	good	high temp. coefficient. not in production.
Force balance	excellent	too heavy
Piezoelectric	poor	no static pressure
Digital	poor	high hysteresis

3.2.3.1 Transducers - cont'd

3.2.3.1.2 Transducer Errors

The error to be found in a pressure system from the transducer to the printout of the data can result from a number of causes. Nearly every item in the system contributes values that may, or may not be, significant. The more important ones are:

a. Thermal zero shift
b. Thermal sensitivity
c. Thermal shock
d. Vibration sensitivity
e. Calibration
f. Hysteresis
g. Linearity
h. Pressure sensitivity
i. Excitation voltage
j. Data processing

Thermal zero shift and sensitivity errors are caused by dimensional and electrical changes in the transducer. Commercial compensated transducers have errors in the order of .01% of full scale per degree Fahrenheit. The errors introduced by these causes for the standard models are:

Temperature Change °F	Thermal Zero Shift (%F.S.)	Sensitivity Change (%F.S.)	Total Error (R.M.S.) (% F.S.)
25	±0.25	±0.25	±0.35
100	±1.0	±1.0	±1.41
300	±3.0	±3.0	±4.23
500	±5.0	±5.0	±7.07

This points up the requirements for temperature control in ramjet instrumentation. Special transducers can be obtained by selection with coefficients as good as 0.005 at a nominal increase in cost. Attempts to achieve stability better than this result in a manufacturing yield so low as to be impractical. If high measurement precision is to be attained even with the best possible transducers available at the present state of the art, an R.M.S. error of 2.11% of full scale reading can be expected when measuring a pressure with a single transducer. This assumes selected transducers and a temperature change of 300°F.

3.2.3.1 Transducers - cont'd

When a pressure transducer is subjected to a fast thermal transient, dimension changes occur in the transducer due to the thermal gradient. This type of error is not normally expressed in manufacturing specifications. Careful design of the case to equalize the heat gradient on the strain gage bridge and compensation network is required to minimize the problem. In practical flight test it can provide the major source of error for pressure measurements. For example, in recent maneuvering flights with transducers located in the engine bay without thermal protection, transient zero shifts greater than 10% of full scale were experienced. This occurred where the temperature conditions changed from above +200°F to about -50°F. Personnel at the National Bureau of Standards in Colorado pointed out that transient shifts of above .03% per degree Fahrenheit is possible during cryogenic testing with superior transducers.

It is recommended that in order to control this problem during flight test transducers must be thermally lagged. Discussion with transducer manufacturers indicate temperature rates in the order of 5 to 10°F per minute will not appreciably degrade accuracy. There is still a great deal that is unknown about this problem. A practical standard test would be helpful in comparing transducers.

Vibration sensitivity of a transducer is primarily a function of the spring coefficient of the diaphragm and the mass of the attached recording mechanism. Certain variable reluctance and capacitive units achieve a very low mass loading on the diaphragm and are far superior to most other transducers in this matter, but the signal conditioning requires electronics such as carrier oscillators and a ring demodulator system. This generally results in increased weight as well as additional errors being contributed by the electronics.

Vibration sensitivity is associated with the mechanical design of a pressure transducer and for any one model is more critical at the lower ranges. For a typical transducer model, the 40 g acceleration anticipated during the ramjet test would have the following effect:

Pressure Range of Transducer	Dynamic Signal Error (% of full scale)	Frequency Range
0 - 5 psia	16 %	to 2500 cps
0 - 10 psia	6 %	to 2500 cps
0 - 25 psia	2 %	to 2500 cps
0 - 100 psia	0.4 %	to 2500 cps

Measurement of pressure fluctuations with this type of transducer are difficult if engine acceleration occurs simultaneously in the plane of the transducer most sensitive to vibration.

3.2.3.1 Transducers - cont'd

The PCM recording system will record a frequency error which is difficult to evaluate. If the vibration or pressure frequency is greater than 1/2 the sampling rate, folding takes place which changes the true frequency to a lower frequency. Assuming the dynamic signal is 202 cps and the scan rate is 200 S/S, an effective 2-cps signal will be generated. This will appear as a significant error unless the PCM gate filter is better than the presently existing R-C filter. There is no simple answer to accurate pressure measurements in a high "G" environment. If high frequency response is not required, isolation of the transducer from the high "G" environment is recommended together with averaging during data processing for steady state information. It is desirable to have the filter knee frequency at 1/3 to 1/5 the sampling rate to provide a large attenuation at one half the sampling frequency. The present 200 sps channels have a filter knee at 40 cps or 1/5 the sampling frequency.

Calibration error should be discussed in several modes, depending on the approach to the program. Component calibration and subsequent installation in the ramjet instrumentation system can result in some rather sizable errors when compared with end to end calibration directly on the aircraft with the recording system. The major disadvantage with end to end calibration is that it ties up the complete aircraft. An error evaluation of the two systems should be considered using an unbonded strain gage bridge to determine the trade off possibilities. End to end calibration provides improvement in the following factors:

a. Eliminates bridge voltage uncertainty at the transducer. The estimated error in percent of full scale assuming an uncertainty of 1 ohm in lead resistance for a 350 ohm bridge is ±0.29%.

b. Eliminates the requirement to measure each gate in the PCM system and make a manual correction. Without correction the X-15 P.C.M. encoder has demonstrated deviation of 0.7% between separate gates.

c. Provides complete assurance on the system during pre and post flight calibration.

d. Permits automatic generation of calibration factors from P.C.M. calibration tapes. Factors are used to correct flight data during data processing.

To summarize end to end calibration techniques, appropriate data reduction procedures will reduce systematic errors to at least 0.9% of full scale.

Hysteresis error is an indication of the repeatability of the transducer and results from the mechanical motion of the diaphragm and strain gage arm. Discussions with vendors indicated values less than ±.25% of full scale are normal with standard units.

Linearity of a pressure transducer is in the order of ±0.50% of full scale. To obtain best accuracy, the automatic data reduction facility should be provided with tape data from calibration that will permit them to write a routine that will correct non-lineratity of both the transducer and the amplifier.

3.2.3.1 Transducers - cont'd

3.2.3.1.2 Transducer Errors - cont'd

Pressure sensitivity of the transducer case to outside changes in pressure results in negligible error for the ranges of ambient pressure expected during the ramjet test program.

Knowledge of the excitation voltage at the transducer is important to determine the sensitivity of the transducer when laboratory calibration is made. There is a change in poser lead resistance due to a temperature change during test. This is small for the expected lead lengths in the aricraft.

Recording and data reduction errors depend on the particular system in use. The two systems on the X-15 are the PCM and the FM-FM data system. Information supplied by NASA indicates the following:

FM-FM system	±7% of full scale
PCM system with individual channel calibration	±.5% of full scale

3.2.3.1.3 Transducer Selection

If the ramjet manufacturer uses an adequately insulated compartment for instrumentation the components will be exposed to a maximum temperature of 250°F. As pointed out previously, data accuracy is poor unless the temperature control is maintained. The ramjet vibration specification of 40 G between 200 and 250 CPS will require some assurance testing of assemblies and components. Most transducer proof testing has been done at 35 "G's" but no real problem really exists since the prepared instrumentation package should be mounted on an isolation pad to minimize transducer "G" and thermal shock data errors. Several transducer manufacturers indicate their units will pass proof testing at the 40 "G" level.

Selection of a pressure transducer required consideration of shape because of space limitation. A cylindrical unit with the pressure tap at the opposite end from the electrical connector would permit optimum packing density. A diameter of about 1" will allow a reasonable size pressure compartment.

There are many pressure transducers that fit these criteria. Typical choices are the Statham PA220TC and the CEC model 4-236. Both are well isolated units as far as thermal shock is concerned. To save weight it is recommended these units be ordered with 24" leads which eliminates output plugs. The use of insert pins, as a patch board on the pressure package disconnect, will allow different equipment to be installed with ease.

3.2.3.1 Transducers - cont'd

3.2.3.1.3 Transducer Selection - cont'd

These transducers will provide measurements of pressure in the order of 0.6% F.S. with end to end calibration in a controlled environment. They are suitable above 5 psia for a quasi-steady state measurement. The tubing runs to the compartment will cause an acceptable attenuation at 1 cps. For measurements below 5 psia, diaphragm transducers are available but the selection is generally limited to sensing units that impose less mass on the diaphragm than unbonded strain gages do. Capacitive and reluctance units are candidates but require complex signal conditioning. The signal conditioning equipment is comparatively expensive if designed properly. The result of the study was to select the unbonded strain gage pressure transducer to evaluate ramjet engine performance and obtain transient information.

A typical error analysis for a good unbonded strain gage transducer and recording system is shown in Table II. The analysis assumes a system calibration prior toflight. The dependence of the total error on ambient temperature points up the requirement for holding the temperature of the ramjet instrumentation pressure package as constant as practical.

TABLE II

Error Classification	(Temp. ±25°F)	(Temp. Shift ±180°F)
Stability - three weeks	±0.25	± 0.35
Hysteresis	±0.20	±0.20
Thermal zero shift	±0.25	±1.80
Thermal sensitivity shift	±0.25	±1.80
"G" sensitivity (40G)	±0.40	±0.40
Voltage supply - 12 volts	±0.10	±0.10
PCM - 0-45 cps response	±1.0	±1.0
Temp. transient-simulated flight	Less than 0.5	Large (value unknown)

3.2.3.2 Central Instrumentation Package

3.2.3.2.1 Insulation Requirements

Some ides of the temperature rise in an insulated central instrumentation package can be obtained by making reasonable assumptions. This will determine the class of instruments capable of being used in the package. Assume a thermal input to the bay is in the form of a function with an initial and final value of 100°F and an elevated temperature averaging 350°F for 15 minutes:

Compartment size = 16" x 9" x 22"
Surface area = 10 feet^2

$t = 1/4$ hr
$k = .02$ btu/hr/ft/°F
$A = 10\ \text{ft.}^2$
$w = 0.083$ ft.
$\Delta T = 250°F$

The heat input with 1" of glass wool insulation is:

$$Q = tk \frac{A}{W} \Delta T$$

$$Q = 1/4\ (.02) \frac{10}{.083} \times 250$$

$$Q = 150 \text{ BTU}$$

The temperature rise of the instrumentation package through the glass wool insulation, assuming a 25-pound package is:

for stainless steel:
$c_p = .214$ btu/#/°F
$w = 25\#$

$$\Delta T' = \frac{Q}{wc_p}$$

$$\Delta T' = \frac{150}{25 \times .214} = 27°F$$

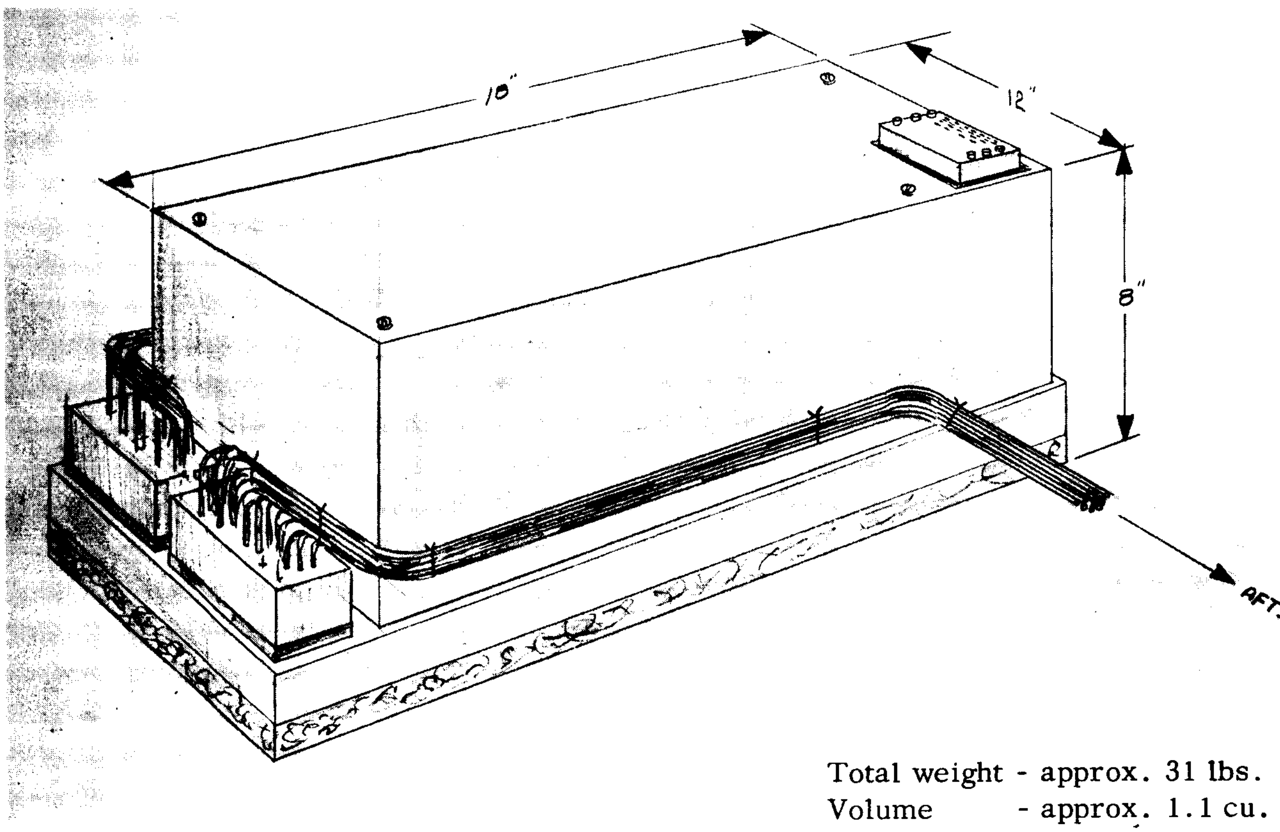
Additional heat rise will come from the conduction through the base and connections. If the connections are arranged to go an extended distance through the glass wool, the base will contribute the majority of heat input.

Assume: Base size = 18" x 12" x 1"
Base material - Teflon

$k = 0.14$ btu/hr/ft/°F

$$Q = \frac{1/4(.14)(1.5)(250)}{(.0833)} = 156 \text{ btu}$$

$$\Delta T = \frac{156}{25 \times .214} = 29°F$$



Total weight - approx. 31 lbs.
Volume - approx. 1.1 cu. ft.

Figure 22 Basic Package Layout of Recommended Pressure System

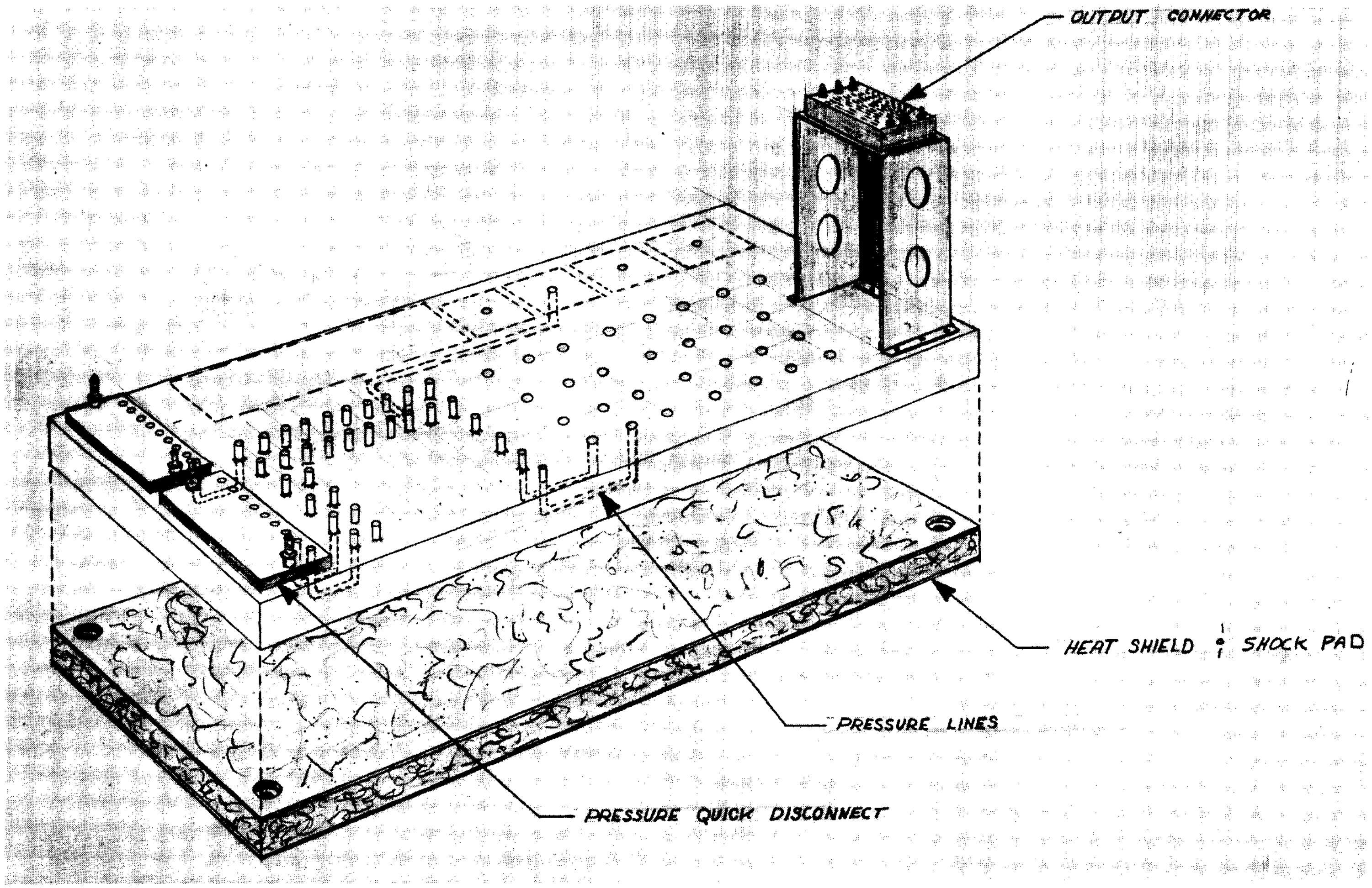


Figure 23 Recommended Pressure System - Transducer Platform

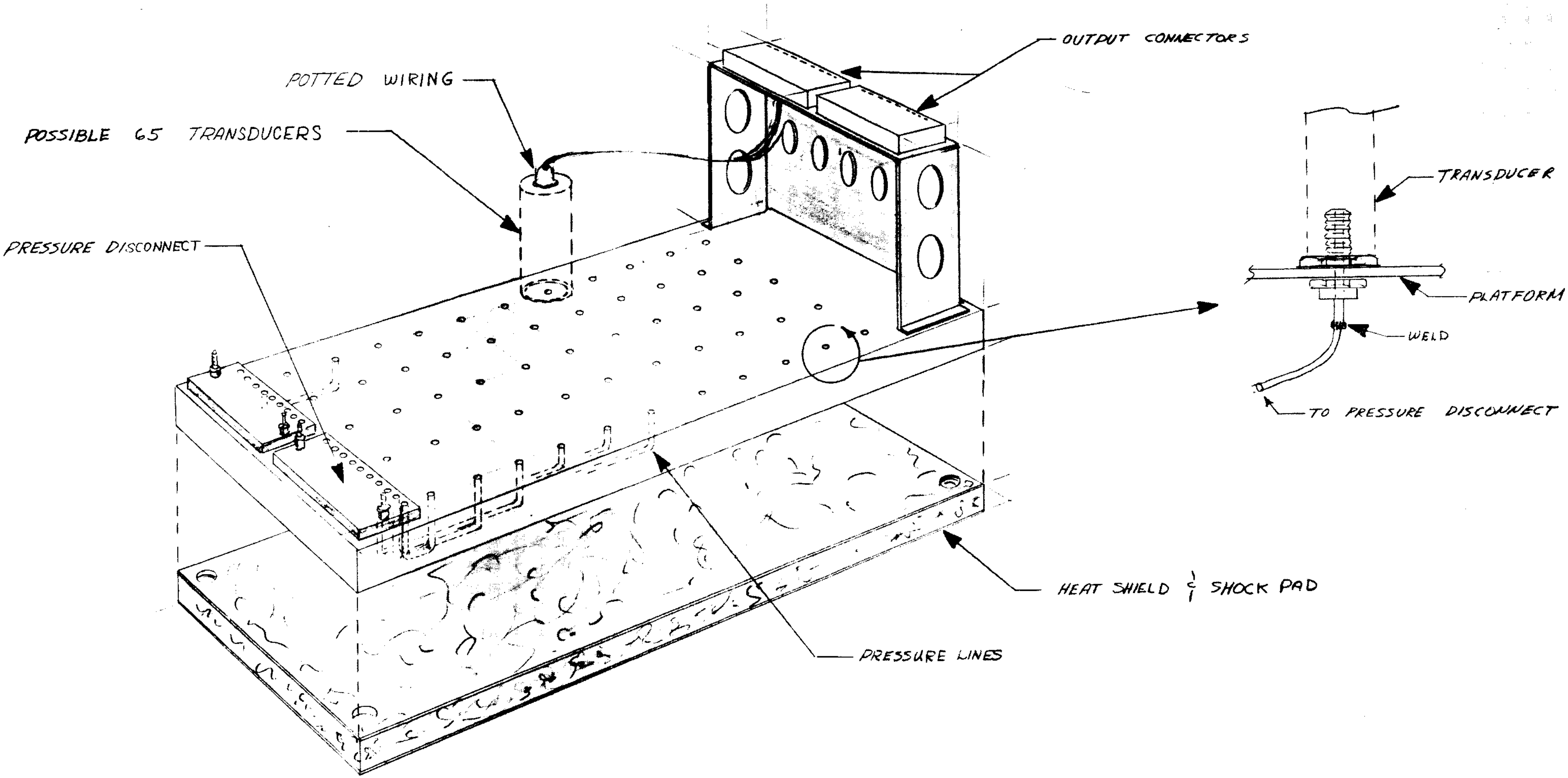


Figure 24 Recommended Pressure System - Transducer Platform

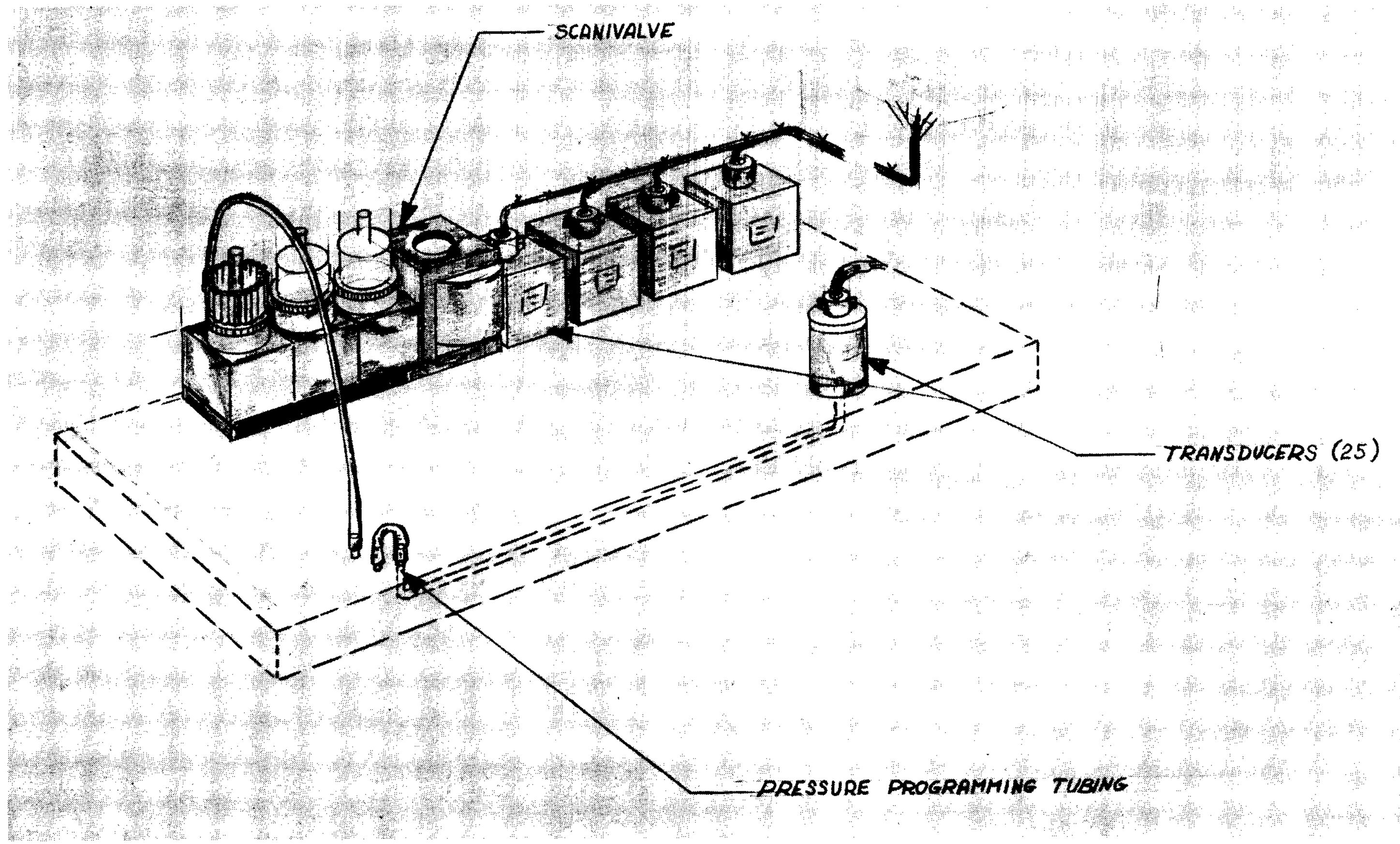


Figure 25 Recommended Pressure System - Transducer Layout

3.2.3.2.1 Insulation Requirements cont'd

Total heat rise is the sum of the two or 56°F. This results in a heat rise in the package at the time of test much lower than this value since the test will be over in less than 10 minutes after frame temperatures start exceeding the 350°F limit. It permits the use of light weight pressure measuring equipment that have temperature limits of 250°F.

An estimate of the power required to hold the compartment at +100°F with the ramjet structure at -50°F which is the case prior to release from the mother ship can be determined:

For ΔT of 150°F using the previous material assumptions

$$\text{Heat rate} = \frac{Q}{T} = 528 \text{ BTU/hr. or } 153 \text{ watts.}$$

3.2.3.2.2 Package Design

Installation of the pressure measurement systems in the centrally located compartment is most simply accomplished by mounting each transducer on a platform and connecting the pressure line to the transducer with a coupling. This is the lightest method but makes it difficult to conduct a good calibration. A method of doing end to end calibration with this approach would be to make fixtures to cover the ports and pressurize the port with a portable calibration stand.

A more practical method would be to use a single or dual pressure disconnect. A concept of this is shown in figures 22, 23, 24, and 25. This approach has several advantages and disadvantages that should be discussed.

a. Provides quick end to end system calibration of all transducers that are needed for accurate data.
b. Additional weight required.
c. Permits quick changes with different preprogrammed packages if necessary.
d. Provides a quick pre-mate check of the pressure package.
e. Contamination-sensitive.

The quick disconnect pressure plug will provide for rapid calibration of all transducers by mating it with a properly programed plug connected to a portable pressure source with a set of secondary pressure standards.

3.2.3.2.2. Package Design - cont'd

Transducers of the same pressure would be attached to a common pressure line that would provide calibration pressure to be applied to all simultaneously. With the ramjet connected to the X-15 via an electrical jumper cable, the PCM system can be used to record data. The advantages of this method are:

a. Establish systematic errors such as bridge voltage uncertainty, PCM gate offsets, and voltage differences.

b. Automatic calibration factors obtainable with proper data reduction.

c. Minimizes human errors.

d. Decreases manual handling of data.

In addition, the pressure disconnect plug approach permits the flight objectives to be modified quickly by providing several packages with different component arrangements. This would allow closer flight scheduling and permit evaluation of the data on the previous flight to be scrutinized longer before the decision is required as to the next flight objective. These are important factors in any flight program.

A pre-flight check of all pressure transducers could be accomplished to check out the total system. If the pressure plug was made accessible with the ramjet in the mated position, a pre-flight check could be planned just a few hours before the flight.

There are some penalties attached to the pressure plug. The first is weight. The estimated weight from a manufacturer of this type of equipment was obtained at less than 1.5 pounds for two 40 tube male and female disconnects. This is quite acceptable considering all the advantages. The second is more serious. Good light weight tubing for the ramjet testing is 1/8" O.D. This could have an I.D. of .069". The contamination problem with this hole size is obvious. Real care would have to be exercised by quality control. Utilizing 3/16" tubing with an I.D. of 144" would be better, but an estimated weight for the tubing runs with an average of six feet would result in a weight budget of 15.3 pounds as compared with 10.5 for the 1/8" tubing.

To counter these disadvantages, pressure disconnects of this type have been available commercially by Cannon and Scanivalve for many years. They are used successfully on tubing as low as 1/8" O.D. without excessive problems on ground and flight applications. At the larger tubing sizes, inset O rings are recommended at high levels of ramjet pressure.

This item has been applied in many aerodynamic facilities. The California Institute of Technology makes use of pressure plugs extensively. Perhaps the most applicable experience has been in jet engine testing in the high mach number tunnel at Arnold Engineering Development Center, Tullahoma, Tenn. In this facility the jet engines are frequently instrumented with all pressure probes going to a single disconnect. One system used around 300 pressure taps in a single plug and permitted objectives and engines to be quickly changed without requiring extensive down time from the instrumentation. The pressure levels in this facility are in the magnitude for the ramjet test program.

3.2.3.2.2. Package Design - cont'd

The incorporation of a pressure plug is recommended to provide for easy removal of instrument package and in place end to end calibration of pressure measurement system.

Several package configurations have been studied. The first one looked at uses 55 single transducers that will provide for basic pressure surveys. This number assumes a smaller number of total pressures measured than indicated in the guide lines. The reason for this change is the engine designers report that the shocks from many total probes in the gas stream would disturb the engine performance excessively. An estimated weight for the system is:

a.	Tubing runs (1/8" tubing)	10.5 pounds
b.	Pressure plugs (2)	1.5 pounds
c.	Transducers	10.3 pounds
d.	Platform, cover, heat control, shock pad, and cover insulation	10.3 pounds
e.	Compartment insulation	4.0 pounds
f.	Electrical harness and plugs (all)	5.0 pounds
	Total	41.6 pounds

This systems provides end to end calibration, removable modular construction and meets a reasonable weight budget.

The estimated space to permit access to this 1.1 cubic foot package and allow adequate insulation is approximately 2.0 cubic feet.

The development of this package is recommended.

The attenuation on transient data for this temperature controlled package can be estimated, making certain assumptions:

1. Length of tubing runs - 7 feet (estimated maximum)
2. Tube diameter - 0.08" I.D. (1/8" tubing)

As determined from Section 3.2.2, this will result in the following errors:

Frequency (CPS)	Attenuation (%)
0.1	2
1	6
3	10
10	20

These values refer only to the attenuation of the transient portion of the pressure level. The data is acceptable for steady state engine performance.

3.2.3.2.2. Package Design - cont'd

The second harmonic distortion on dynamic pressure data for the temperature controlled transducers can be estimated making certain assumptions:

a. The dynamic signal is 5% of the total measured pressure.
b. Average temperature in the tubing run - 610°R.
c. Length of tubing run - 7 feet.

Referring again to Section 3.2.2., this will result in distortion values of :

Frequency	Distortion (%)
1 cps	0.7
10 cps	6.3
100 cps	70.0

3.2.3.3. Pressure Measurement System Concepts

3.2.3.3.1 Multi-Transducer

The pressure measurement range to be covered during the ramjet testing extends over more than two decades of pressure as shown on Figure 26. It is not possible to cover this range with a single transducer and still provide the desired accuracy. Two methods have been considered to provide both range and accuracy as follows:

a. Over pressure single transducer
b. Provide multiple transducers in the same line with gage savers provided to protect lowest range transducers.

Of the two, the latter appears to be the practical approach. An example of the expected accuracies available with a gage saver system is shown in Figure 27. Current commercial gage savers are not directly applicable to flight systems because of range frequency response and weight. In view of the accuracy and range requirements for certain critical pressure measurements such as static pressures along the external ramjet structure, it is recommended that an adequate gage saver be developed.

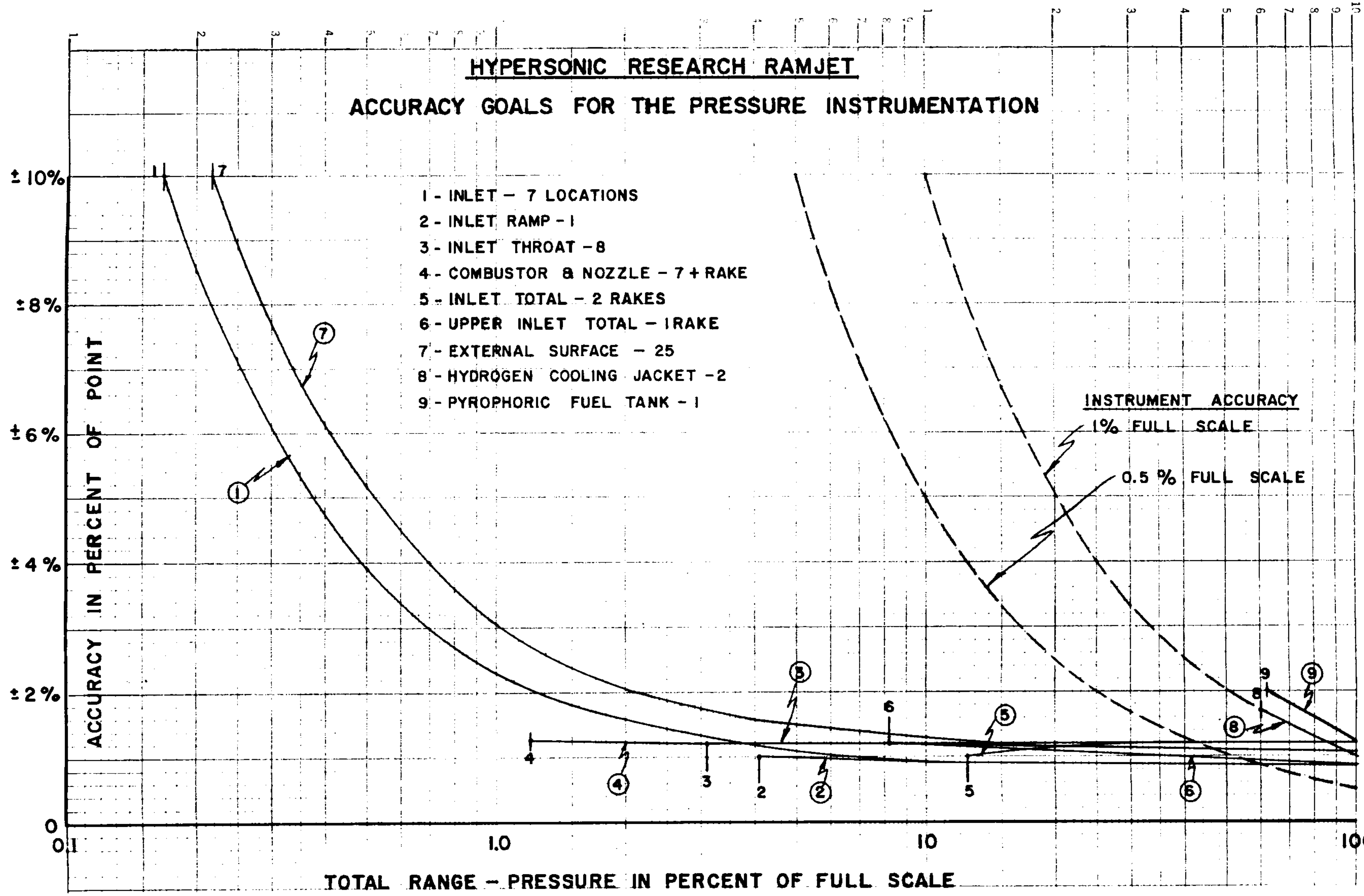
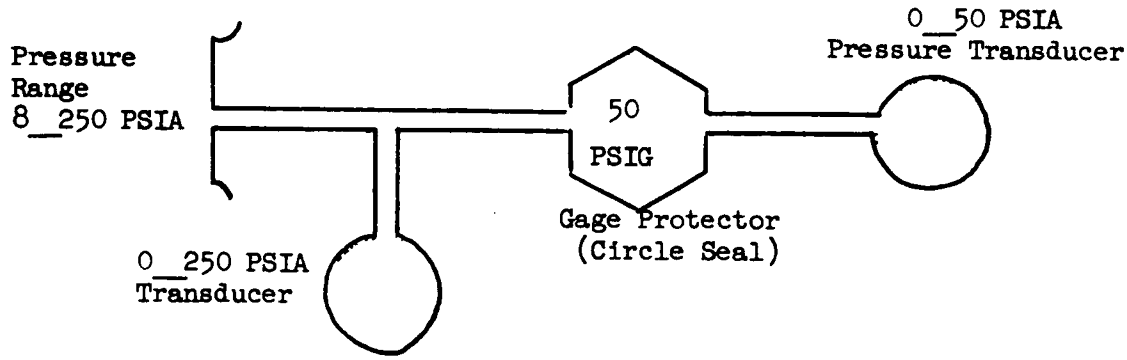

HYPERSONIC RESEARCH RAMJET
ACCURACY GOALS FOR THE PRESSURE INSTRUMENTATION
1 - INLET — 7 LOCATIONS
2 - INLET RAMP - 1
3 - INLET THROAT - 8
4 - COMBUSTOR & NOZZLE - 7 + RAKE
5 - INLET TOTAL - 2 RAKES
6 - UPPER INLET TOTAL - 1 RAKE
7 - EXTERNAL SURFACE - 25
8 - HYDROGEN COOLING JACKET - 2
9 - PYROPHORIC FUEL TANK - 1
INSTRUMENT ACCURACY
1% FULL SCALE
0.5 % FULL SCALE
± 10%
± 8%
± 6%
± 4%
± 2%
0
ACCURACY IN PERCENT OF POINT
0.1
1.0
10
100
TOTAL RANGE — PRESSURE IN PERCENT OF FULL SCALE

Figure 26



READING (PSIA)	ACCURACY (% of Reading)	REQUIRED ACCURACY (% of Reading)
250.0	±0.62	±1.2
125.0	±1.24	±1.2
62.5	±2.48	±1.2
50.0	±0.62	±1.2
25.0	±1.24	±1.2
12.5	±2.48	±1.25
8.0	±3.90	±1.25

PRESSURE RANGE EXTENDER

Figure 27

3.2.3.3.2 Pressure Scanning

The application of a scanning type pressure system offers an approach of considerable merit in ramjet testing. It is the lightest system evaluated and results in decreased calibration times. A basic schematic of such a system is shown in Figure 28. It consists of a single transducer, either absolute or differential, that can be connected to different pressure ports by means of an automatically controlled pressure switch. Each pressure port is normally sealed off unless applied to the transducer. This provides for a zero flow system except during stabilization of the pressure within the transducer and the required switching lines. To allow rapid stabilization after switching, it is essential that the transducer and switching line volume be held at a minimum. Short line lengths from the pressure port to the pressure switch are also desirable. The basic problem is to allow an adequate gas flow to pressurize the switched transducer volume in a short time when stepping from one pressure level to the next.

For the designer of a scanning system the most suitable method of controlling transducer volume is to select a small flush diaphragm pressure transducer and design the pressure switch around the transducer. This has been done by at least one manufacturer using the industry's standard 1/2" diameter flush transducer with satisfactory results within certain limitations of port to scanning line lengths and port scanning speeds. Application information on these limitations for a practical system is to be found in reference 57.

The scanning method has been used by General Electric Flight Test to good advantage in a number of installations. It has been flown on the B66 and F4 aircraft. This, however, does not directly qualify the scanning approach to be used in the environment of the ramjet. The only product investigated is suitable in a temperature range between 32°F and 257°F and must therefore be utilized in a thermally controlled instrumentation space. In addition, it has not been qualified for the vibrational specification of the ramjet. The vendor has indicated his product will pass this requirement with nominal changes in the present design.

Some of the advantages and limitations of the "present state of the art" with respect to scanning systems are given below:

Weight	1/3 of a single transducer system
Size	1/5 of a single transducer system
Accuracy	Nearly the same as a single transducer
Cost	1/6 of a single transducer system
Saves calibration time	
Maximum practical sampling rate	24 ports in 1.2 seconds
Adjacent port pressure ratio	1.5 maximum
Low pressure limit	1 port - 8 psia
Low pressure limit	2 parallel ports - 2 psia

PNEUMATIC DIAGRAM OF A TYPICAL SCANNING APPLICATION TO DETERMINE PRESSURE PROFILE ON THE RAM JET

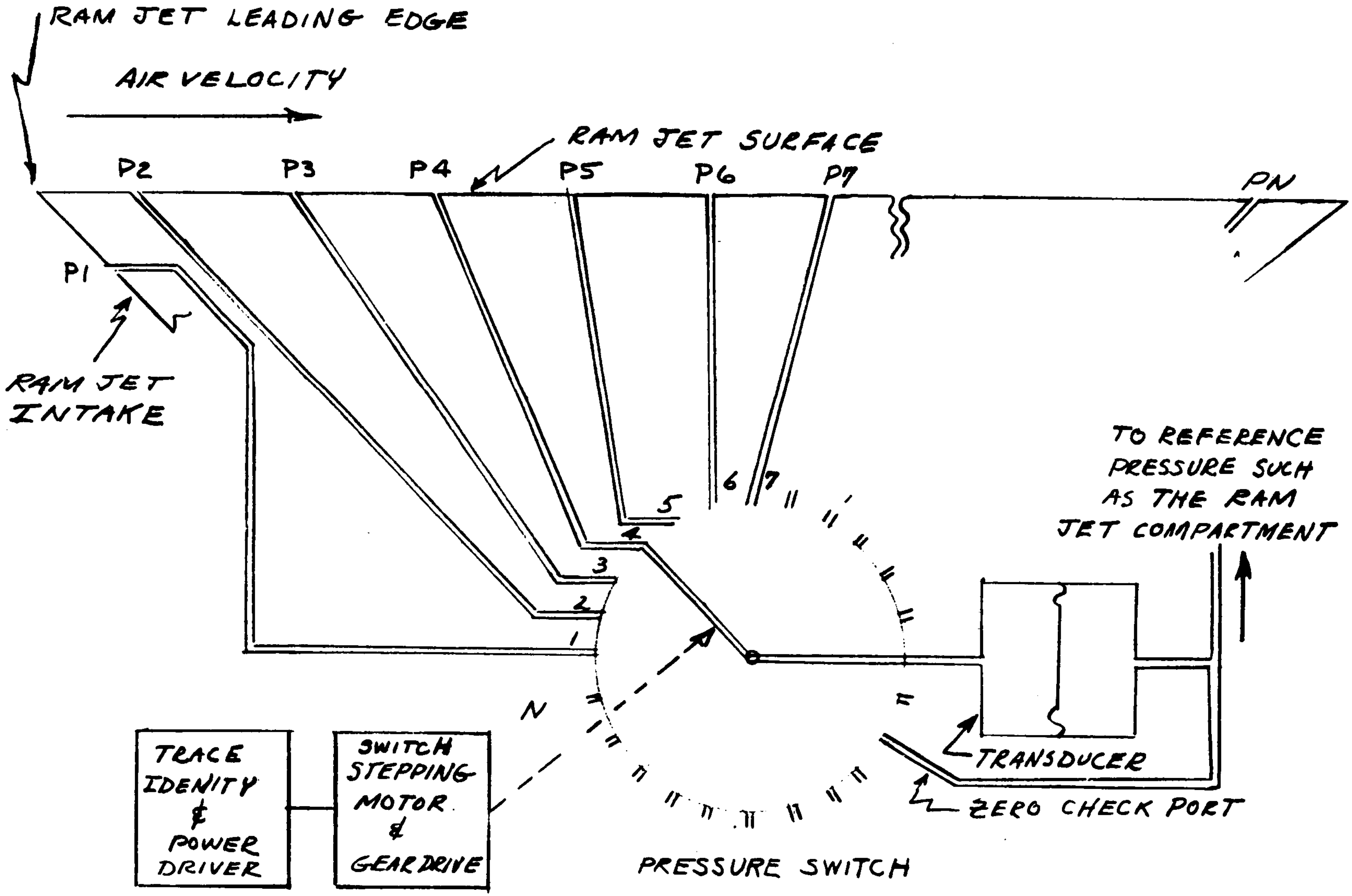


FIGURE 28

3.2.3.3.2 Pressure Scanning - cont'd

And idea of the weight saving can be ascertained by comparing required systems:

		lbs.
72 port scanning unit		
with 3 transducers		7.5
Mounting-shock		.5
Wiring		neg.
	Total	8.0
67 pressure transducers		12.0
Mounting-shock		8.0
Wiring		4.0
	Total	24.0

The accuracy of a scanning system operating at a sampling rate of 20 ports per second can be nearly the same as that of a single pressure transducer if certain precautions are observed in obtaining adequate stabilization after switching. The very limited data available from reference 57 on scanning speed versus line length indicates this error is a function of absolute pressure as well as the pressure ratio (psia) between ports. For a typical system installed in the ramjet, pressures higher than 8 psia will result in stabilization errors of less than 0.5% of reading with adjacent pressure port ratios of less than 1.5 to 1. Most significant ramjet data will meet these requirements. Instrumentation Engineering can easily program adjacent port pressures to be less tnan 1.5 to 1. In cases where lower pressures are indicated during engine performance evaluation, paralleling of ports will achieve adequate stabilization time at a sacrifice in the number of measurements. At the suggested scan rates, it is estimated 1 to 2 psia is a lower limit with the 1.5 pressure ratio.

The small number of transducers needed in the scanning system permits time to be taken between flights for a complete end to end calibration. The preflight assurance check in the last hours can be accomplished easily with pressure excursions on only three pressure taps.

The scan rate of 20 ports in one second will provide for each port to be scanned every 1.2 seconds. This will result in a limited number of points during the test, but in steady state operation would be quite satisfactory to obtain pressure profile data on external surfaces as well as some other measurements.

The utilization of opposite ports on the same scanner will permit the interval to be 0.6 seconds. Since a proposed package would include 72 scan ports and some continuous scan transducers, most of the critical parameters would be scanned at this latter rate and result in 33 samples per measurement during a ramjet test time of 20 seconds.

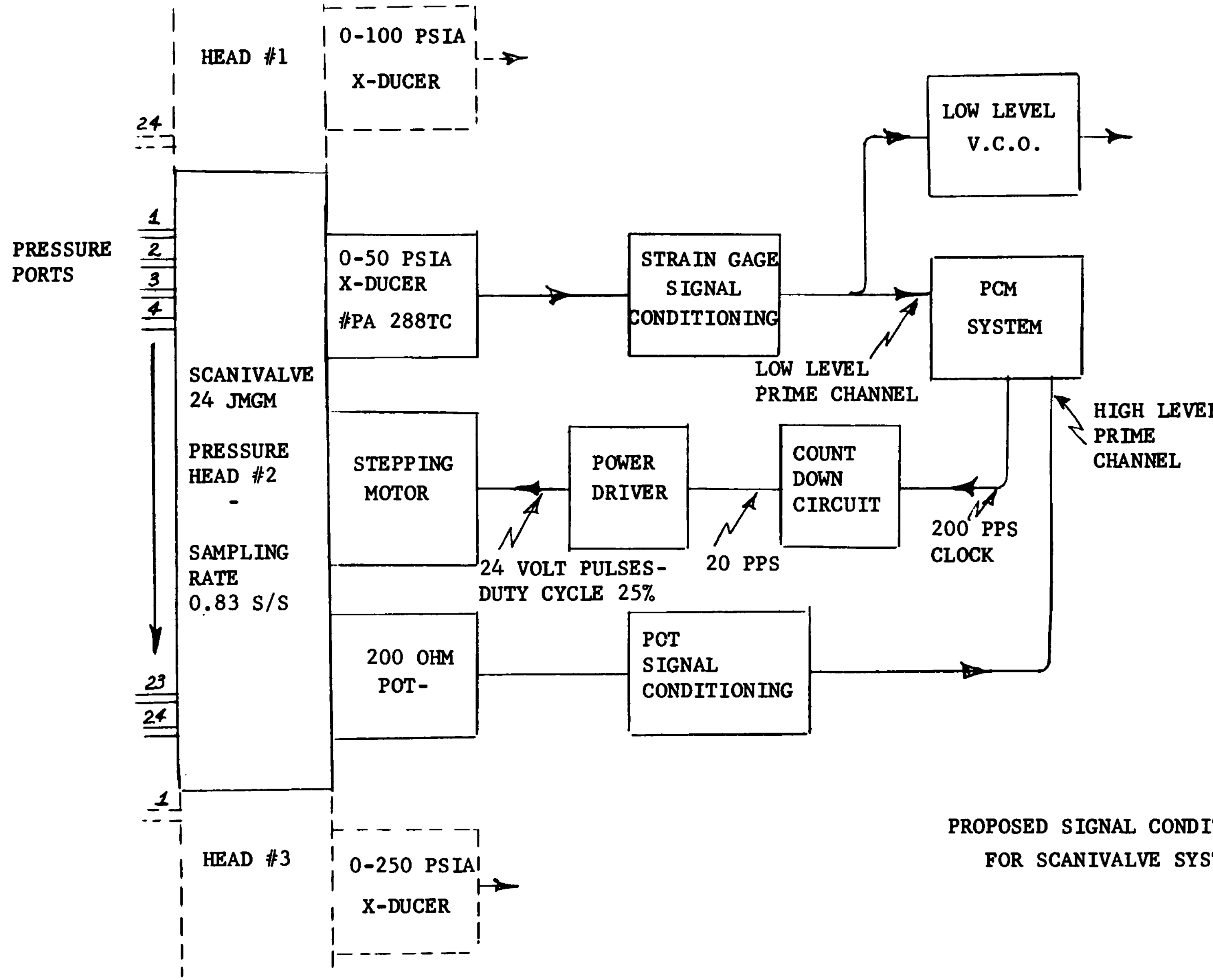
3.3.3.3.2 Pressure Scanning - cont'd

Signal conditioning of a special nature will be required to apply the scanning valve to the PCM system. It is necessary to know when a sample from the PCM system is stabilized so it can be identified automatically as good data. The method used by General Electric to achieve this is to control the stepping motor by the PCM clock. In addition, a trace identifier potentiometer is monitored by the PCM. These inputs are programmed to the data computer to select the stabilized sample and determine assurance of stabilization. A conceptual system is given in figure 29.

A superior method from a data reduction point of view on trace identification for scanning systems would utilize a digital code rather than a potentiometer. The X-15 PCM system can accomodate a 9-bit digital word. Scanivalve Company makes on special order a 7-bit binary code that would be suitable in the application. If digital channels are available this is a recommended option.

The selection of pressure transducers for the practical scanning system depends on the requirement to use either absolute or differential methods of measuring pressures. Figure 29 describes this approach using absolute transducers and indicates a suitable transducer that can be utilized with the Scanivalve.

As an option on differential measurements where space and weight limitations are critical, the same differential pressure transducer indicated as suitable in continuous differential measurements may be used in the scanning valve. A pressure reference is required as indicated in Figure 28. This reference should be monitored with a continuous, absolute pressure transducer to provide level information and should vary relatively slowly with respect to time to permit the same pressure to be present at the back of the differential pressure transducer diaphragm and at the absolute pressure transducer diaphragm. The obvious penalty for not doing this is a loss in dynamic accuracy. For further details see the special section on differential measurements.



PROPOSED SIGNAL CONDITIONING
FOR SCANIVALVE SYSTEM

FIGURE 29

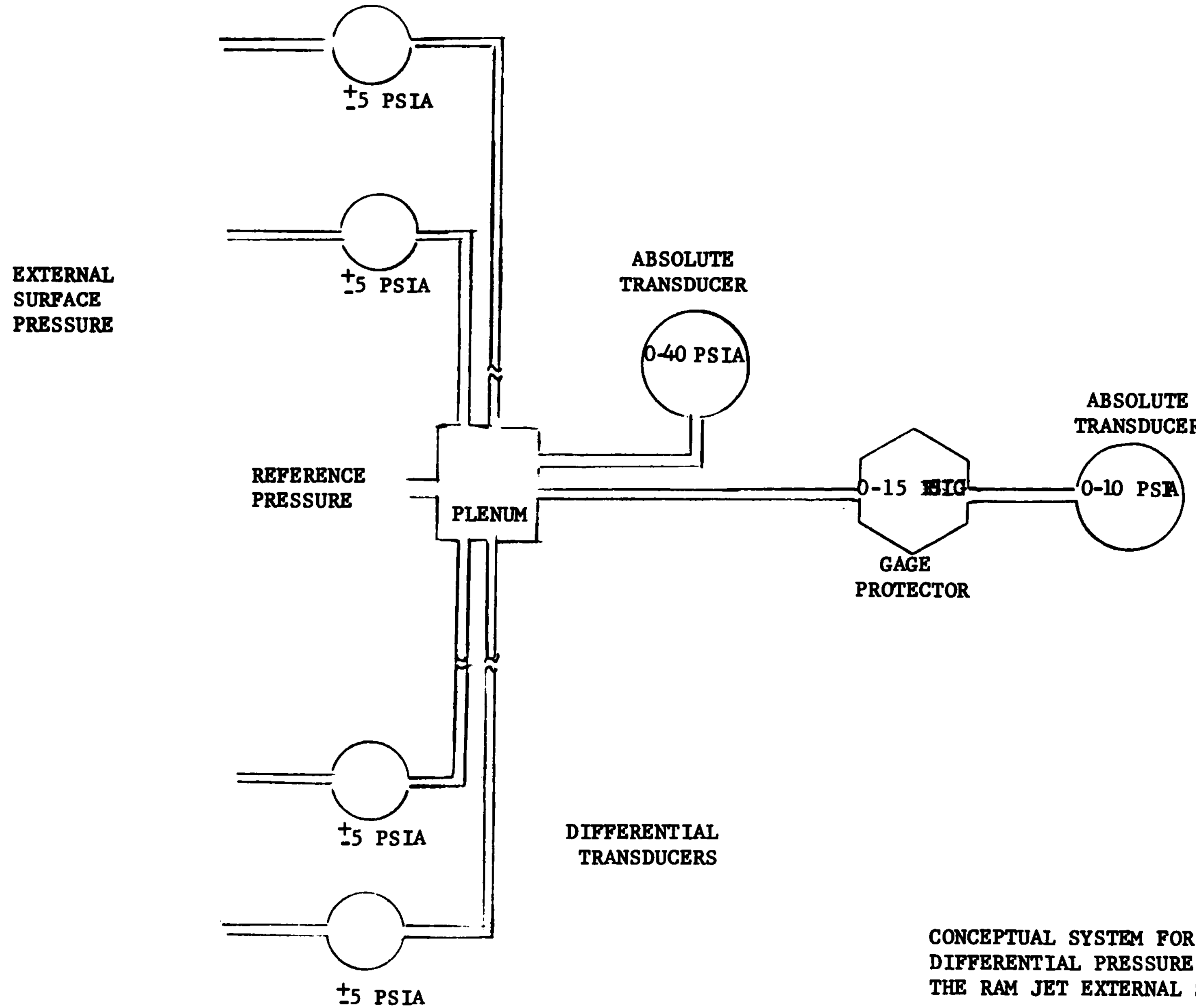
3.2.3.3.3 Differential Transducer

Differential pressure measurements have been utilized as a standard in flight test to acquire knowledge of pressure profiles. They are valuable where the profile pressure change across the surface is small relative to the absolute pressure. This may not be true in ramjet testing at high mach numbers where it is possible to have a large pressure change occur across some profiles. When this occurs, the advantage of differential pressure measurements tends to disappear.

The application of differential transducers to the pressure within the engine is not recommended. Shocks will exist along with a high pressure rise in the inlet. External surface pressures appears to be one application on the ramjet that differential pressure transducers might be suitable. This is recommended for the latter part of the program where the approximate pressure levels are rather well known. A wide range conceptual system is shown in the figure 30. Good profile measurements can be obtained over ranges of 2 to 40 psia. This, of course, assumes the pressure profile is rather flat. Equipment that would be suitable in the lagged instrumentation bay to achieve this measurement is available.

This system would be extremely light because the differential transducer selected is a flush type unit with an adaptor. The net weight of the adaptor and transducer is less than one ounce.

The accuracy is difficult to define in a system of this nature. Any frequency fluctuations in the plenum results in differential pressure changes that are not easy to evaluate. Assuming the plenum is designed properly, the errors are similar to the absolute pressure transducer. With the system given, differential data can be obtained as good as 0.63% of full scale with end to end calibration on the transducers. The absolute value of the readings is degraded by the requirement to utilize two pressure transducers to calculate the port pressure. Since the delta transducer generally reads only a small percentage of the pressure, this degradation factor is also small.



CONCEPTUAL SYSTEM FOR WIDE RANGE DIFFERENTIAL PRESSURE MEASUREMENT ON THE RAM JET EXTERNAL SURFACE

FIGURE 30

3.3 Structural Measurements

3.3.1 Metal Surfaces

3.3.1.1 Temperature Measurements

3.3.1.1.1 Requirements

A reliable method is needed for measuring the temperature of metal structures of the ramjet engine. Specifications: Range, 390° - 2500°R, Measuring range, 1000°R - 2500°R, Accuracy ± 1% of reading.

3.3.1.1.2 Temperature Measurements Systems

Many different measuring systems have been used to measure the temperature of structures. Three general types of measuring systems were considered for this application:

a. Systems that utilize the thermal radiation from the surface:
   1. Total radiation pyrometers
   2. Optical pyrometers
   3. I. R. Pyrometers
   4. 2-Color Pyrometers.

B. Systems that depend upon a visible change in the surface:
   1. Temperature paint
   2. Radioactive Krypton

c. Sensors that produce a signal that can be read remotely:
   1. Resistance thermometer
   2. Thermocouples

Systems that utilize the thermal radiation from the surface such as optical pyrometers were one of the first methods of measuring surface temperatures. All types of optical pyrometers must provide an optical path from the surface to the detector in the pyrometer.

The most common optical pyrometer is the vanishing filament type that operates on 6500 Å and is adjusted manually. This instrument has been modified to operate remotely and is commercially available. The lower temperature limit is approximately 1300°R and the remote instrument is very heavy and expensive.

Total radiation pyrometers have a lower reading limit of approximately 1000°R. The pyrometer is sensitive to the emissivity of the target and the minimum target size is not small enough to measure the detail that is often needed for measuring temperature gradients on structures.

3.3.1.1.2 Temperature Measurements Systems - con't

Infra-Red pyrometers can be used to measure surface temperatures as low as 400°R. The instruments are cumbersome and need special attention. The temperature determination is dependent upon the emissivity of the target.

Two color pyrometers on certain materials eliminate the need for determining the emissivity. Most of the two-color pyrometers have a temperature range of 2000°R and up, although special ones can be obtained for temperatures as low as 1500°R.

A light pipe used in conjunction with a two-color pyrometer can be used to measure remotely the temperature of a very small area and could be used to measure ablating surfaces in the ramjet. (ref. 58)

Surface Indicator

Temperature indicating paints are a very inexpensive and lightweight method for measuring surface temperatures. If the paints are applied properly,and used according to directions,an accuracy of ±10°R can be achieved. A great disadvantage of temperature indicating paints is that it only records the peak temperature that the surface has attained and it does not provide a time at temperature history of the structure. One must know something about the expected temperature range before he can intelligently select the best paint for the application.

The technique utilizing radioactive Krypton (reference 59) does not suffer from selecting the proper paint for each location. This technique involves kryptonating the surfaces before exposure and analyzing the parts after exposure by controlled heating and counting the radioactivity.

Remote Indicator

Small sensors that can be read remotely are very attractive for ramjet measurements. Paste on platinum resistance thermometers have been used to measure surface temperatures. A grid much like a strain gage is attached to the surface to be measured and the resistance change of the gage can be used to measure temperature. The fact that the gage must be electrically insulated from the part but not thermally insulated persents a problem under conditions of high heat flux. The physical size of the resistance thermometers present other attachment problems.

One of the advantages of the resistance thermometer is that no reference temperature is needed. A special signal conditioning bridge and an external power source is needed for each sensor.

3.3.1.1.2 Temperature Measurement Systems - cont'd

Thermocouples are a very common method for measuring the temperature of surfaces. The actual sensing element can be quite small, it can be made an integral part of the structure that is being instrumented, and it does not need an external power source. Accuracy of ±1% is obtainable with thermocouples.

3.3.1.1.3 Selection of Sensor

Thermocouples are recommended as the measuring sensor for the surface temperatures. The considerations were light weight, ruggedness, cost, and compatability with the PCM system on the X-15. Thermocouples do not present the same risk as some of the other systems because the thermocouple state of the art is very well established.

The recommendations are:

a. Use swaged chromel-alumel thermocouple assemblies with enclosed grounded thermocouple junctions.
b. Provide a reference junction system incorporating the floating reference block system for referencing the thermocouple. (Ref. 60)
c. The signal should be read out on the X-15's PCM system.

Chromel-alumel was chosen as the thermocouple elements because it meets the temperature range and is very compatible with common sheath materials. Other thermocouples elements considered were:

a. Copper-Constantan - a very stable thermocouple at low temperatures but cannot be used at 2500°R.
b. Iron-constantan - subject to inhomogeneity and calibration drift problems.
c. PtRh/Pt - Has a low output, is expensive and temperature range does not warrant noble metal series.
d. WRe/W - Thermocouples are very stable at low temperature but the junctions tend to be fragile and thermocouples cannot be used in an oxidizing atmosphere unprotected.
e. Driver Harris - 242/33 Alloy-Thermocouple is reported to be good in ozidizing or reducing atmosphere. Does have application for instrumented parts that must be subjected to a brazing cycle. Thermocouple does not hold its calibration as close as CA.

Swaged thermocouple assemblies are recommended because the thermocouples are very small, are easy to install, are somewhat flexible, have high temperature insulation, can be made to give a pressure seal and the complete assembly can be checked before the thermocouple is installed.

The floating reference block system is recommended because it provides advantages of weight, reliability and complexity over conventional reference systems.

3.3.1.1.4 Fabrication and Installation of Thermocouples

a. Fabrication of Swaged Thermocouple Assemblies

Good swaged thermocouple assemblies can be obtained commercially as off-the-shelf items. However, there are certain advantages to fabricating the thermocouple assemblies for a particular job. Sufficient detail is included to enable a technician familiar with the art of thermocouple and strain gage instrumentation to perform the necessary operations.

The basic swaged thermocouple wire should be purchased from a reputable supplier of metal sheathed ceramic insulated thermocouple wire. It is strongly recommended that it be purchased according to specification JMT-I.48.07, a copy of which is included in Appendix IV.

The sheath material should be compatible with,or the same material as, the structure to which the thermocouples will be attached. (Inco 702 sheath has been found to have very good oxidation resistance.). Over the temperature range of 1000°R to 2500°R, the MgO insulation supplied in commercial sheathed thermocouples wire is an adequate insultation. Swaged wire can be supplied in many sizes. For this application a .020" diameter sheath is recommended. However, if a small temperature zone must be measured an .010" dia. can be used.

The thermocouple wire should be inspected by the user to make certain that it meets the specifications in Appendix IV. Checks such as physical size, insulation resistance, both hot and cold, are important. The thermoelectric check should be amended to give a deviation curve from NBS #561 so that this calibration curve can be used in the data reduction program if necessary.

The spurious voltage test is used to give the deviations that might exist in a thermocouple calibration due to the fact that the thermocouple leads are subjected to a temperature gradient. This test being performed is shown in figure 31.

After the wire has been tested one should have for the fabrication of the thermocouples a roll of wire that is homogeneous and has a known calibration.

The decision to use a grounded or ungrounded junction is based upon two considerations; the temperature gradient in the part to be measured and the readout system. If the thermocouple is placed in a high temperature gradient a grounded junction is the best because the measuring junction is a part of the structure whose temperature is being measured. An insulated or non-grounded junction is compatible with most readout systems and usually does not need as much filtering in the input circuit as the grounded junctions. Trouble shooting non grounded junctions for secondary thermocouples and grounds is less complicated than for grounded junctions.

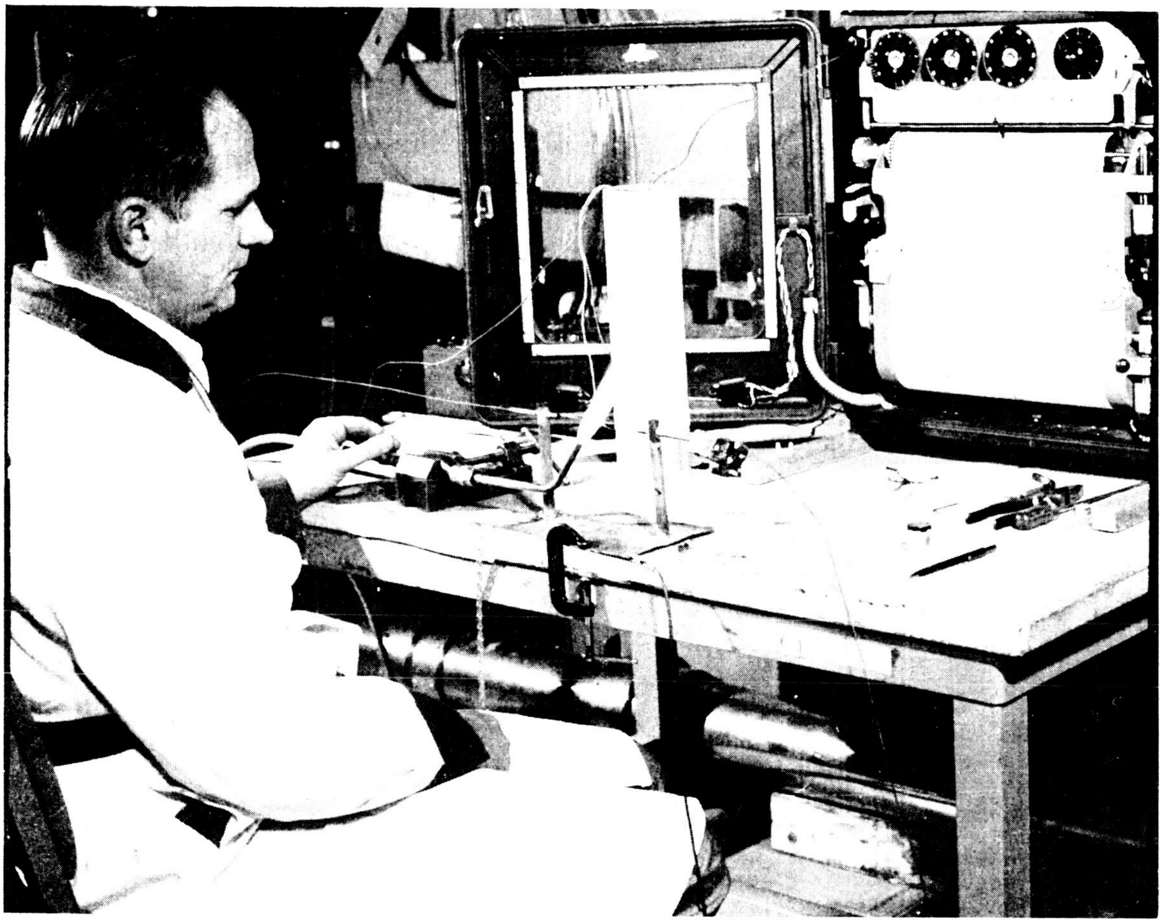


Figure 31 Laboratory Check for Sheathed Wire Homogeneity

3.3.1.1.4 Fabrication and Installation of Thermocouples - cont'd

Fabrication of Swaged Thermocouple Assemblies - cont'd

A trouble shooting tip for detecting secondary thermocouples and secondary grounds in grounded thermocouples is to apply heat point by point along the thermocouple sheath and to monitor the output of the thermocouple elements and the output of the thermocouple element and the sheath. It is recommended that grounded junctions be considered for this application to increase the accuracy of the measurement.

The first step in making the actual ungrounded junction is to expose the wire by stripping the sheath. This task can be simplified by the use of a commercially available wire stripper which was designed for this task. After the sheath has been bared some of the MgO insulation should be removed and the thermocouple junction formed down inside the small sheath by the use of an inert arc welder. If the final junction is to be insulated, pure MgO is packed inside the sheath and over the thermocouple junction. The end of the sheath is capped by the use of an inert arc welder using the same filler material as the sheath.

In the case of the grounded junction the junction is not completely covered with insulation and the end of the sheath is welded to the thermocouple junction. It should be emphasized that voids cannot be tolerated in the end of the thermocouple and that pure, dry insulation should be used for packing. After the junction has been made, it should be checked for continuity and thermal shocked for at least 5 cycles. Heated in air to 2000°R and doused in cold water is the recommended cycle test. If the thermocouple assembly will be subjected to hydrogen during the testing or be subjected to a reducing atmosphere during the fabrication of the parts, the thermocouple should be leaked checked. The recommended procedure for leak checking is to expose the thermocouple to 2000# of Helium pressure for a half hour and place the assemblies in water and check for leaks.

Although the swaged wire is somewhat flexible a more flexible lead wire is often advantageous. One procedure for making this splice is as follows: First obtain a roll of 28 AWG CA thermocouple wire with silicone impregnated glass asbestos insulation. It is very important that the swaged wire and the flexible wire have the same calibration or a mismatch will exist at the splice. To prepare the wires for splicing, the ceramic insulated wire is exposed by stripping the sheath and the flexible wire by stripping the insulation and then flattening the ends of the wires. A small pad is attached to the swaged tube and the flexible wire is secured (fig. 32) to the pad by use of a nichrome strap. The pad also provides a flat for securing the splice. Care must be exercised to make certain that the alumel wire is spliced to the alumel wire and the chromel wire to the chromel wire without grounding or shorting either splice. The splice is insulated from the flat on the pad by using a cement that will withstand the expected temperature environment at the splice.

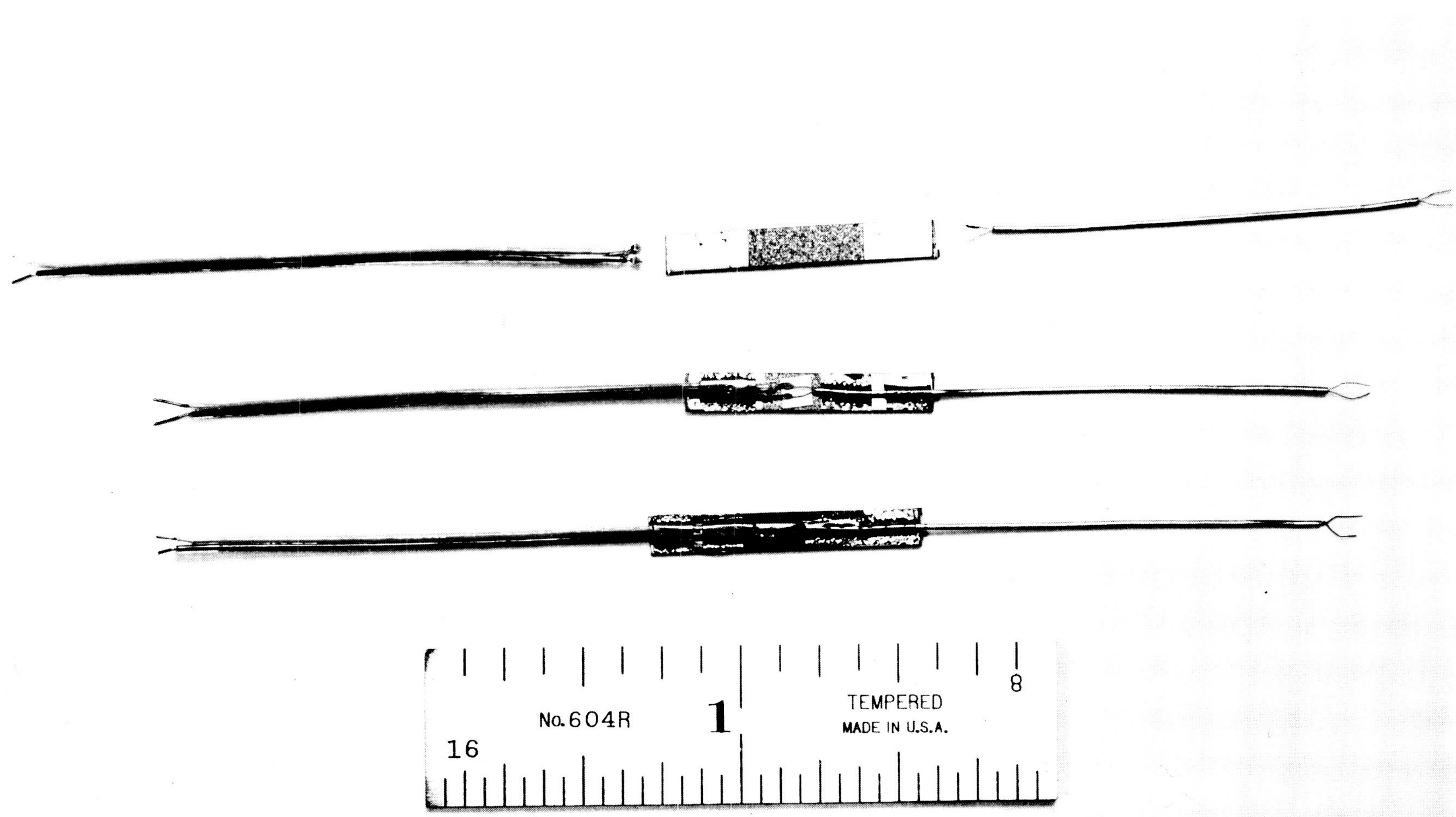


FIGURE 32 SPLICE OF SHEATHED TO FLEXIBLE WIRE

3.3.1.1.4 Fabrication and Installation of Thermocouples - cont'd

b. Installation of the Thermocouple

The most preferred method of attaching the thermocouple to the surface to be measured is the inlaid thermocouple. The steps in this operation are shown in figure 33a . The depth and width of the groove for the .020 thermocouple should be .022-.024". The best method for making a good groove is by using a brass electrode on a metal deposition machine such as an Elox. The thermocouple is secured in the groove by a technique that utilizes a capacitance discharge welder such as the Weldmatic of Unitek. Eight to ten mil Chromel A wires are laid parallel with the thermocouple and welded into the groove. The spot welder power setting is approximately 15 watt seconds. and the wires are spot welded with a multitude of discharges until the wire blends into the piece. The work is dressed off until it presents a smooth surface. The finished product is a thermocouple that is in intimate contact with the surface and it presents no aerodynamic disturbance.

The thermocouple sheath can be secured along its length by capacitance discharge welding small nichrome straps over the thermocouple sheath.

It is not always possible to use the inlaid thermocouple technique or a welded technique because of compromising the integrity of the structure. After this has been adequately discussed by the designer and the instrumentation engineer, a compromise technique can be used. This technique is used for attaching strain gages and is called the flame spraying technique. (Reference 61 - figure 33b) The thermocouple junction is made from bare 1-3 mil chromel alumel wire or 1 x 32 mil flat ribbon or exposed wire from the end of the swaged .020 thermocouple wire. The area where the thermocouple junction and its leads will be secured should be cleaned thoroughly and roughened by a grit blast If the surface cannot be roughened, it should be cleaned thoroughly and flame sprayed with a coat of nickel aluminide such as Metco 404, and then a layer of nichrome applied as a base coat. After the surface has been prepared an insulation coat of Al_2O_3 rod is used with a ceramic spray gun. A layer of 2-3 mils thick should be sufficient for a base coat. If the measurement system will tolerate a grounded junction and the designer will allow a light tack weld, a better thermocouple installation will result if the junction is spot welded directly to the structure. The wires are then pulled tight and taped by strips of masking tape that does not leave a residue such as mystic tape, Then the exposed wires and the strips of tape are flame sprayed. The strips of tape are removed and the previously covered wires and the exposed wires are covered with flame spray. If separate thermocouple wires were used for this operation, a high temperature splice must be made to the lead wire, and the lead wires are treated in the same manner as the imbedded thermocouples.

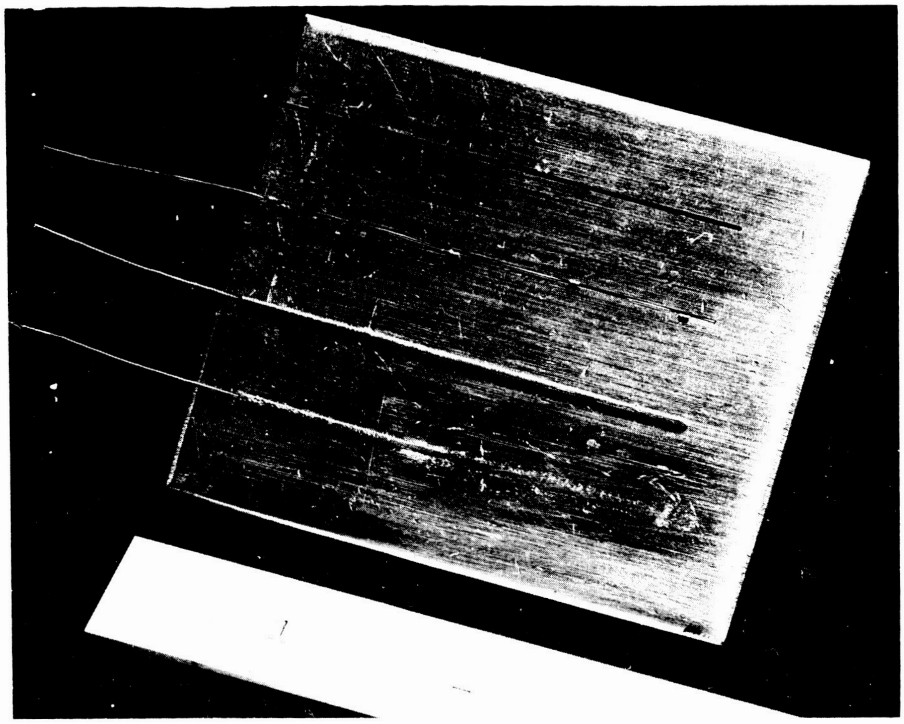


FIGURE 33a Imbedded Thermocouple In Various Stages of Installation

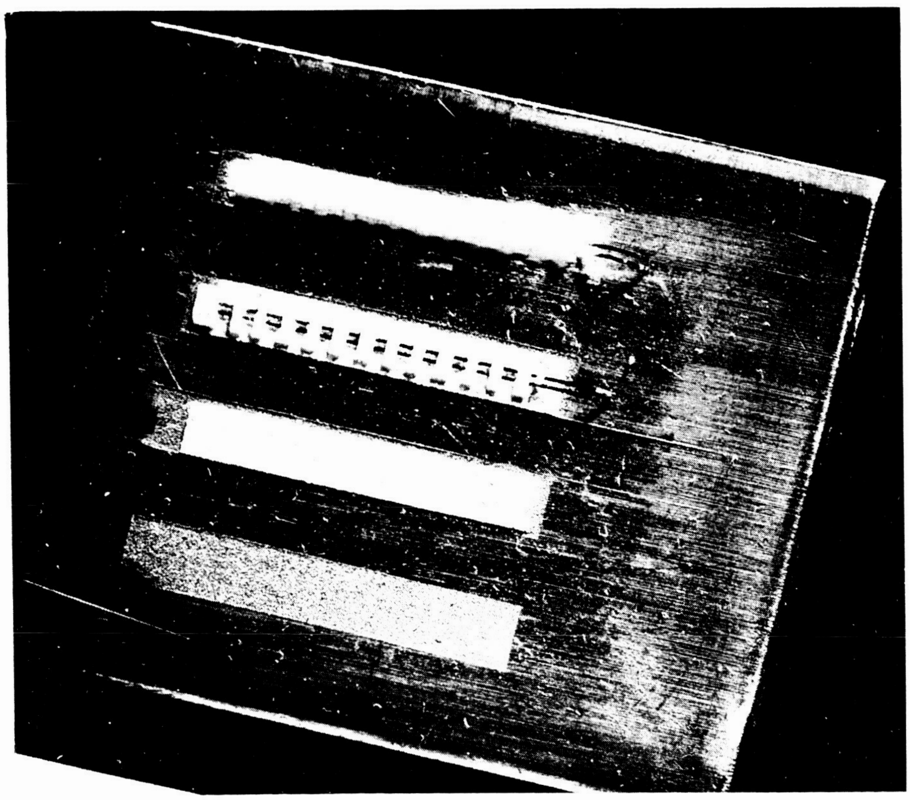


FIGURE 33b Flame Sprayed Thermocouples in Various Stages of Installation

3.3.1.1.4 Fabrication and Installation of Thermocouples - cont'd

b. Installation of the Thermocouple - cont'd

If the measuring thermocouple cannot be installed with either of the recommended practices, other methods of attachment are possible. A good method is to bare the thermocouple junction, secure the sheath to the surface by nichrome strapping, and then tweezer welding the junction to the surface. It is recommended that the wires be bent to provide expansion joints. The junctions and the end of the swaged wire should be covered with a nichrome band. See figure 34.

The instrumentation of cooling tube bundles presents additional problems. It is recommended that capped thermocouples be used and the thermocouples be lead from the cold side through holes in the braze, run along the crevice in the tube for a short distance to minimize conduction and then fasten the thermocouple to the tube by nichrome strapping. See figure 11.

3.3.1.1.5 Reference Junctions

A complete thermocouple system consists of a hot junction, lead wire, a reference junction, and a millivolt meter. The temperature of the hot junction can be determined if the temperature of the reference junction is known and the voltage developed by the thermocouple junctions is accurately measured.

Several reference junction concepts were considered in this program. A very good reference junction for thermocouples is a junction immersed in oil and maintained at the ice point with a mixture of ice and water. (Reference 62). Unfortunately this setup is bulky for a large number of junctions.

Kaye Company of Cambridge Mass. sells a unit which utilizes a thermoelectric heater and cooler to maintain a reference junction at 32°F.

A common reference junction is a heated junction that is maintained at some temperature above ambient. It is difficult to build such units small, and maintain small temperature gradients in the reference block.

For users that like a reference of 32°F but want to use heated junctions, this can be obtained by having two thermocouple junction in series, at two different temperatures. The difference can produce a voltage that is equivalent to a 32°reference. Another very common type of temperature compensator uses a resistor with a unique coefficient of resistance. This system is used in many direct reading temperature instruments. The resistor whose resistance changes with temperature is placed in the bridge so that the zero reading of the bridge will be equal to the temperature of the resistor in the bridge. Some very light weight airborne compensators are commercially available that operate on this principle.

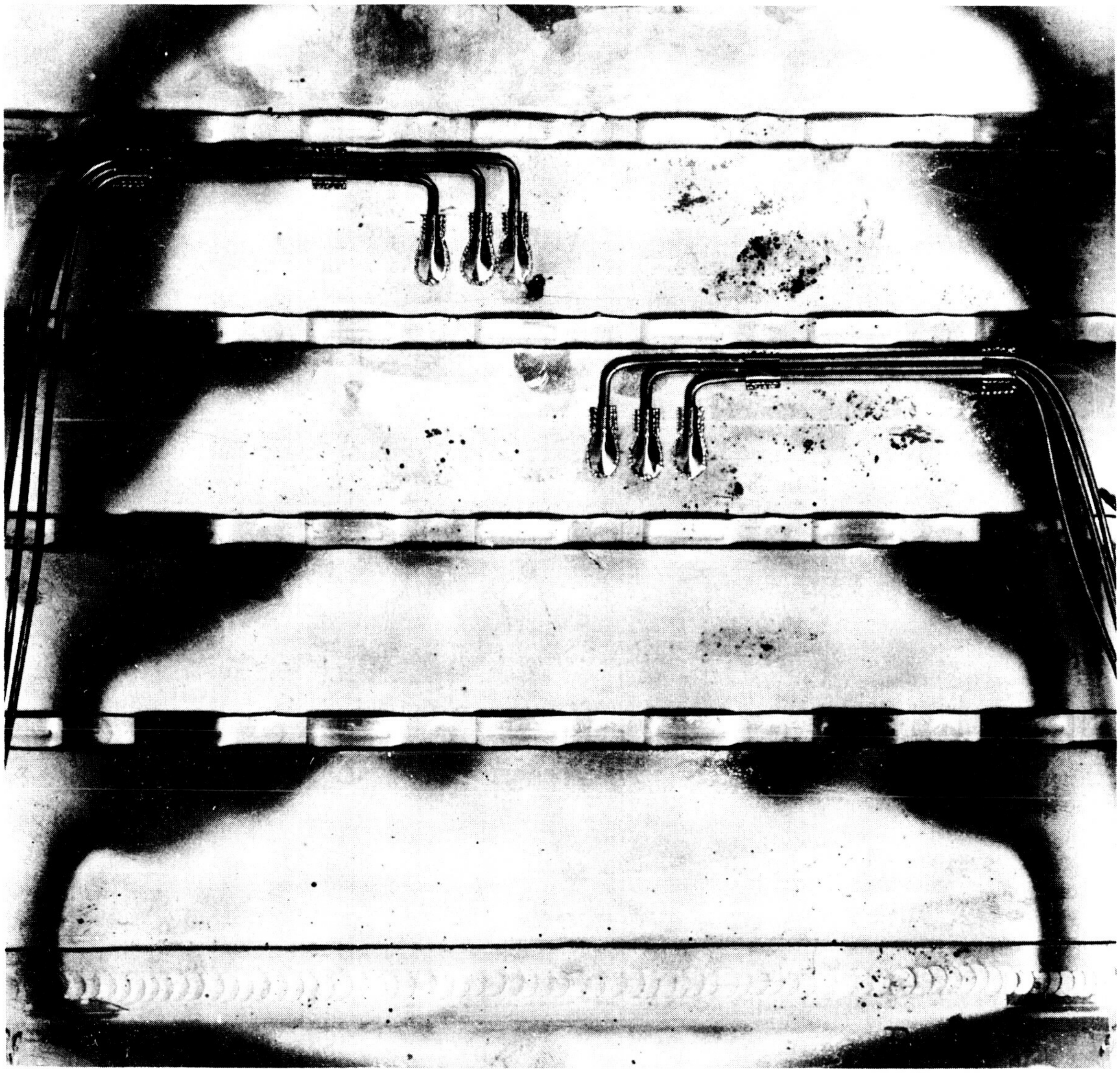


Figure 34 Sheathed Thermocouples Provided with Protective Shields

3.3.1.1.5 Reference Junctions - cont'd

All of the systems described need one or more controlled junctions for each measuring thermocouple. The system recommended for this application is referred to as the CATS system in reference 60, and a zone box in reference 63. The zone box makes use of the fact that it is easier to go with nature than try to control it. The general schematic diagram of the proposed system is shown in figure 35.

The details of making the floating reference junction box can vary to meet the specified purpose. For this application, it is recommended that the aluminum block be made for 100 thermocouples. The block should be at least 1/2" x 2" x 8", and drilled with 200 - .086" through holes.

Chromel-copper and alumel copper junctions should be made by soldering, and insulating with a good cement such as RTV 104. All of the junctions should be placed in the holes in the aluminum block and glued into place. It is recommended that platinum resistance thermometers, attached to the reference block, be used to monitor reference temperature. The aluminum block with its leads should be encapsulated in a plastic such as RTV-104, with insulation on all 6 sides of the aluminum block. The leads should be spiralled around the block and the complete unit provided with additional insulation. The lead wire from the thermocouples should be attached to the chromel-alumel leads from the zone box and the copper leads should terminate in an electrical connector that is compatible with the PCM system.

3.3.1.1.6 Error Analysis

There are several sources of error which can be attributed to the thermocouple system.

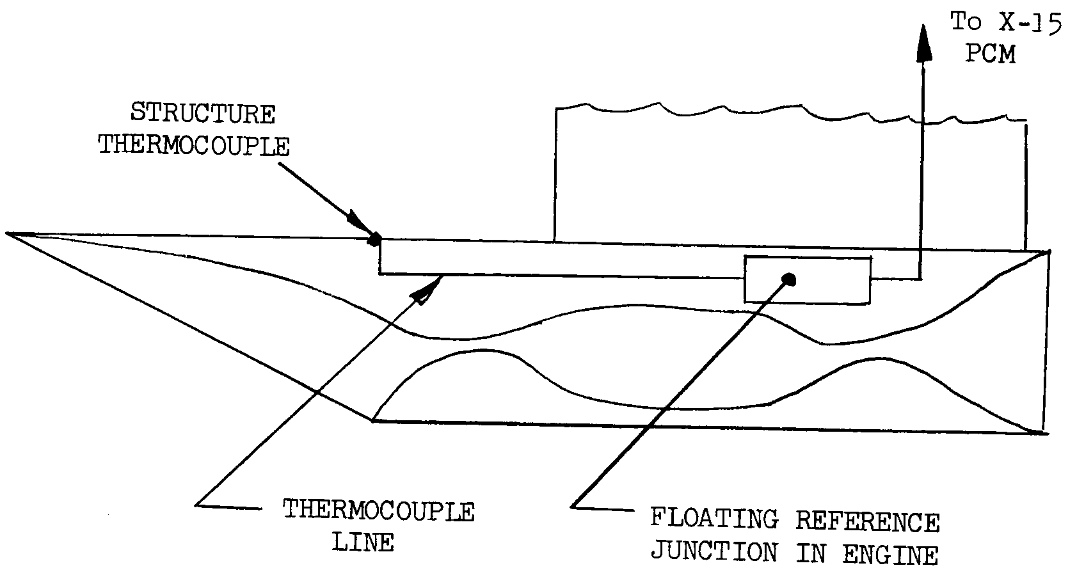
a. Premium wire can be specified with an accuracy as low as 3/8% of reading. This is approximately 3°R at the low end of the temperature requirement.

b. Spurious voltage checks to evaluate inhomogeneity and spurious voltage due to insulation is specified as ±100 μV (±5°R).

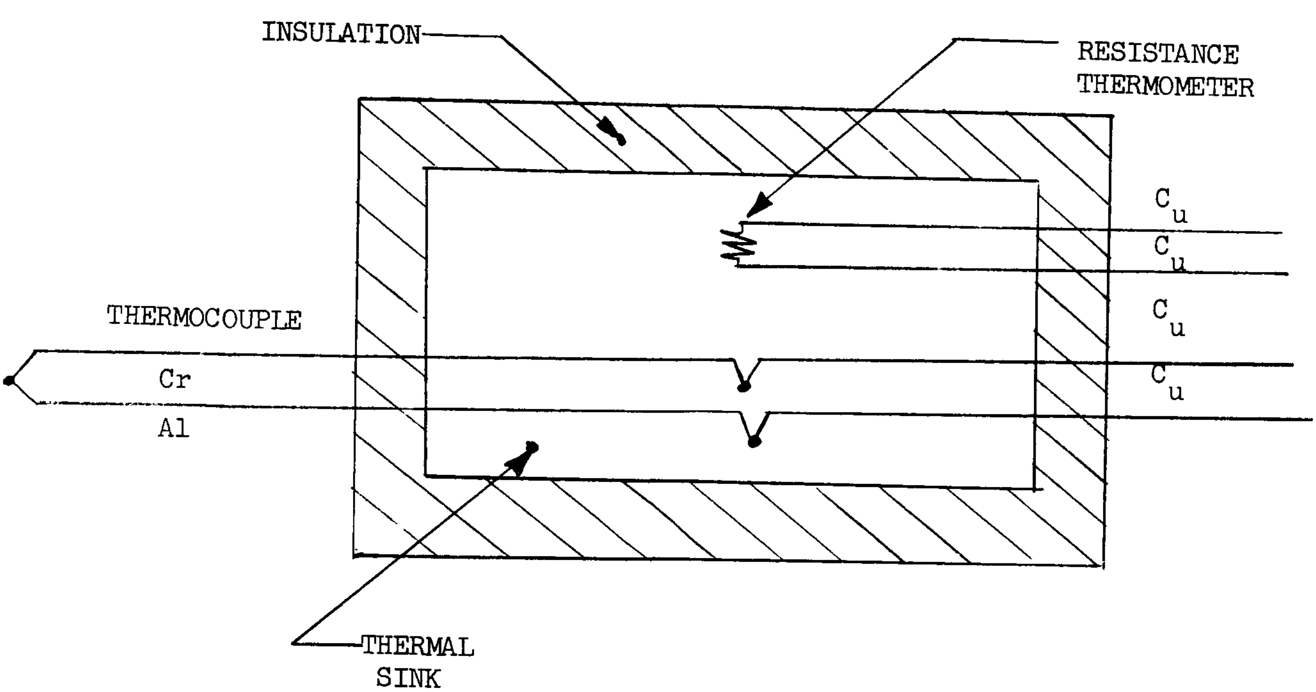
c. Splices made with different lots of wire can result in errors as great as ±2°R.

d. Reference junction temperature uncertainty should be limited to less than 1°R.

e. Current drawing signal conditioners such as resistance dividers should be avoided. Thermocouple lead wire resistance changes during test are not easily identified.



a) RAMJET INSTALLATION



b) FLOATING REFERENCE JUNCTION SCHEMATIC

THERMOCOUPLE SYSTEM

FIGURE 35

3.3.1.2 Strain Measurements

3.3.1.2.1 Requirements

Measurements of the mechanical performance of the ramjet structures will be important to the engine designer in view of the criteria to provide for light weight design. In addition to an analysis of thermal gradients and thermal stresses, it will be necessary to identify surface strains resulting from steady loads, (aerodynamic drag and aircraft maneuvers) and vibratory loads resulting from mechanical resonance and excitation by engine instabilities.

3.3.1.2.2. Sensor Selection

Wire resistance strain gages provide the only practical method for measuring strains in flight. In a recent article by G. R. Higson, (ref. 64) an excellent review of the current state of the art in strain gages is presented. A complete summary of available gage materials and cements as well as their mechanical properties can be found in ref. 64,65, 66, and 67.

Although the field of strain measurements has required an exhaustive development of techniques and materials , only a few are available for ramjet testing in view of sensor criteria:

a. Gage will be exposed to a wide range of temperature (-40°F to 1200°F)
b. Sensor circuitry must be simple in order to minimize weight of associated hardware.
c. Sensors must be reliable even after long periods of inactivity.
d. Gage installation must be adaptable to light weight structures.

For these reasons, it is recommended that uncompensated gages of Karma (74% Ni, 20% cr, 3% Fe, and 3% Cu) in conjunction with flame spray insulation (section 3.3.1.1.4) should be selected. It will be necessary to provide for separate measurements of steady state and vibratory strain primarily because of the requirement for different signal conditioning and recording. Practical steady state measurements are limited to 650°F because of gage wire stability and vibratory to 1500°F, because of leakage to ground through the gage insulation.

3.3.1.3 Vibration Measurements

3.3.1.3.1. Requirements

Three axis measurement

a. Range:	0-200 G	between 200-2500 cps
b. Measuring range:	0-50 G	between 200-2500 cps
c. Accuracy:	±2.5 G and ±25 cps.	

3.3.1.3.2 Transducer Selection

A review of accelerometers was conducted to determine the specific state-of-the-art component suitable for the ramjet program. The frequency as well as the temperature requirements indicate the measurement can be best achieved with piezoelectric accelerometers. Reluctance and unbonded strain gage units were reviewed. Their frequency response and temperature range were not acceptable for this application.

Piezoelectric accelerometers are divided into classes, depending on the voltage generating element. The generating elements looked at were quartz and piezoelectric ceramics. A comparison of the two types is given in the following table.

Characteristics	Quartz	Piezoelectric Ceramics
Temperature Range	-320 to + 750	-450 to + 750
Stability:		
below 500°F	Superior	Good
500-750°F	Severe problems	Superior
Gain Sensitivity	2.5 pico coulombs/g	4 pico coulombs/g
Thermal Drift	.01% per°F	.015% per °F
System Noise Sensitivity	Good	Best

It is evident for this application that the piezoelectric ceramics are more desirable since the temperature span is wider and the sensitivity is higher. An error analysis can be derived from the following major factors:

			Type of Error
Calibration error -200 to 2500 cps		±2.5%	Random
Temperature error - 750°F			
with data reduction correction		±3.0%	Random
without temperature correction		±8.0%	Systematic
Amplifier error - linearity			
to 2500 cps (located in X-15 inst. bay)		±2.5%	Frequency sensitive
Error-cable capacitance change (1% per 1500 pf)		±1.0%	Random
Recording errors (FM system) (Including playback)	estim.	±3.0-±5%	Random

3.3.1.3.2 Transducer Selection - cont'd

A method of obtaining the required accuracy would be to monitor the temperature of the accelerometer and correct for sensitivity change during data processing. This is a feasible method which generates data assurance and entails only a moderate programming cost. It is estimated that the method would provide approximately ±5% data (±2.5G) whereas without the temperature correction an acceleration uncertainty of about 11% can be expected with good calibration practice.

In considering the temperature correction routine, an evaluation should be made of just what acceleration data means to the ramjet designer. Knowing the vibration at one point, just how well can it be extrapolated in the particular structure devised? This is beyond the scope of this study. A major use of the measurement will be to provide safety limits for flight test as established during the ramjet design and ground test programs. Accordingly, the accelerometers should be fixed in their locations during the ramjet design phase. The transducers should be positioned on stiff main structural members near the throat of the engine as recommended by the design and test experience. The temperature requirements of a suitable transducer is -450 to +750°F. The ramjet environment requirements can be met with this unit by utilizing a standard insulating pad. This pad is required for signal conditioning to insulate the transducer from ground. It may be necessary to replace these pads, and possibly the accelerometer, after flight; consequently, the accelerometers should be accessible and temperature monitored.

3.3.1.3.3 Amplifiers

As an electric source, a piezoelectric transducer may be considered to be a very small capacitor which is a coulomb generator. To signal condition this device, special matching electronics are needed such as:

a. High input impedance voltage amplifier.
b. Charge sensing amplifier.

For the application on the ramjet with the requirements for an extended cable, the charge sensing amplifier in the X-15 is the most suitable since system sensitivity is not affected by the cable length as it is with a voltage amplifier. Calibration assurance is more satisfactory. The key advantages to a good charge amplifier are:

a. The low frequency response of a charge amplifier is not a function of input time constant. This means that calculations involving transducer capacity, cable length, and amplifier input are not needed. The amplifier only is involved in frequency response.
b. Charge amplifiers do not require the high input impedance of voltage amplifiers.
c. The sensitivity of the system is not affected to a major degree by cable lengths.
d. Laboratory calibration is suitable without appreciable correction.
e. The transducer thermal sensitivity is much less than in a voltage measuring system.
f. Signal to noise is more favorable in a charge system with a long cable.

3.3.1.3.4 System Weight

The estimated weight chargeable to the ramjet package consists of insulating pads, transducers, cabling, and special plugs. It can be estimated as:

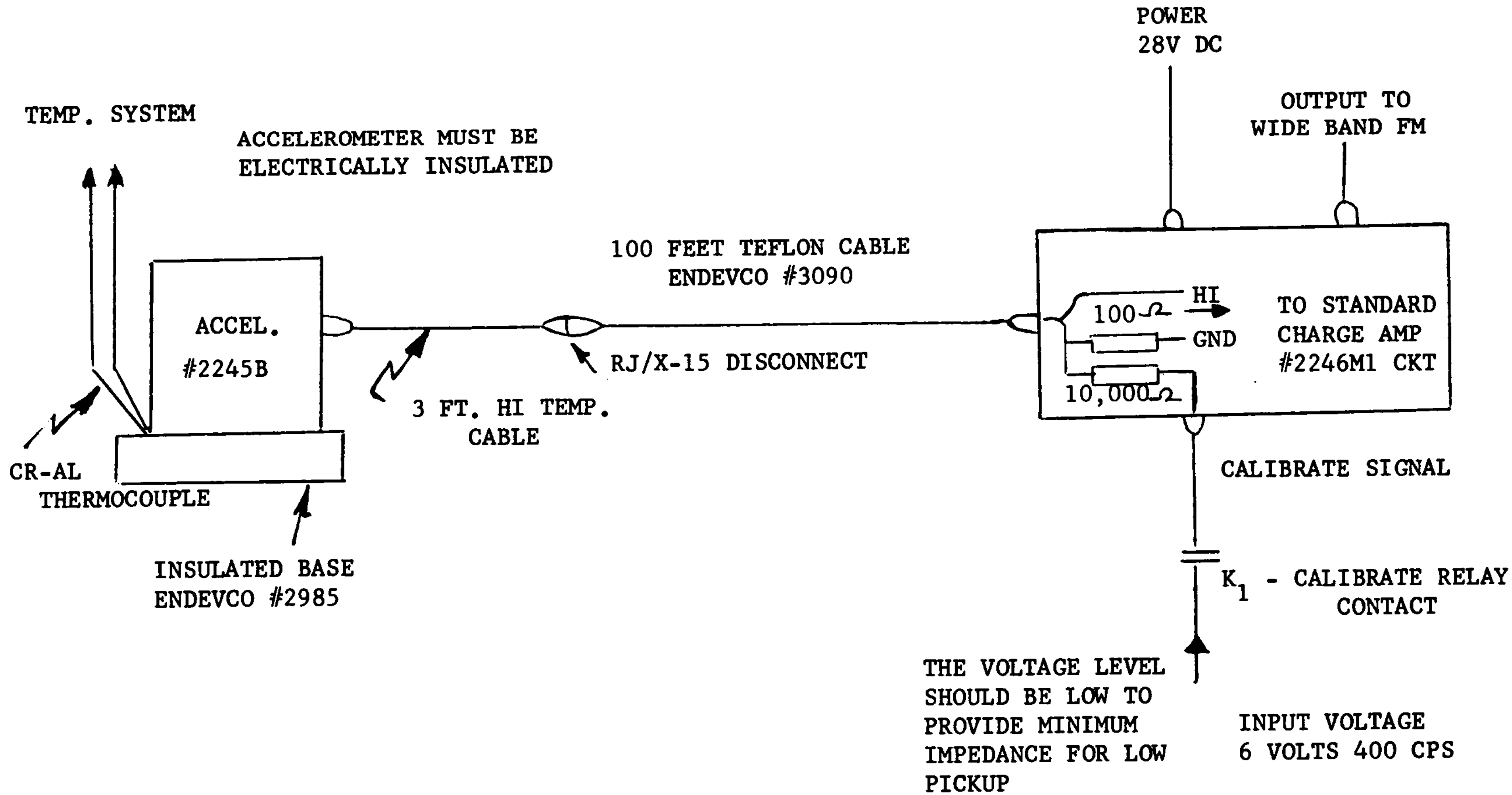
a.	Three transducers and pads	0.25#
b.	Shielded cabling	0.20#
c.	Plugs	0.80#
	Total Weight	1.25#

3.3.1.3.5 Data Assurance

It is recommended to modify the charge amplifier to include a 100 ohm resistor in the ground leg and a voltage divider to provide for preflight and postflight assurance of the accelerometer system. This will permit checkout of all the electrical harness and the gain of the charge amplifier. A recommended schematic is given in figure 36.

3.3.1.3.6 Calibration

Accelerometer, charge amplifier and appropriate length of cable should be calibrated together for best results. A frequency response curve should be run on the system from 60 to 2500 cps using a laboratory shake table. Such a suitable table is available at the NASA Edwards Facility. During the laboratory testing, a standard 400 cps voltage should be supplied to determine the "G" sensitivity of the calibrate terminal on the amplifier in terms of "G" per volt. This will permit future adjustment of the charge amplifier on the aircraft to a different range setting at a later date if it is required.



RECOMMENDED ACCELEROMETER SYSTEM

FIGURE 36

3.3.2 Ablation Surfaces

Ablative materials may be required in the design of the ramjet engine in order to provide for thermal protection of engine structures

Considerable experience in the use of ablatives has resulted from their application as nose cone and high temperature rocket nozzle protection. In these applications the principal measurements have been surface pressure, surface temperature and regression rate. These measurements will also be necessary for ramjet evaluation, however, it is expected that the accuracy requirements will be more stringent since ablation will affect engine performance through dimensional changes of wall surfaces and addition of constituents to gas stream.

Most successful technique for performing wall pressure measurement has been to simply drill pressure taps in ablative material and provide pressure tubing at base. (figure 37A) Surface erosion around the tap constitutes a major problem as pointed out in earlier discussions. Attempts have been made to provide for a continuous smooth surface around the pressure tap through the use of thin discs of various materials stacked in the ablation surface (figure 37A) with the intention that the discs would erode in one piece during the regression of the ablation material. This technique has been unreliable because of a resulting mismatch in thermal conductivities.

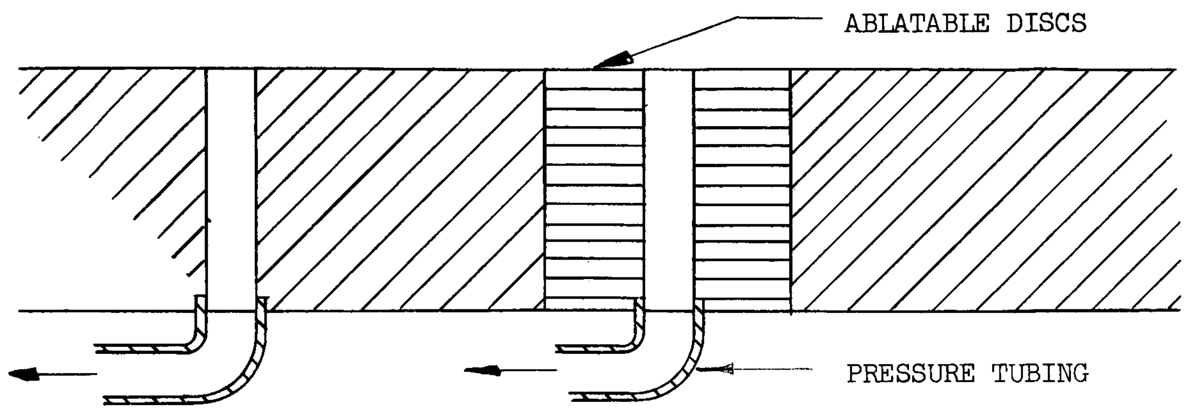
Surface temperatures are measured either directly through the use of imbedded thermocouples (figure 37B) or indirectly through optical measurement of the surface infra-red emission (figure 37B). Optical techniques for temperature measurements tend to be complex with considerable inaccuracy due to the uncertainty of the surface emissivity. Imbedded thermocouples have performed satisfactorily when small wires (.001 - .003) are used and properly oriented to insure clean burn out. (Reference 68) Plugs of ablation material containing thermocouples can be made and inserted into ablation surface. Plugs must be of the same material.

Since ablation regression is a direct indication of its effectiveness, considerably more effort has been directed toward this measurement. Methods fall into three classes:

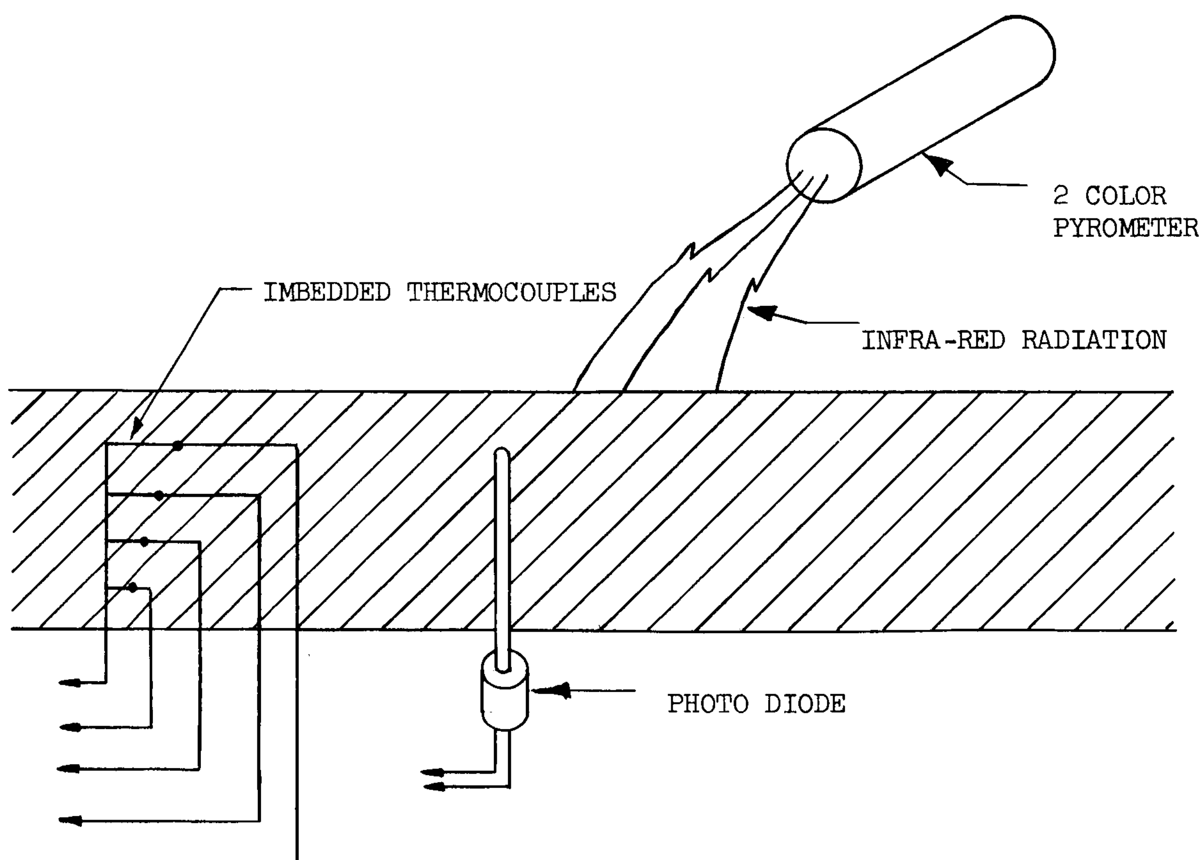
a. radio isotope
b. electrical
c. surface erosion.

Figure 38 schematically depicts several methods in each classification which have been applied. The electrical methods are not recommended for charring or conductive materials such as phenolic base plastics and pyrolytic graphite. Methods which rely on a discontinuity in the surface for indication such as pushrod, pressure tube burnout and photoelectric detection are not adaptable for easy replacement which will be a requirement of ramjet instrumentation.

MEASUREMENTS ON ABLATING SURFACES

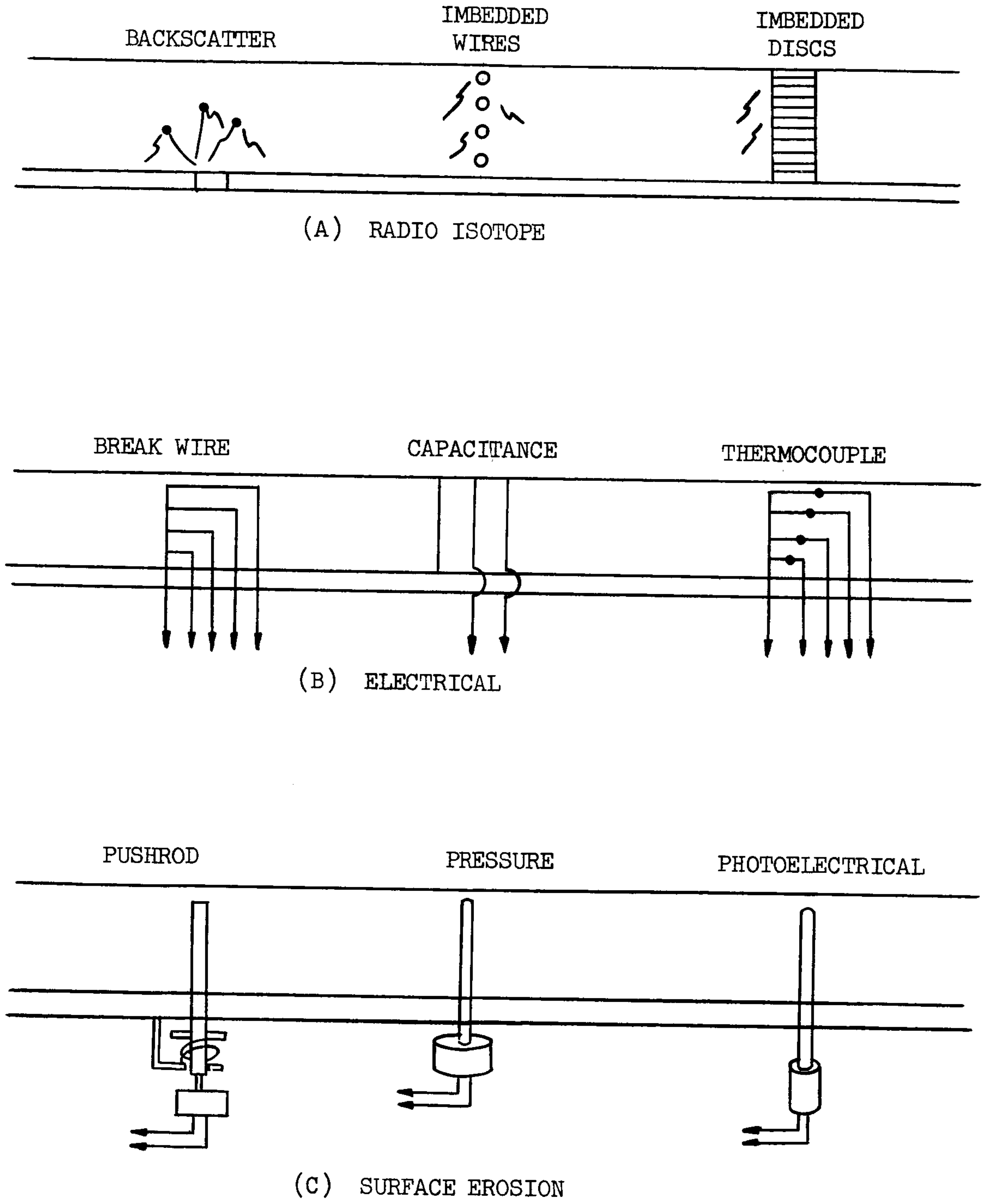


(A) SURFACE PRESSURE



(B) SURFACE TEMPERATURE

FIGURE 37



REGRESSION RATE SENSORS FOR ABLATION SURFACES

FIGURE 38

3.3.2 Ablation Surfaces - cont'd

Considerable effort is currently being directed toward the application of radio isotope techniques. Systems using imbedded radioactive wires and discs have been flight tested. Backscattering which should provide continuous measurement of regression is under development. The nature of radio isotope techniques for measurement require counting procedures which seriously limit its application on transient and short duration tests.

Although the investigation of ablation measurements during this study was cursory, and conducted primarily through discussions of measurements with nose cone specialists, it is apparent that current techniques are not adequate to provide critical ramjet data relative to regression rates of ablation materials or surface pressures and temperatures.

3.4 Exhaust Gas Measurements

3.4.1 Mid Stream Probing

3.4.1.1 Probe Interference

Probe interference effects will limit the use of probes to locations aft of the exit nozzle under engine operating conditions. The shock wave generated by any probe inserted in the stream will be severe enough to very seriously disturb the engine operation. At any point where unreacted fuel and air are present, the probes will almost certainly act as flame holders. The extra high local heat release due to flame holding action will require extra heat protection on all local surfaces. Even without flame holding action the local interaction heating due to shock wave impingement as discussed in Appendix I may require special thermal protection. The effects of local interaction heating are shown quite clearly in figure 12.

3.4.1.2 Probe Support

Probes will be required for measuring stream temperature and pressure, for taking stream gas samples and may be required to support optical heads in the stream. Structurally the probes for each of these functions will be the same. The only difference will be in the applied sensor and in its mounting. For each engine location or each engine design the actual probe design will differ as the stream conditions differ. During this study one sample probe design was completed for one set of aerodynamic conditions and should be a realistic guide as to what can be expected in a final probe design (Appendix I and II).

The heat input to a probe will (in general) be fixed by the required probe geometry to support a sensor in the stream and the gas stream conditions. For a given set of engine conditions, the probe weight will depend directly upon the technique used to remove heat. The probe may be:

a. Made of high temperature materials which will withstand the imposed temperature
b. Protected with an ablative material
c. Cooled with a fluid coolant (water, air LN_2, etc.)
d. Used as or attached to a heat sink.

The probe weight-estimated for 6" probe immersion at nozzle exit, max.Q, 20 second run:

1.	Coated tungsten	.46 lb.
2.	Pyrolytic graphite protected steel (ablative)	.72 lb.
3.	Cu as heat sink	~ 6 lb.
4.	H_2O as heat sink	~5.5 lb. plus pump, lines, and tank weight

3.4.1.2 Probe Support - cont'd

The high temperature material approach will be the lightest weight if a satisfactory material can be found. Various materials such as molybdenum, tantalum, and tungsten variously alloyed and coated have been proposed. At least one manufacturer sells, as a regular catalog item, a coated molybdenum probe rated up to 3200°F in an oxidizing atmosphere. Figure 39 shows the results of a test reported in reference 69 in which the probes were subjected to flame tunnel conditions at 2200°F, which is much lower than the temperatures which will occur in a hypersonic ramjet engine. High temperature materials need to be considered but until more reliable protection methods are developed, they cannot be recommended.

With no heat sink available, ablatively protected probes will be the lightest weight. One probe design for estimated maximum engine conditions was completed as a sample of the procedure which must be followed and to estimate the maximum weight for a probe. Final design of a probe must, of course, be based on actual engine operating parameters and allowable mounting arrangements. The design analysis for an ablative probe was done by the General Electric Missile and Space Vehicle Department at Philadelphia, Pa. Their results are shown as Appendices I and II. They have had extensive experience in design of ablatives for missile nose cones. The analyses presented are preliminary, and are based on estimated engine conditions. It will be absolutely necessary to build and evaluate several probes to determine the actual heat transfer rate, the shock effects and the vibration characteristics before a final probe can be put into an engine. Much of this can and should be done during early ground testing of an engine.

Figures 12A & 12B are typical of the erosion which can be expected on a probe. They are the results of ablation testing for 4 seconds on a phenolic nylon ablation material at high enthalpy levels which are very roughly comparable with those which can be expected in a hypersonic ramjet engine. About 3/4" of the material was removed in the 4 second run. Pyrolytic graphite will not ablate nearly as rapidly as the phenolic ablatives, but the ablation pattern should be similar. Notice the large groove which has ablated at the base of the fin due to interaction heating where the shock wave from the leading edge of the fin impinged on the wall. It will be necessary to provide extra ablative material at the base of the probe as suggested in Appendix I or provide extra cooling capacity at the wall depending on how the engine is designed.

Should any source of coolant such as fuel, spent coolant used at some other point, spent hydraulic fluids, or spent pressurizing gasses become available, the choice between ablative protection and cooling must be reevaluated.

All of the above analysis is based on estimated maximum engine operating conditions. (Mach 8 and 85,000 ft.). At lower speeds, it will be possible to use conventional stainless steel and similar materials. For any engine operating conditions for which the probe temperature will not exceed approximately 1800°F conventional materials should be suitable.

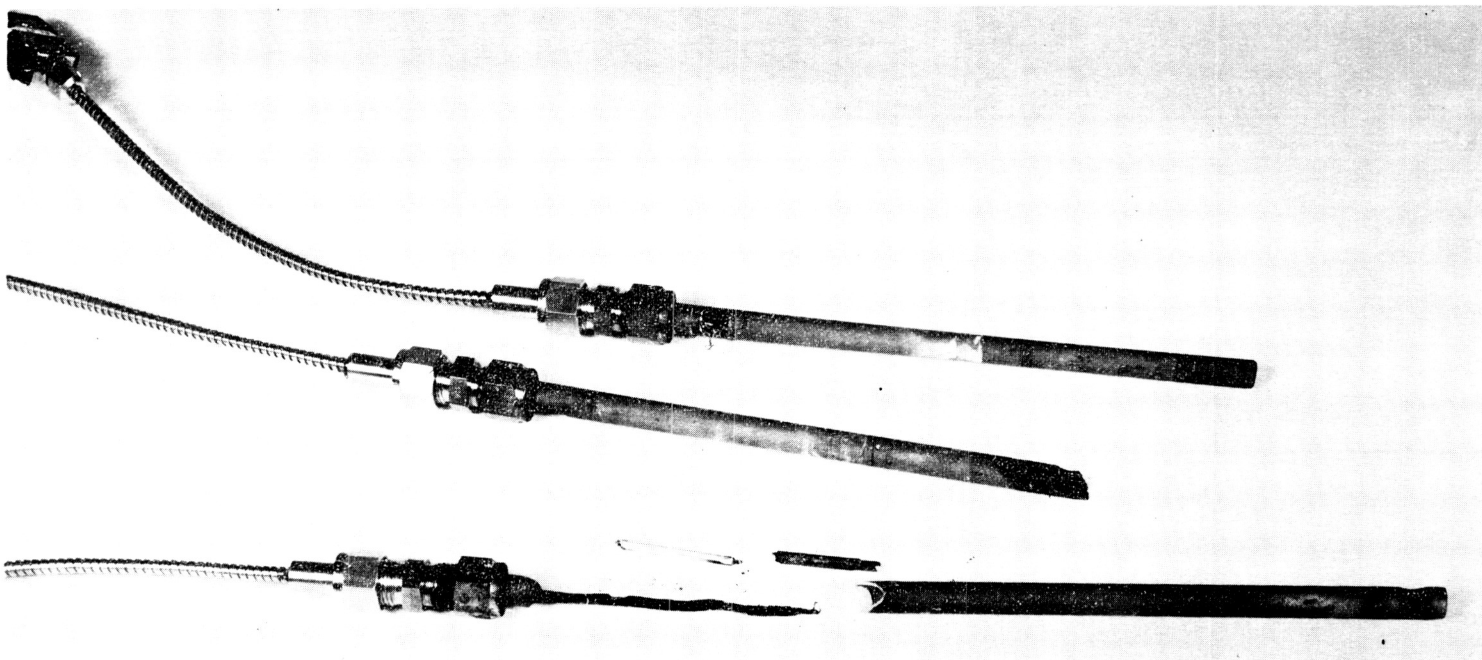


Figure 39   Commercial Coated Molybdenum Probes After 2200°F Test

3.4.1.2 Probe support - cont'd

If the final engine design has struts across the flow path, it may be quite easy to measure the pressure on the leading and trailing edges of the struts and use these pressures to calculate engine flow conditions.

3.4.1.3 Probe Functions

3.4.1.3.1 Total Temperature

Thermocouples are the most common way of measuring the gas temperature of jet engines. It is a logical suggestion that thermocouples be investigated to measure ram jet gas temperatures. General thermocouple design criteria is to design the probes so that it operates as close to gas temperature as possible. This is done by maximizing the heat input and minimizing the heat loss. The running factor, which must be determined for each probe configuration establishes the difference between probe indicated temperature and actual gas temperature.

In considering the requirements of 6500°R, it is questionable whether a thermocouple can withstand this temperature. The thermocouple that has shown a lot of promise in the high temperature range is Tungsten Rhenium-Tungsten. Tungsten has a melting point of approximately 6600°R, and Tantalum of 6200°R, alloys of tungsten and rhenium - 5800°R. Tungsten Rhenium-Tungsten have been calibrated up to 5500°R (reference 70). Reasonable values for the effects of radiation and recovery would make the operating temperature of the probe low enough to use tungsten rhenium, However, tungsten and rhenium must be protected in an oxidizing atmosphere.

As the result of a survey of individuals actively working on the problem of tungsten rhenium-tungsten protection from oxidation was that presently there is no satisfactory coating for protecting tungsten and tungsten rhenium alloys against oxidation at high temperatures. However, several of the individuals expressed optimism of soon having such a coating.

Assuming that a thermocouple capable of withstanding a 6500°R total temperature stream will be developed, other practical problems exist for this application. A quick review of the factors that determine the indicated temperature of a thermocouple immersed in a gas stream should be helpful. (Reference 71).

a. Heat transfer from the boundary layer to the probe sensor by convection, $q = hA(T_g - Ti)$
b. Heat transfer to or from the probe by radiation
$$q = \sigma fe\, A(T_j^4 - T_w^4)$$
c. Heat transfer by conduction
$$E_c = \frac{T_i - T_b}{\cosh mL} \qquad \text{where } m = \sqrt{\frac{hc}{R_p}\ \frac{P}{a}}$$
d. Conversion of kinetic energy to thermal energy in the boundary layer aournd the thermocouple.
$$\text{Recovery factor} = \frac{T_T - T_i}{T_T - T_E}$$

PROBE TIPS

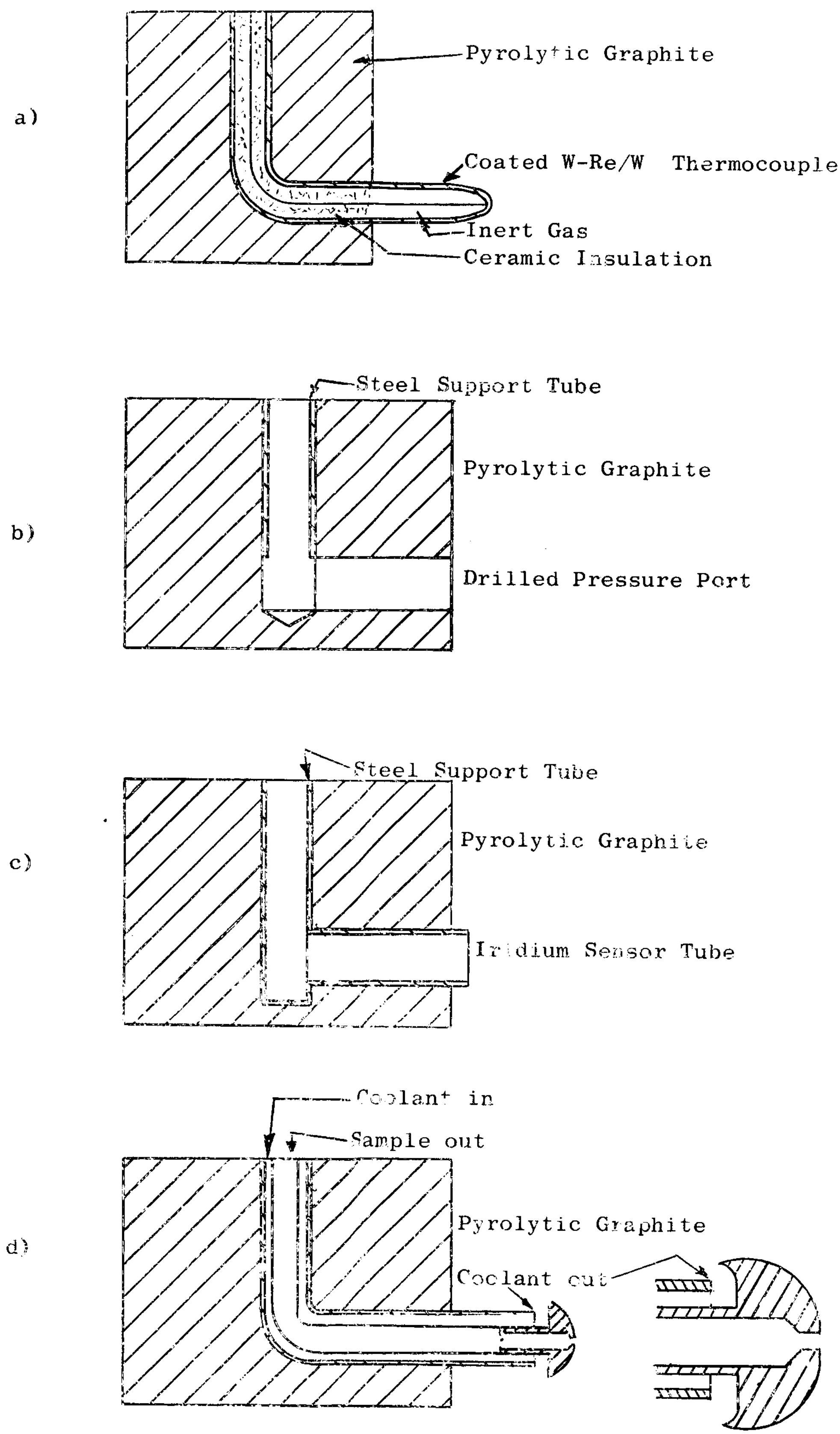


Figure 40

3.4.1.3.1 Total Temperature - cont'd

e. The inability of the probe sensor to follow gas stream conditions due to response time.
f. Chemical energy that is converted to heat on the surface of the probe sensor.

The heat transfer coefficient is difficult to obtain in subsonic streams and is more difficult to determine in supersonic streams. However, determinations are made by heat transfer people for structure and probe support designs.

h_c = heat transfer coefficient should be available. Number will probably be subject to much uncertainty.
A = area of probe.
T_i = indicated temperature of probe.
will be measurable quantities.

The factors that are needed to determine the heat loss by radiation should be determinable.

σ = Boltzman Constant
f = Angle factor
A = Area of probe.
are all measurable quantities or known constants.

e = Emissivity of the coatings at elevated temperatures will be available when the coating is developed.
T_i = The indicated temperature of the junction will be recorded.
T_w = The temperature of the wall can be estimated with some degree certainty.

It should be possible to evaluate the conduction error by evaluating the following factors:

P = Perimeter of probe.
a = Cross sectional area of probe
Rp = Thermal conductivity of probe
L = Length of immersion of the probe.

These factors should be supplied by the probe manufacturer.

T_b = Temperature of the base should be obtained from the probe support.
h_c = The heat transfer coefficient.

Since the proposed probe support is non cooled $T_i - T_b$ should be a small number and the conduction error should be small.

The recovery factor of thermocouple probes can be determined with good certainty at subsonic velocities and work has been done at supersonic velocities. (reference 72) The difference between T_T, the total temperature and T_S, the static temperature is large at supersonic velocities. Therefore, a small error in the determination of the recovery factor is a large error in the measurement of total temperature.

3.4.1.3.1. Total Temperature - cont'd

A thermocouple with a slow time response will only read an average temperature and it is not able to accurately measure the temperature of a gas stream that exhibits rapid temperature and pressure fluctuations.

The burning of combustibles on the surface of a probe results in a higher indicated temperature than the true gas temperature and is referred to as surface reaction. Dissociated combustibles at high temperatures are in equilibrium with products of combustion in an efficient combustion process. The effects of surface reaction on the probe in streams that contain disassociated combustibles that are in equilibrium to high temperature and pressure can be calculated. However, the effect of surface reaction in inefficient streams is unpredictable and it can be a large source of error.

Discussion

General thermocouple design attempts to maximize the heat into the probe by increasing the heat transfer coefficient, decrease the radiation loss by use of hot shields, minimize the conduction error by making the stems long and the base hot, and to minimize the recovery error by slowing the gas down to a low velocity so the difference between total and indicated temperature is small. By using the probes on steady state, non fluctuating gas stream with high combustion efficiency, the response time and surface reaction problem can be ignored. It is expected that in the case of ramjet testing, these conditions are not present and consequently response time and surface reaction are expected to be serious problems.

Probe types other than thermocouples have been used to measure gas temperatures such as pneumatic probes, calorimeter probes, and stagnation point probes. (reference 73) Many of these probes allow the actual sensor to operate at a lower temperature than gas temperature and provides a method for calculating the difference.

Unfortunately all of the designs studied suffer from the fault that the probe would interfere with the gas stream and could very well make combustion take place in a stream with very low combustion efficiency.

3.4.1.3.1 Total Temperature - cont'd

Recommendation:

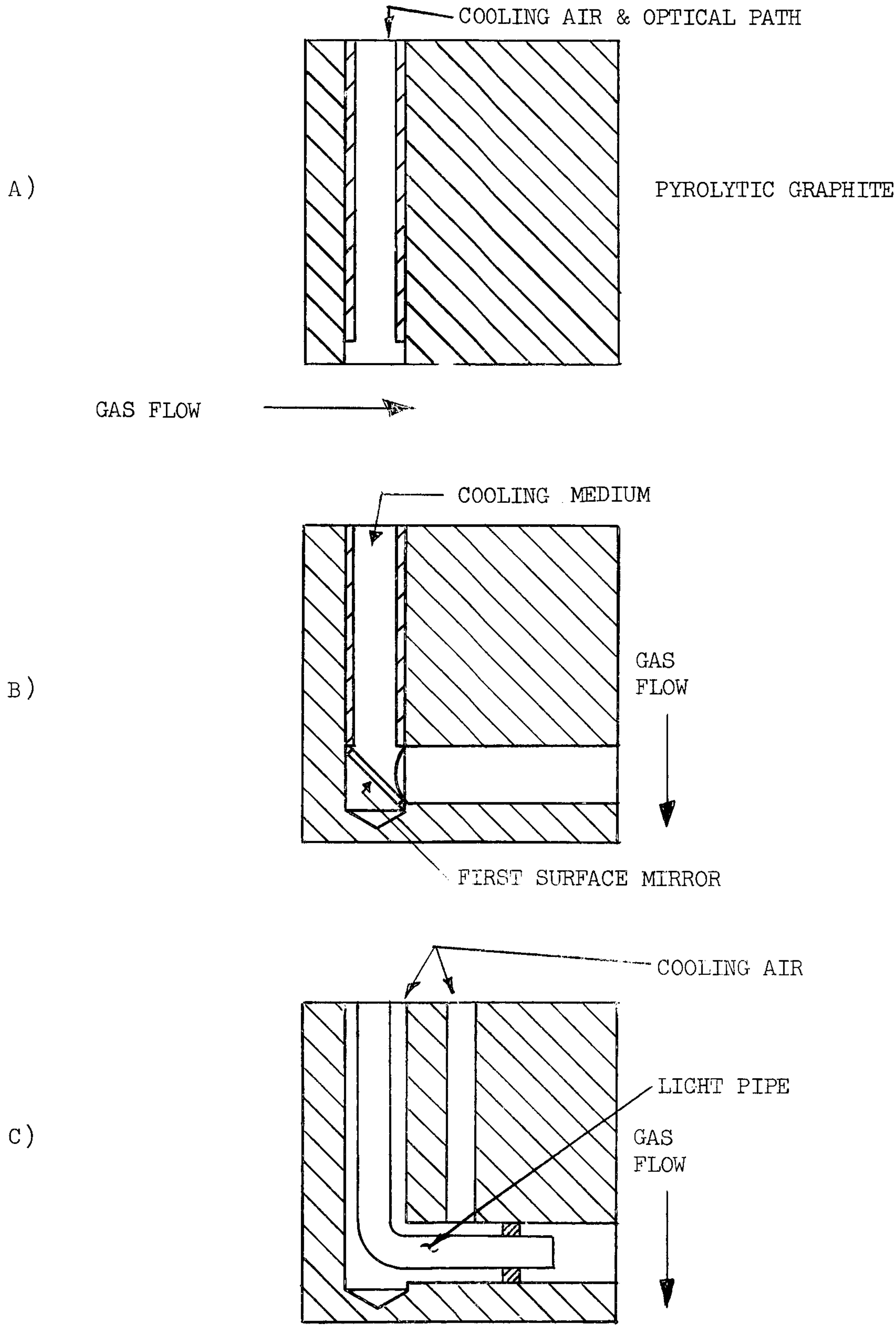
The development of high temperature coatings for Tungsten Rhenium-Tungsten thermocouples should be encouraged. High temperature thermocouples will serve a useful purpose for some ground testing. Additional work must be performed on the effects that a probe has on a supersonic gas stream containing unreacted combustibles before a high temperature probe can be used to measure temperature accurately for this application.

3.4.1.3.2 Impact Pressure

The impact pressure sensor will be the simplest of the sensors to build for probe mountings. Under some conditions it may be possible to simply drill a hole through the front of the graphite protection as shown in Figure 40b. It will be necessary to test this kind of probe under ablating conditions to determine ablation rate and particularly the effect of ablation on impact pressure error. See Figure 12, which shows the local ablation which will occur at holes in an ablative material. A more desirable probe would have an Iridium tube fitted into the front, as in figure 40c. Iridium with its high melting point could be expected to ablate more slowly than the graphite and would thus maintain a small protruding tube in front of the probe body. This will tend to decrease impact pressure error both by protruding and by being more shape stable during ablation than an ablating hole. It will have the undesirable effect of producing a small local shock with interference heating effects which will tend to cut into the probe body. This configuration will also have to be tested under ablating conditions to determine an acceptable design and to determine the errors. The material is quite difficult to work. The choice between the two methods will depend on the results of tests which can be run during early ground testing of the engine.

3.4.1.3.3. Optical

Optical instrumentation that may be used which will require probes in the stream is distinctly developmental and it can vary quite widely in its requirements for probes. A pyrolytic graphite protection sheath will lend itself quite readily to many forms of optical probes. Figure 41 shows simple suggested forms. If an optical path across the stream is needed, a simple steel tube with graphite protection as at Figure 41 (a) will suffice. Cooling (and purge) air may be blown down the tube to keep local heating and ablation of the end of the probe down. If a folded light path is required either looking upstream, downstream, or to either side of the probe a first surface mirror can be mounted inside the probe at figure 41 (b). In this case clean purge gas will certainly be required to keep the mirror clean. Should a light pipe be required, it can be mounted with cooling as at Figure 41 (c). Here cooling and purge both will be required.



OPTICAL PROBE TIPS

FIGURE 41

3.4.1.3.4 Gas Sampling

3.4.1.3.4.1 Sample Extraction

Gas Sampling (Ideal Probe)

An ideal gas sampling probe would take a sample from the stream to the analyzer without any reactions occuring. If the gas is disassociated, as it will be at high temperatures, the disassociated portion will, of course recombine if the gas is cooled. If the gas is not cooled, but is contained at normal densities, it will rapidly react to equilibrium composition for the particular temperature and pressure.

The allowable holding time (the minimum period of gas stagnation before gas reaction and recombination is initiated) depends on pressure and temperature, but is a very small fraction of a second. Ionized gases at very high temperatures have been sampled and analyzed within this time by a quite elaborate probe built directly on a special mass spectrometer (ref. 74) which is far too complex, fragile, and heavy to use in flight. There is a possibility that such a system could be used in early ground testing.

Gas Sampling (Shock Swallowing)

Figure 42 represents the situation for sampling probes with cooling of the sample. The ideal probe would take a sample from the stream as at fig.42a and instantly cool it to a temperature at which no reactions occur except radical recombinations. The nearest practical approach to this for a supersonic gas stream is shown at fig. 42b, in whieh the gas enters the front of the probe supersonically and is cooled to a temperature low enough to freeze the composition before it is decelerated appreciably. The gas temperature inside the probe should never exceed the free stream static temperature. There will, of course, be an external shock attached to the lip of the probe which will disturb the stream externally, but there should be none inside the inlet of the probe. The problem of designing such a probe is more difficult than designing the inlet of the engine it is to be used in. At the point where gas analysis is required there will have been at least some heat addition to the gas flowing through the engine. The probe must of necessity be quite small which makes aerodynamic design nearly impossible. Surface irregularities which can be ignored in the engine almost completely may be as large as the flow path in the probe. There are certain guide lines which can be stated for such a probe and are illustrated in figures 43 and 44.

a. The inner area of the probe must expand to accomodate supersonic flow with boundary layer buildup until the gas is cooled to a point where shocking down will not exceed reaction temperatures for the gas composition present.

GAS TEMPERATURES OF GAS SAMPLE PROBES

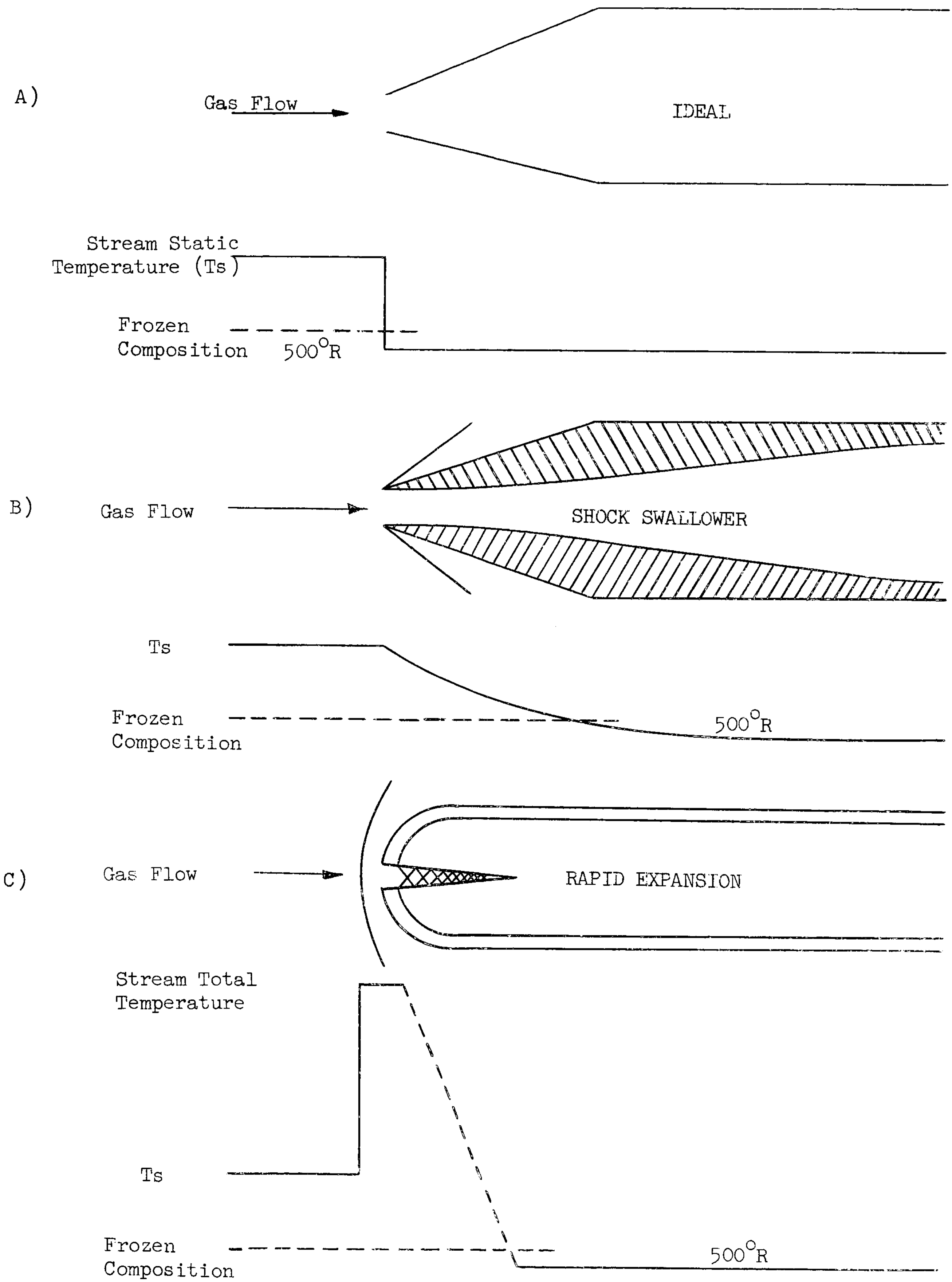
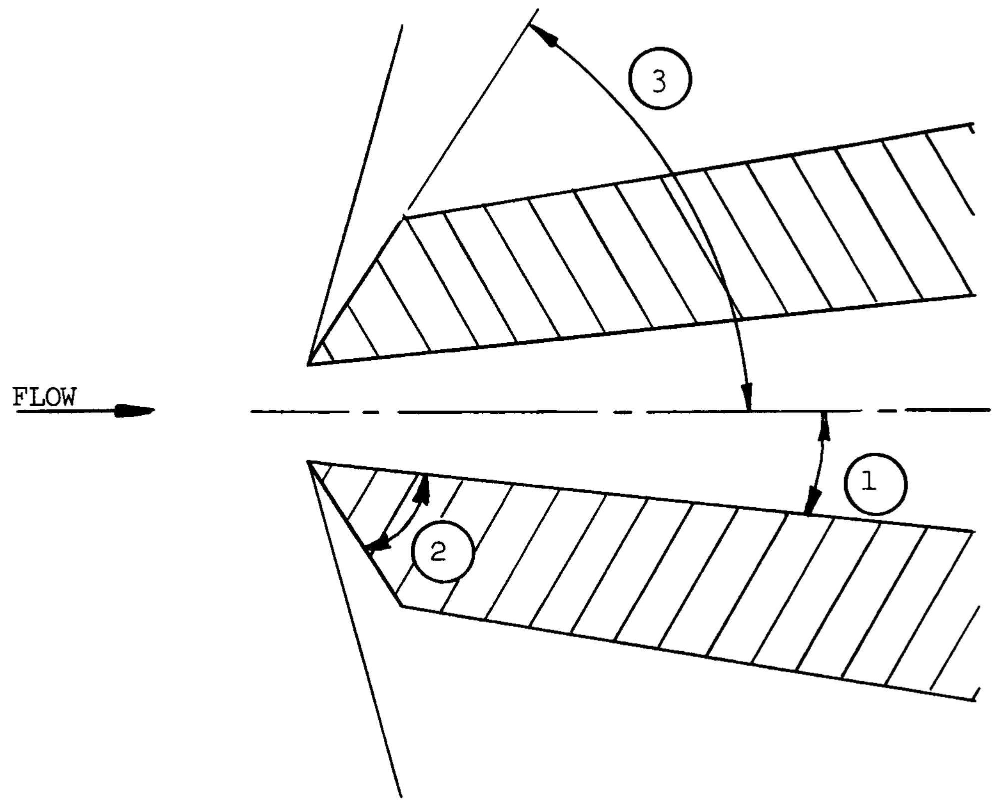


FIGURE 42

ANGLE LIMITS ON SHOCK SWALLOWING PROBE

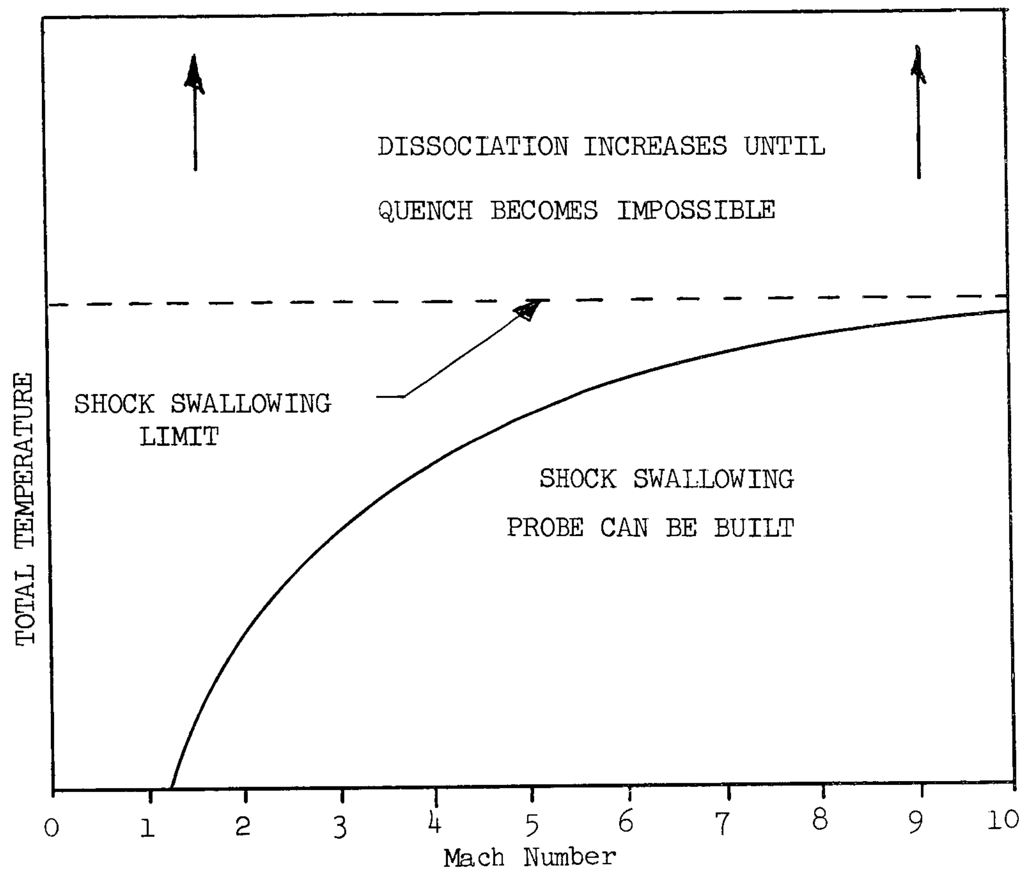


1. INNER CONTOUR ANGLE MUST EXPAND TO MAINTAIN SUPERSONIC FLOW

2. ANGLE MUST BE LARGE ENOUGH TO CONDUCT HEAT FROM SHARP EDGE

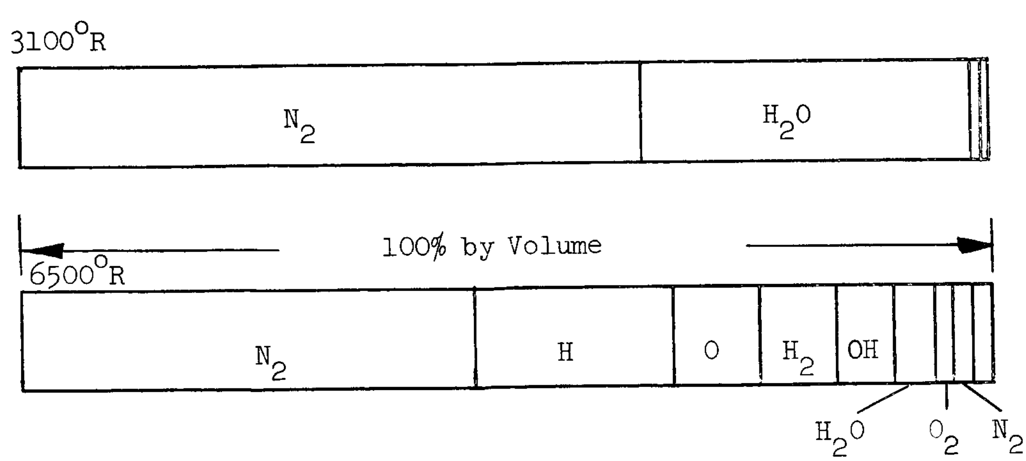
3. MUST NOT EXCEED ANGLE FOR ATTACHED SHOCK

FIGURE 43



GAS SAMPLING PROBE LIMITATIONS

Figure 44



EQUILIBRIUM PRODUCTS OF COMBUSTION (H_2 and Air)

Figure 45

Gas Sampling (Shock Swallowing) - cont'd

b. The lip edge must be sharp to permit an attached shock on the outside of the probe without an internal shock. The angle formed at the leading edge must be sufficiently large to conduct the heat away without reaching a temperature high enough to cause damage.

c. The cone angle at the tip of the probe must be smaller than the critical angle for an attached shock at the local stream Mach number.

Under certain conditions these requirements become mutually exclusive, and there is no possibility of building a shock swallowing probe. This occurs when the stream conditions are such that the total required angle 1 plus 2 is greater than the allowable angle 3. Accurate calculation of these angles is an extremely involved heat transfer and aerodynamics problem. The general shape of the area which can be swallowed is shown in Figure 44, assuming that the probe tip reaches the stream total temperature. As the stream Mach number decreases the allowable stream total temperature decreases to a limit slightly above Mach 1. There is no possibility of attaching a shock wave to the leading edge of a finite thickness probe at or slightly above Mach 1. As the stream Mach number increases the allowable total temperature approaches a limiting temperature asympototically. The limiting temperature will be that temperature for which sufficient cooling can be maintained at the leading edge of the probe at an infinite Mach number to maintain a sharp edge.

As has been stated above, the actual design and development of a shock swallowing probe is a very difficult aerodynamic and heat transfer problem. By using iridium for the sharp leading edge (melting point 4204°F) the limiting stream temperature should be in the region of 4000°F to 5000°F depending upon how much cooling can be supplied to the probe tip. Development of such a probe and identification of the gas stream conditions under which it can be used is recommended.

Gas Sampling (Rapid Expansion)

A rapid expansion probe, figure 42 (c), can be designed for any Mach number or total temperature up to the limit of ability to keep a probe structurally cool enough to not seriously ablate in the region near the sensing port. (See references 75 and 76 for discussion of the design). In a rapid expansion design, a rather blunt (probably spherical) ended probe is placed in the stream which samples a small portion of the gas behind a normal shock.An orifice much smaller than the I.D. of the probe is placed at the inlet. The pressure inside the probe is maintained far below the pressure at the inlet.

3.4.1.3.4.1 Sample Extraction - cont'd

Gas Sampling - (Rapid Expansion) - cont'd

As the gas passes through the shock, its temperature is raised to that which exists behind a normal shock for the local stream Mach number. As it passes on into the probe, it is rapidly cooled by a combination of rapid expansion and mixing with the cooler gas inside the probe. The residence time between the shock and the cooling inside the probe must be kept very short compared to reaction times of all reactions which can occur in the gas. As an example, the equilibrium composition for H_2-air products of combustion are shown in Figure 45.

In Reference 76, Appendix B, "Analysis of Chemical Reaction Quench Rates in the Gas Sampling Probe", the conclusion is drawn that with their rapid expansion probe under the conditions tested, the quench rate was faster than the reaction rate. In a straight tube gas sample quenching did not occur and the reaction went to completion. In their rapid expansion probe the reaction did not go to completion. It was concluded that the rapid expansion probe is better than a plain straight tube for sampling non-equilibrium gas streams. There is apparently no evidence to show what reaction occur in the region between the shock wave and the probe interior for non-equilibrium stream conditions as pointed out in Reference 76, "The Changes in Static Temperature when Passing the Quenched Gas Through the Shocks (inside the probe) are not Clear". Apparently there is little possibility of realistically predicting what happens aerodynamically inside a probe of such small physical size. Since the quench is not instantaneous and particularly since the gas temperature is raised above the free stream, static temperature by the shocks some partial reactions not detected in Reference 76 should be expected.

Referring back to Figure 44, for a rapid expansion probe no limits can be drawn for the area in which it can operate. There will be no Mach number limit since a shock in front of the probe is assumed in the operation and the absence of the shock at subsonic velocities would simplify the analysis. As the static temperature is increased, the equilibrium disassociation increases and the recombination reactions (which cannot be quenched) will limit accuracy.

3.4.1.3.4.2. <u>On Line Gas Analysis</u>

On line gas analysis can be desirable for several reasons:

a. Rapid analysis of samples may return data fast enough to allow modification of engine operating parameters during a run.
b. It could represent a continuous record of gas composition even during slow engine transients.
c. If a large number of data points is desired it may be lighter weight than a gas sampling system.
d. For certain single constituents extremely light weight analyzers are available.

3.4.1.3.4.2 On Line Gas Analysis - cont'd

Gas analysis on line could conceivably be done with several different classes of equipment. These are:

a. Mass spectrometer
b. Gas chromatograph
c. I. R. absorption
d. Thermal conductivity
e. Polarographic equipment.

Mass Spectrometer

At least three basically different principles are used in mass spectrometers. These are: 1) path deflection in a magnetic field; 2) time of flight, and 3) nuclear quadripole resonance. All of the instruments are normally too large and heavy for use in flight applications. Some small instruments have been built and flown. (reference 74) Extreme light weight versions of all three could probably be developed. A reasonable target weight would seem to be 10 to 20 lbs. with the magnetic type probably the heaviest. The nuclear quadripole type is quite new, but may well be developed to a point where it is attractive by the time an analyzer is needed. One "time of flight" instrument has an advantage of monitoring several constituents practically simultaneously. (Reference 74)

A mass spectrometer will not provide any particular advantage over other methods of analysis which are lighter and cheaper unless it is used with special direct sample inlet hardware which permits analysis without cooling the gases. This probably is not possible in flight but may be possible in ground testing. The method has been discussed briefly in the section on quick quench gas sampling and is discussed more fully in Reference 74, and will not be repeated here.

Because of cost, weight, and relatively low data payoff, mass spectrometer analysis in flight is not recommended.

Gas Chromatograph

All gas chromatograph systems investigated are far too slow to be of use. The fastest systems could give an analysis on one sample per minute. For the same weight many samples could be taken and analyzed later on the ground.

I. R. Absorption

Of the gases to be expected in the exhaust of a hydrogen air engine only water vapor has an easily useable absorption in the I.R. region. The systems available would be too heavy for flight use but could be developed into lighter versions. I.R. absorption may be useable as a remote measuring system but offers no special advantages over other available methods.

3.4.1.3.4.2 On Line Gas Analysis - cont'd

Thermal Conductivity

Thermal conductivity measurements are uniquely fitted to hydrogen analyses. Hydrogen has a thermal conductivity much higher than any of the other gases present and can easily be identified by its effect on thermal conductivity of the mixture. There are several thermal conductivity measuring cells commercially available which are quite small and could be adapted readily to ground testing. Some rather minor development to reduce weight could make any of them applicable to flight testing.

Whenever continuous recording of percent hydrogen present is required, a thermal conductivity measurement is recommended.

Polarographic Analyzers

Very small polarographic analyzers for measuring oxygen percentage are commercially available. At least one company is also delivering developmental quantities of polarographic hydrogen analyzers (on Contract NAS 8-11510 to Huntsville). Both systems are somewhat slow on response time but can be used and would be quite attractive if the response time is improved. The analyzer head for both systems can be of the order of one ounce.

The polarographic oxygen analyzer is recommended for continuous monitoring of the gas sample oxygen content regardless of what other analysis or sampling system is used.

Improvement of the response time of the hydrogen analyzer will make it more attractive than the thermal conductivity system because of its lighter weight and lower susceptibility to environmental errors from temperature and pressure changes.

3.4.1.3.4.3 On Board Collection

Collecting the gas samples in glass bottles and analyzing the samples later with a chromatograph is a very practical system for ground testing, and it could be applied to flight measurements.

Different sampling systems have been used for ground testing but unless there is a technical breakthrough in the design of non-contaminating light weight vacuum pumps or in techniques for analyzing low pressure gas samples, none of these techniques can be applied directly to flight test.

Discharging the gas from the sampling probes into evacuated sample bottles is not practical for flight test because of the requirement for low downstream pressure within the sampling probe. This results in a low pressure sample that is difficult to get out of the sample bottle and up to atmospheric pressure required for chromatographic analysis. A vacuum pump could be used in the line to maintain low pressure at the probe and give a high pressure sample. A non-contaminating high vacuum pump must be used and such pumps are not adaptable to flight applications.

3.4.1.3.4.3. On Board Collection - cont'd

A system that would be practical for flight application is shown in Fig. 46. This system isolates the gas sample from the evacuating system by the use of mylar bags. Mylar is reported to be strong and impervious to hydrogen diffusion. (Reference 77) The principle of operation is that the bags are collapsed in a vacuum chamber and the pressure difference between the probe and the chamber fills the bag.

The design of the system is based upon a requirement for 12 samples. A practical volume for commercial analytical equipment is a 10 ml. sample at atmospheric pressure. In order to attain a quenched sample the downstream pressure should not exceed 4 psia, therefore the minimum bag size would be 50 ml.

A scanning valve and room for twelve 50 ml mylar bags could be accomodated in a container 3" diameter and 13" long. The container could be evacuated by an on-board aspirator or a static pressure port on the side of the ship. The bag filling would be sequenced by the scanning valve. The operational sequence of the sampling system could be as follows:

a. fuel turned on
b. scanning switch actuated
c. first bag filled
d. scanning switch exhausts line to evacuated chamber
e. second bag filled
f. exhaust to chamber

This sequence is followed until all bags have been filled.

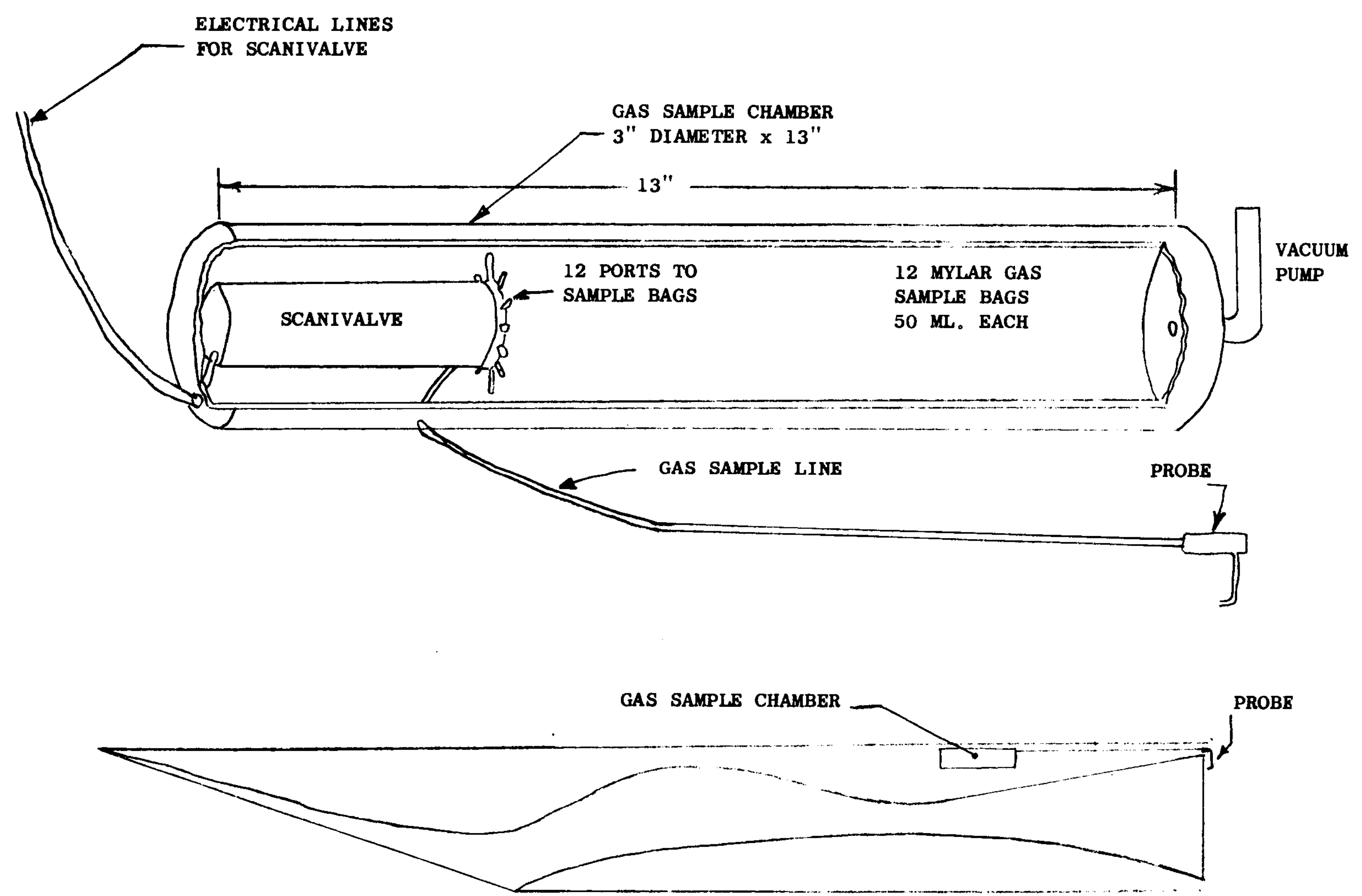
When the samples are on the ground, the gas can be extruded from the bags like toothpaste from a tube and sent to a commercial laboratory for as comprehensive an analysis as desired.

3.4.2 Remote Measurements

3.4.2.1. Requirements

There is a tremendous advantage to being able to measure gas stream conditions remotely. The introduction of probes into the gas stream can seriously affect the performance of the ramjet engine and conversely the probe may be affected by the stream. Although the chance for successfully developing remote instrumentation may be low, the rewards are so great that it should be attempted.

Remote measurements of total and static pressure, total and static temperature, veolcity and gas constituents would be welcome.



GAS SAMPLE CHAMBER

Figure 46

The literature contains references to systems that have been used to measure all of these parameters. However, the systems are usually engineered for a specific problem and are often dependent upon the abilities of a specific individual. A reference list is included in the appendix that verifies this statement. No commercial instrument was found that would measure any of these parameters on a ramjet engine. It should be emphasized that there is a tremendous difference between an instrument developed for a laboratory set up and a dependable flight instrument.

In order to limit the scope of this investigation, it was decided to confine the study to answering this fundamental question: "What is the combustion efficiency of the supersonic ramjet in flight""

The two most promising parameters to measure would be static temperature and gas composition. Methods which are used for measuring static temperature of gas remotely include:

a. Sodium "D" line reversal method (reference 78).
b. Alkali metal line reversals.
c. Iodine absorption (reference 79).
d. Microwave absorption.
e. Untra-sonic absorption (reference 80).
f. Velocity of sound.
g. Ultra-violet, visible and infra-red spectroscopy.
h. Photographic pyrometers.
i. Two color pyrometer.
j. Temperature determination of soot and other particles.
k. Beta-Ray gauge determination of density.
l. Interferometer.
m. Infra-red absorption and emission (reference 81 and 82).

Instruments have been designed and built to measure OH and H_2O concentration (ref. 82). Work has been performed to determine the CO_2 and H_2O concentration in flames, (reference 83).

In order to determine which system would have the greatest chance of success a set of typical engine specifications were assumed. It was arbitrarily decided that the best location for making the measurements would be at or close to the exit of the nozzle. The assumed operating map is shown in figure 47, which gives the Mach number and the range of static temperatures. The profile shown in figure 48 was assumed as typical relationship between the cooled boundary layer, the hot static temperature of the uncooled but completely reacted boundary and the static temperature of the main stream.

The practical limits for Na D line is approximately 2900°R,(ref. 78),with lower limits of 2500°R,(ref. 85). The predicted low static temperature and the difficulties that have been experienced in attempting to seed locally in a supersonic stream eliminated the use of Na D line techniques for measuring the static temperature.

PROJECTED OPERATING RANGES

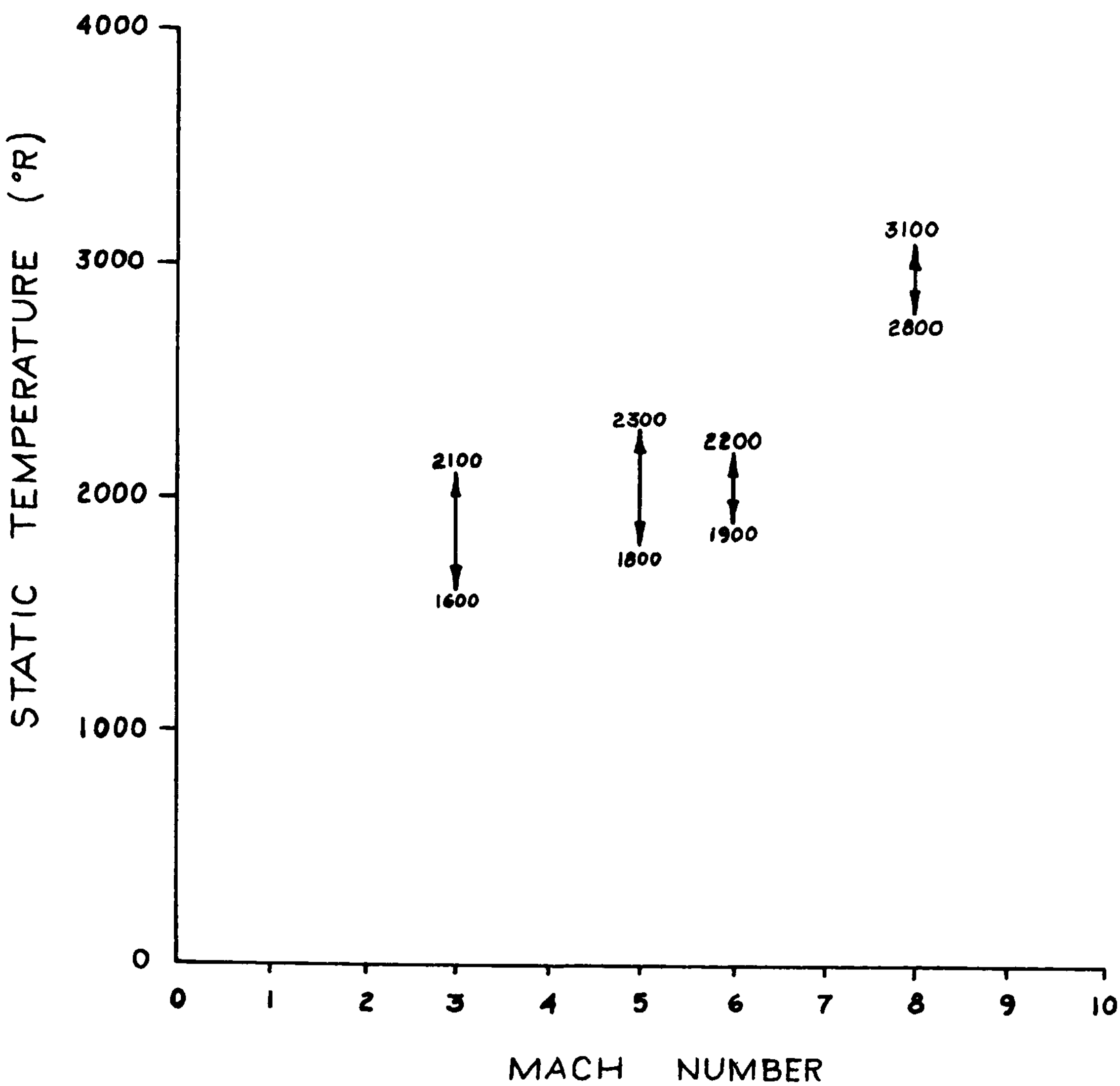
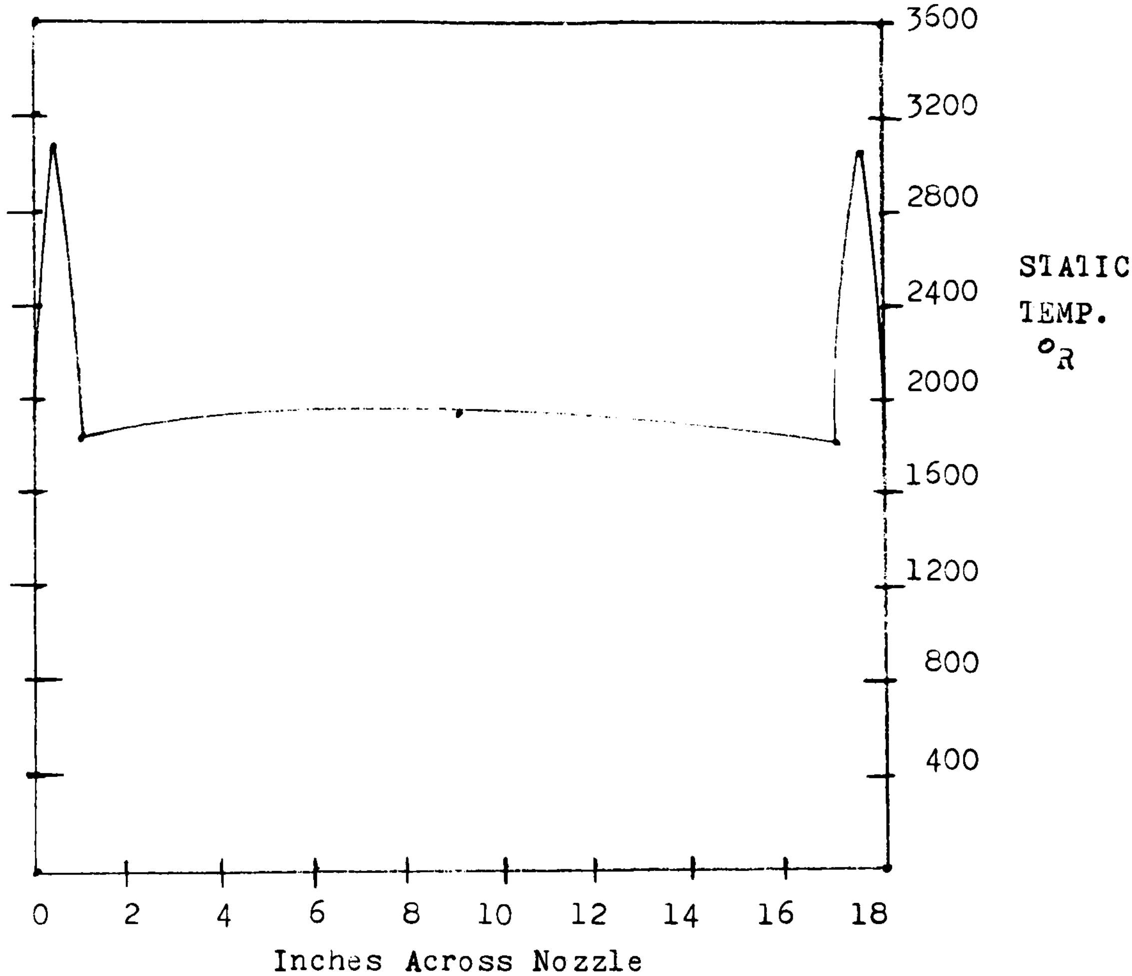


FIGURE 47



ASSUMPTIONS - TEMPERATURE PROFILE AS SHOWN ABOVE
Boundary Layer is one inch thick
Static Pressure is equal to nine pounds pr. square foot

FIGURE 48

3.4.2.1. Requirements - cont'd

The assumption was also made that no contaminants would be present in the optical path such as $B_2 O_3$, carbon, etc. The low static temperature and the difficulty of bringing injected particles up to stream velocity and temperature was used as a basis for eliminating the introduction of solid particles and using a 2 color pyrometer to measure the temperature of the particles.

Another decision was to choose the identification of the products of combustion in the main stream rather than the static temperature if a choice had to be made.

The technique that offered the most promise for making concentration measurements and static temperature profiles is based upon the infrared absorption and emission of the 2.7μ water band.

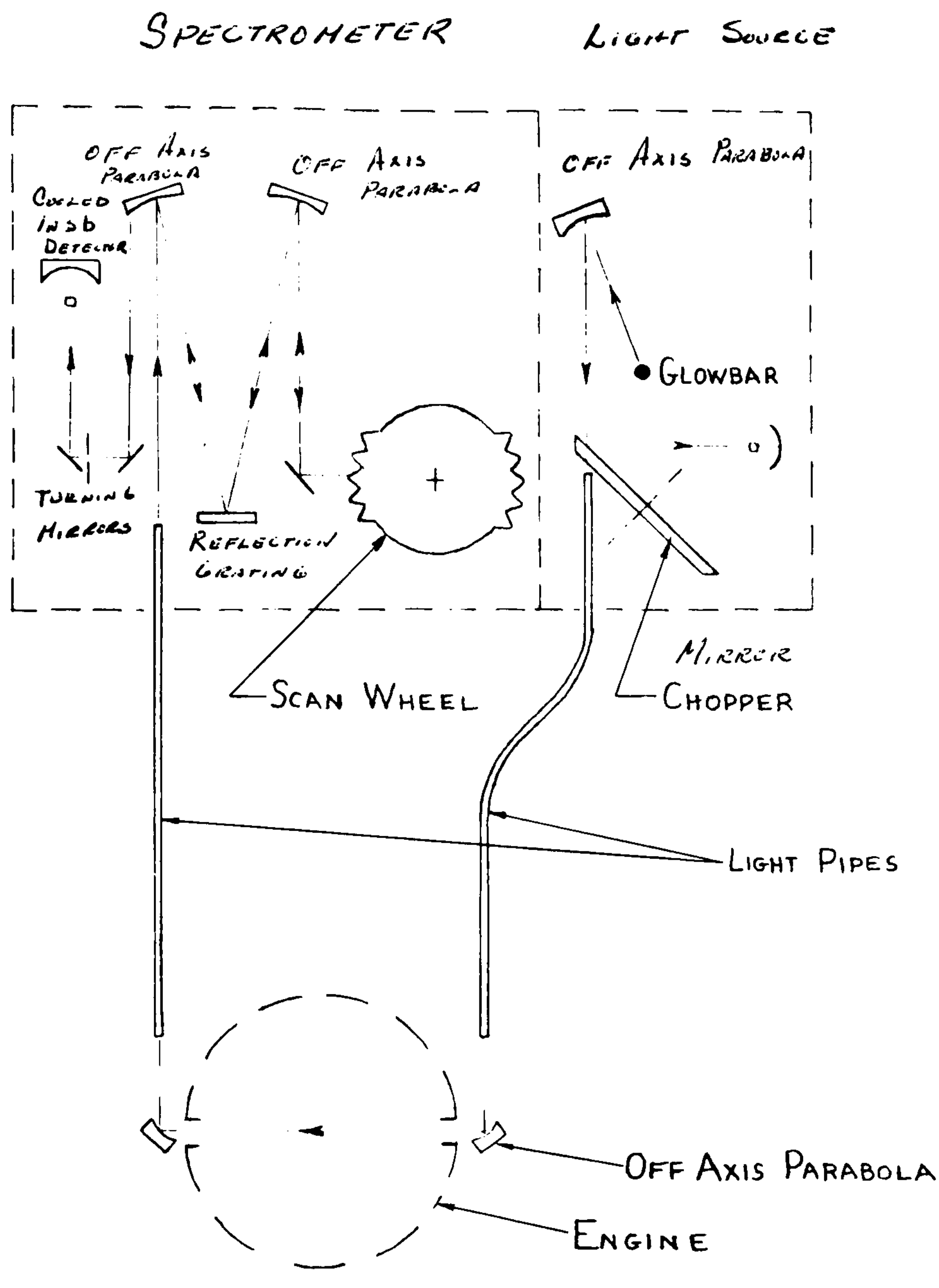
The infrared structure of the emission and the absorption of H_2O molecule in the 2.7 region is a function of the concentration and static temperature of the gas stream. By taking detailed and accurate emission and absorption data at specified wavelengths in and around 2.7μ, it is possible to calculate water concentration and static temperatures. This calculation presupposes certain basic information covering the band model parameters for the strongly absorbing lines near the center of the 2.7μ band of H_2O.

3.4.2.2 Conceptual Design

Figure 49 shows the schematic of a conceptual optical system for measuring infrared emission and absorption spectra at the exit of the ramjet engine. Components selected for this design are identified to demonstrate a principle and are not necessarily optimum components. There are four primary elements which can be identified in the overall system. These include light source, light transmission system, probe supports, and the spectrometer.

The conceptual system outlined would provide infrared emission and absorption measurements. This technique has been used for the strongly absorbing lines near the center of the 2.7μ band of H_2O. Much of the background work for this has been established in previous research studies, (ref. 86). Additional work would have to be performed in order to be applicable to the ramjet program.

The basic principle of the conceptual optical system is as follows. Infrared radiation from the glowbar is collimated by the optical system and chopped at a slow rate. The light pipes (ref. 87) transmits the radiation to the optical probes in the stream. The radiation is transmitted through the hot gases, then by the light pipes to the scanning spectrometer. The scanning spectrometer makes a full spectrogram in absorption. The chopper then cuts off the radiation from the glowbar and the spectrometer makes a scan of the radiation emitted by the hot gases.



SCANNING SPECTROMETER

FIGURE 49

3.4.2.2. Conceptual Design - cont'd

From the shape of these two curves, which could be taken every 500 milliseconds, it is possible to determine the constituents, the concentration, and possibly the static temperature of the stream.

3.4.2.3 Instrument Specifications

The following factors are important in the development of an adequate instrument:

a. The path length across the nozzle
b. An estimate of the thickness of the boundary layer
c. The estimated static and total gas temperature profile across the nozzle at different operating conditions. (This would include the boundary layer and main stream).
d. The estimated static pressure profile at different operating conditions.
e. The combustion efficiency expected, and the lowest expected value.
f. The possibility of impurities that would adversely affect the optical path (such as ablative materials or products from pyrophoric fuels etc.) have been designed into the engine.
g. Estimates of weight and space available on the vehicle.

Instrument specifications should list in order of importance the function of the instrument.

a. Instrument will provide a gas composition and static temperature profile.
b. Instrument will only provide a gas composition profile.
c. Instrument will only provide a static temperature profile.
d. Instrument will only indicate if burning exists in the supersonic stream.

3.4.2.3 Definition of the Program

An integrated two part program resulting in an air borne instrument that can be used to measure the composition profile at the exit of a ramjet is recommended; the applied research portion to supply the basic information needed for the instrument design and the interpretation of the data. The instrument design portion should supply the operational instrument.

Some of the objectives of this program might be:

a. A complete understanding of the operating and environmental conditions.
b. A definition of the wavelength interval, resolution and other important measurement characteristics.
c. Re-evaluation of the feasibility of designing an instrument based upon I.R. absorption principle.
d. Start design of instrument.
e. Construct instrument.
f. Laboratory checkout of instrument.
g. Ground test instrument.
h. Review data - make design changes.
i. Flight test instrument.
j. Review

3.5 Signal Conditioning and X-15 Interfaces

3.5.1 Signal Conditioning

The basic objectives in selecting specific signal conditioning circuitry for the various parameters are the following:

a. Maximum reliability for airborne system.
b. Minimum checkout, trouble shooting and adjustment time.
c. Minimum weight for the test vehicle installation.
d. Maximum utilization of capabilities of the data acquisition system and the transducers.

Types of transducers for which signal conditioning will be required are the following:

a. Strain gage pressure transducers.
b. Static strain gages.
c. Thermocouples.
d. Thrust measurement system.
e. Flow transducers.
f. Accelerometers.
g. Resistance temperature detectors.

Discussion of all items except accelerometers and resistance temperature detectors are covered in this section. The exceptions are handled in the applicable measurement section.

Very careful examination of the proposed thermocouple attenuation method is recommended from the point of view of its use in other measurements. The measurement constraints of a PCM system with only two voltage levels of ±15 MV and ±5.0 volts full scale on instrumentation outputs is very undesirable. The introduction of many voltage levels would result in simplification of signal conditioning equipment and data quality improvement. It would permit transducers to operate at optimum signal outputs, decrease shielding requirements, and allow correct power supply voltages to be applied directly to strain gage bridges.

It is recommended that the next generation of PCM systems be specified with a multilevel selectable gain amplifier programmed to the particular channel.

3.5.1.1 Pressure Transducer Signal Conditioning

The recommended signal conditioning circuitry for strain gage bridge pressure transducers is shown in Figure 50. This circuit has the following characteristics:

a. Transducer power is carried to the test vehicle on a common pair of wires.
b. Voltage regulation feedback signal is taken from a point near the transducer.
c. Power supply voltage is selected to provide ±14MV output range for the transducers.
d. Power supply voltage switched "off" for "zero cal" step. (zero calibration)
e. Shunt resistance for "delta cal" (sensitivity calibration) step.

This circuit represents the simplest, most reliable signal conditioning for this type transducer and requires minimum wiring to be run to the test vehicle. Other advantages include elimination of sensitivity changes with changes in power lead resistance and the absence of balance controls. To make use of this circuit, however, there are limitations in flexibility in application, including the following:

a. Transducers must be designed to balance at midrange for maximum resolution in recording.
b. Sensitivity (full scale output voltage for a given excitation) must be approximately the same for all transducers operating from the common power supply.

Use of a common power supply voltage has the advantage that the voltage can be regulated and monitored at the transducer (if transducers are in one location) terminals eliminating any errors which may result from variations in series resistance of the circuit, either in wire resistance or a dropping resistance. Recording the voltage at the common point near the transducers on one channel of the PCM system will give further confidence in data quality.

Elimination of the balance control by specifying the transducers to balance at the midpoint of their range also adds to the reliability and accuracy of the system. With the use of computer processing, it is readily feasible to correct for minor deviations from the optimum balance point. If a transducer deviates significantly from its design balance point, there is a good likelihood that it has been damaged in some way and quite likely is deteriorated in other performance characteristics as well as balance, and should be repaired or replaced rather than rebalanced by external adjustment.

Preflight and inflight checkout capability includes means for removing power from the bridge to give a zero voltage output and shunting a resistance across one arm of the bridge to give a step change in output. These outputs do not check the zero or sensitivity of the transducer but serve only to give a zero reference for the recording system, a rough check on the sensitivity of the recording system, and an indication of malfunctions in the circuitry associated with the particular channel or the power source.

PRESSURE TRANSDUCER SIGNAL CONDITIONING

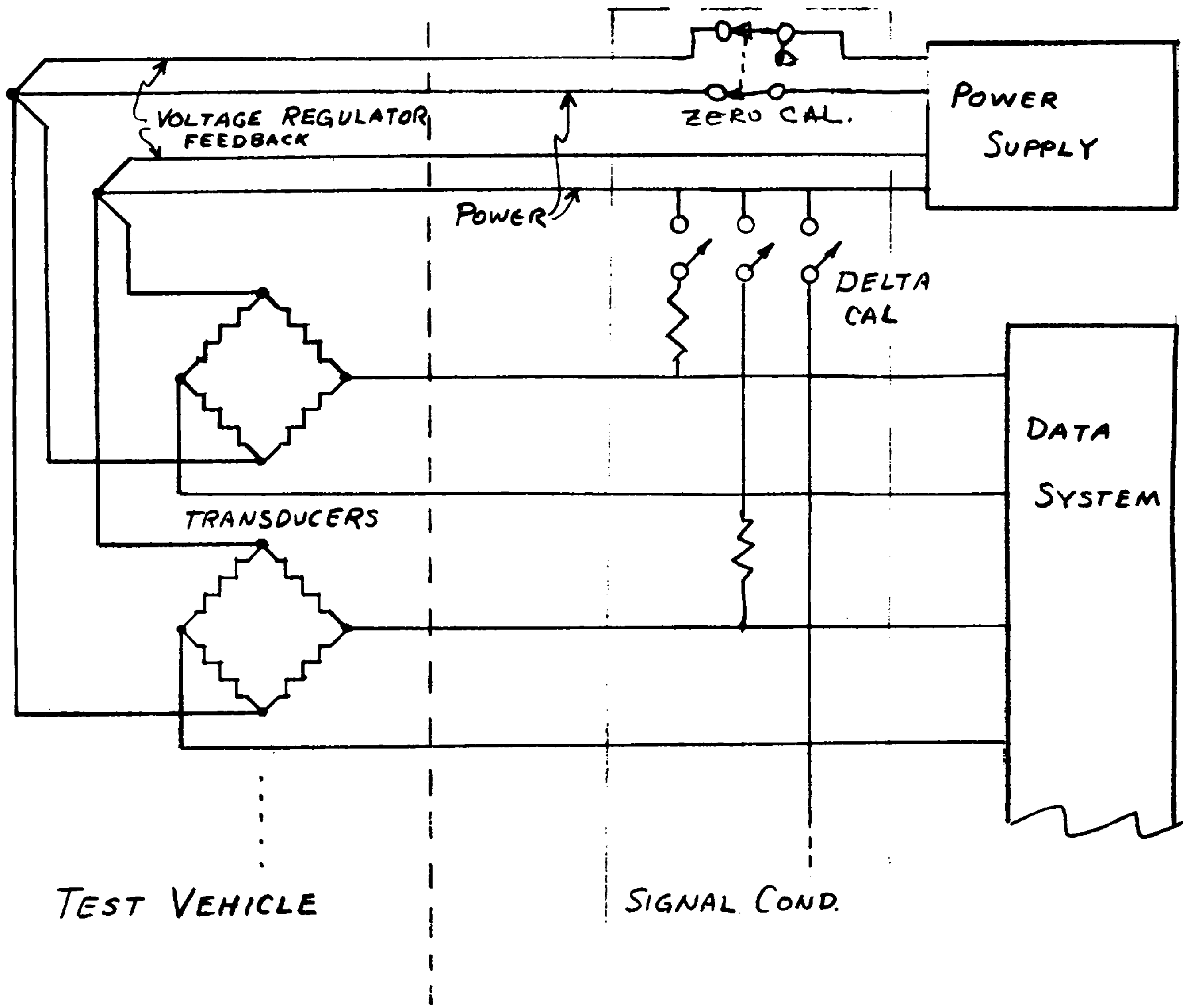


FIGURE 50

Pressure Transducer Signal Conditioning - cont'd

The "zero cal" step will indicate any changes in zero of the recording system with the transducer still connected in its normal manner but with excitation power removed. This will serve as a check on zero offset of the input gates and possible thermocouple effects in the wiring. In case signigicant shifts occur during a flight it may be possible to recover data by means of this reference. However, this should not be considered a normal practice and the system should be repaired to eliminate the source of the offset.

The "delta cal" step will give a reasonably good check on recording system sensitivity during system preflight checkout when temperatures of the system are nearly constant, but should not be used as a standard for correcting data. The primary function of this check is to assure that there are no gross malfunctions in the circuitry. An open or high resistance lead, for example, will result in a large deviation from the standard delta cal step. If there is a change in recording system sensitivity, a reference voltage on another input channel will give a more reliable source of correction data; however, either of these references should be used for data correction only in attempts to recover data which may possibly be salvageable in case of system malfunctions. A six-wire system with the shunt resistance built into the transducer for temperature compensation would give a more repeatable "delta cal" during flight conditions. However, the added weight and complexity of this approach is not considered to be justified in view of the potential benefits. Since the recording system has a high input impedance and the supply voltage is regulated and monitored at a point near the transducer, the variations in lead wire resistance with temperature changes will not affect the sensitivity of the transducer. If the supply voltage is accurately known and the circuit is demonstrated to be intact, the delta cal value will not improve the quality of the data.

Signal conditioning for transducers which do not meet the requirements of midrange balance and common sensitivity can be accomplished by means of the NASA 20 channel strain gage control box, drawing EDF-695, which includes balance and shunt calibration capability. In addition, transducer sensitivity must be matched to the ±15 MV range of the PCM system. This may be accomplished either by addition of dropping resistance in series with the transducer power leads, providing selected power supply voltages, or attenuating the signals. Of these options, selection of power supply voltages to give the desired sensitivity without individual channel adjustment or attenuation would result in the most simple and reliable system.

3.5.1.2 Static Strain Signal Conditioning

Signal conditioning requirements for static strain measurements are similar to those for bridge transducers except that the bridge must be completed in the signal conditioner and there must be provision for balancing the bridge. "Zero cal", "delta cal," and sensitivity provisions and functions are similar to those discussed for strain gage bridges.

The NASA Hi-Temp Strain Gage System, Drawing ED-1-535, could be used for this purpose. However, the scanner portion of this system is not required nor desirable for this application. The basic signal conditioning circuit required is shown in Figure 51 .

3.5.1.3 Thermocouple Signal Conditioning

Thermocouple signal conditioning will require attenuation of the high temperature inputs to fall within the ±15 MV data system range. Attenuation of signals ahead of the PCM system is possible but undesirable. A compromise must be reached between source impedance for the data system inputs and load impedance in the transducer circuits. Without attenuation the source impedance is low and the load impedance is high, which is the ideal condition. Increases in source impedance will make the system more susceptible to extraneous noise signals and effects of back current in the electronic gates. Decreases in load impedance will result in variations in sensitivity with changes in source impedance such as changes in wire resistance as a function of temperature.

The design of the NASA CT 77 data acquisition system includes a feature which may make possible the attenuation of signals in groups of ten channels without requiring these compromises. The multiplexer is made up of modules (rows) of ten channels with an RC filter at the input of each channel and a series switch following each row of ten channels. An attenuator between the data gates and the series switch, Figure 52, will permit attenuation of the associated ten channels with a relatively low resistance attenuator and still not significantly load the source. The data switch is closed for an individual channel only for the duration of one data word or 65 microseconds. With the data gate open between samples the capacitance of the RC filter is charged to the full level of the signal. When the data gate is closed for the 65 microseconds period the voltage across the filter capacitor is switched across the attenuator network and current flowing through the resistor gives the desired attenuation at the series switch input. If the data gate were "on" for an extended period the capacitance would discharge down to a steady state condition determined by the resistance values of the series resistance of the filter and the resistance of the attenuator. However, with the gate turned on for only 65 microseconds the capacitance discharges only a small amount and the voltage drop at the capacitor is consequently low.

STATIC STRAIN SIGNAL CONDITIONING

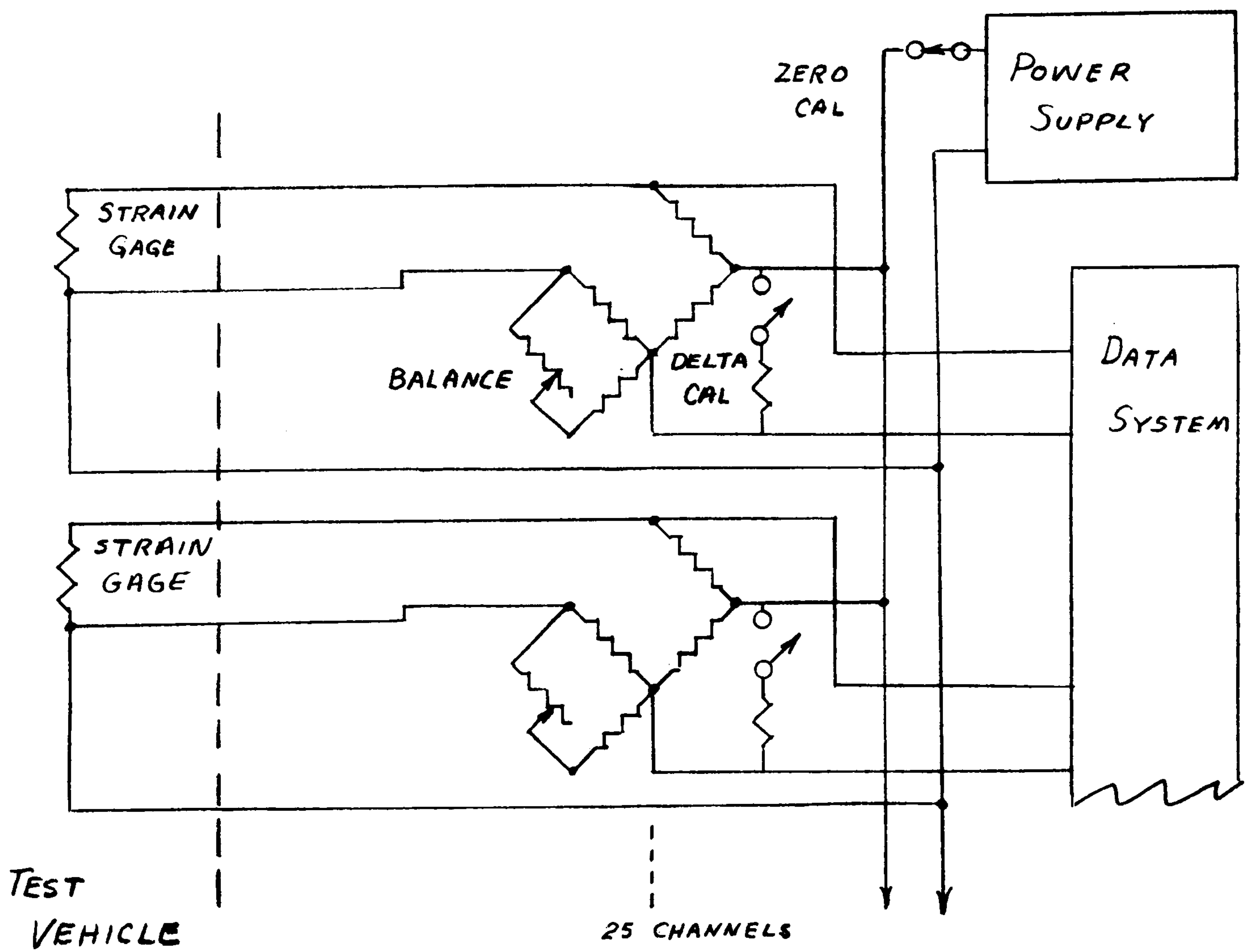


FIGURE 51

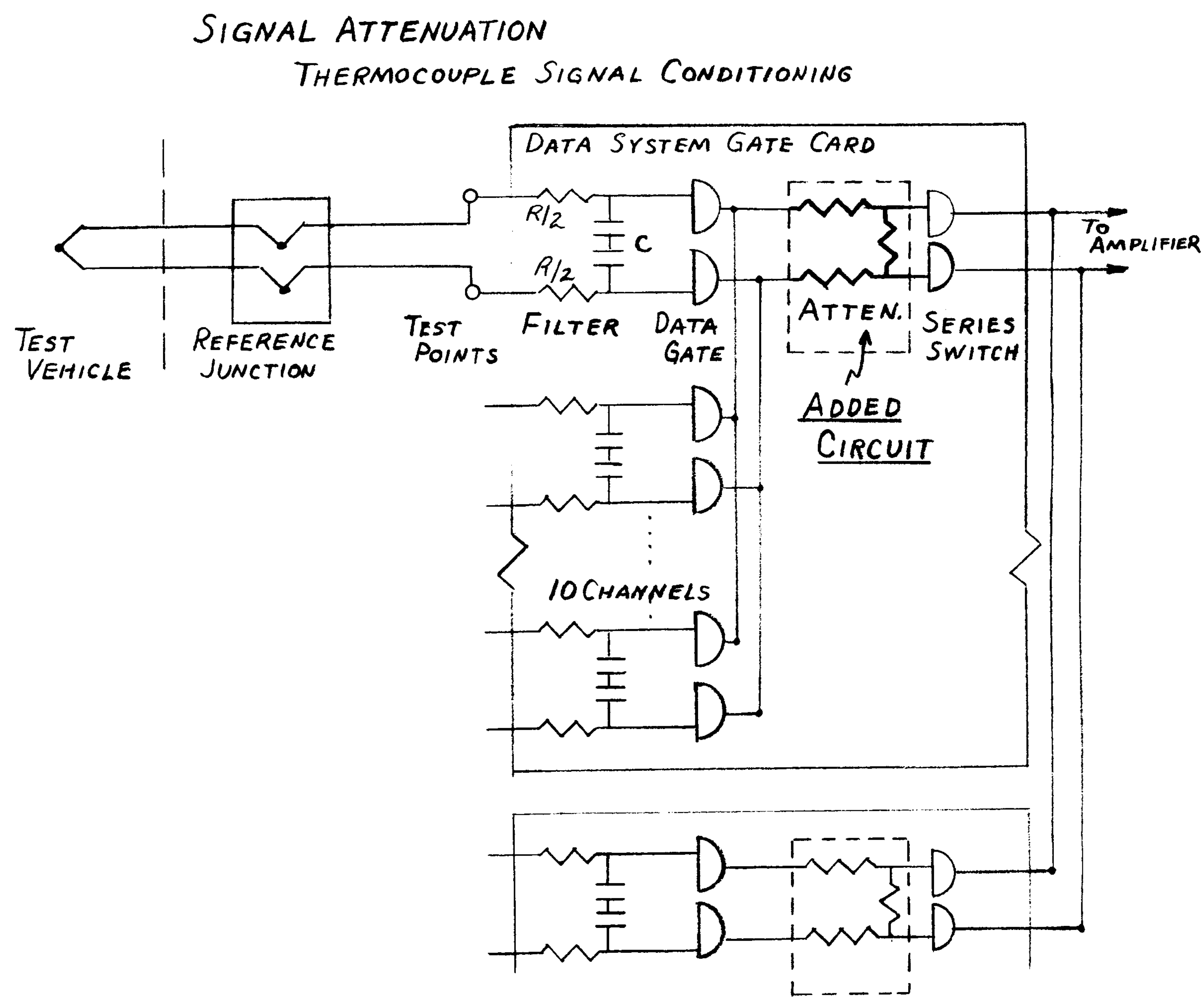

SIGNAL ATTENUATION
THERMOCOUPLE SIGNAL CONDITIONING
DATA SYSTEM GATE CARD
R/2
C
R/2
TO AMPLIFIER
TEST VEHICLE
REFERENCE JUNCTION
TEST POINTS
FILTER
DATA GATE
ATTEN.
SERIES SWITCH
ADDED CIRCUIT
10 CHANNELS

FIGURE 52

Thermocouple Signal Conditioning - cont'd

This can be shown as follows:

$$E_o = Ee^{\frac{t}{RC}}$$

t = time following data gate closure
R = loop resistance of attenuator network
C = capacitance of filter output.

for t = 65 microseconds
R = 1500 ohms
C = microfarad

$$E_o = Ee^{\frac{65 \times 10^{-6}}{1.5 \times 10^{3} \times 3 \times 10^{-6}}} = Ee^{-1.44 \times 10^{-2}} = .9857\ E$$

If C can be changed to 30 microfarad, which is desirable for the 20-per-second rate, E_o becomes 0.9986 E. Since there is no filter on the sub-com gates this modification must be made to the particular prime channel filter.

To assure that this approach is feasible, a study must be conducted of the magnitude and stability of the "on" resistance of the data gates and whether the attenuator network can be physically installed in the multiplexer system.

An alternate possibility which should be considered is the installation of additional amplifiers in the system along with programmer modifications to permit selecting of the desired amplifier for a particular channel.

Pre-flight checkout of the thermocouple channels should include the following:

a. Loop resistance check
b. Resistance to vehicle ground
c. Ambient temperature measurement

These resistance checks can be accomplished either manually on an individual channel basis or semi-automatically by means of a special test system. Ambient temperatures can be recorded as a data record on tape or read manually from a visual display.

In-flight calibration on an individual channel basis is not feasible. For maximum assurance of proper operation of the system at least one data channel should be used to monitor the reference junction temperature. If sufficient data channels are available, a further degree of reliability could be achieved by measuring a known reference voltage on one channel of each ten-channel multiplexer module. This reference channel would provide a continuous check of the complete recording system except for the individual data gates.

3.5.1.4 Thrust Measurement Signal Conditioning

Transducers for thrust measurement will be LVDT type with an associated electronic system to provide carrier excitation and demodulation. Output of the system is a DC voltage with a full scale range of ±1 volt.

Associated with the thrust transducers are two accelerometers to provide correction signals for the thrust measurements. These accelerometers provide output signals of .2 to 7.5 V.D.C. for the range of operation.

To increase the resolution of the thrust and acceleration measurements, a Vernier Range Extender, Donner Model 4106, is included in the recommended system. This device puts out two 0-5 VDC signals for each measurement. The standard model would therefore use only half of the PCM system resolution with zero thrust or acceleration at half scale. A modification in specifications for these units is recommended to produce ±5 VDC output range with zero voltage at zero thrust.

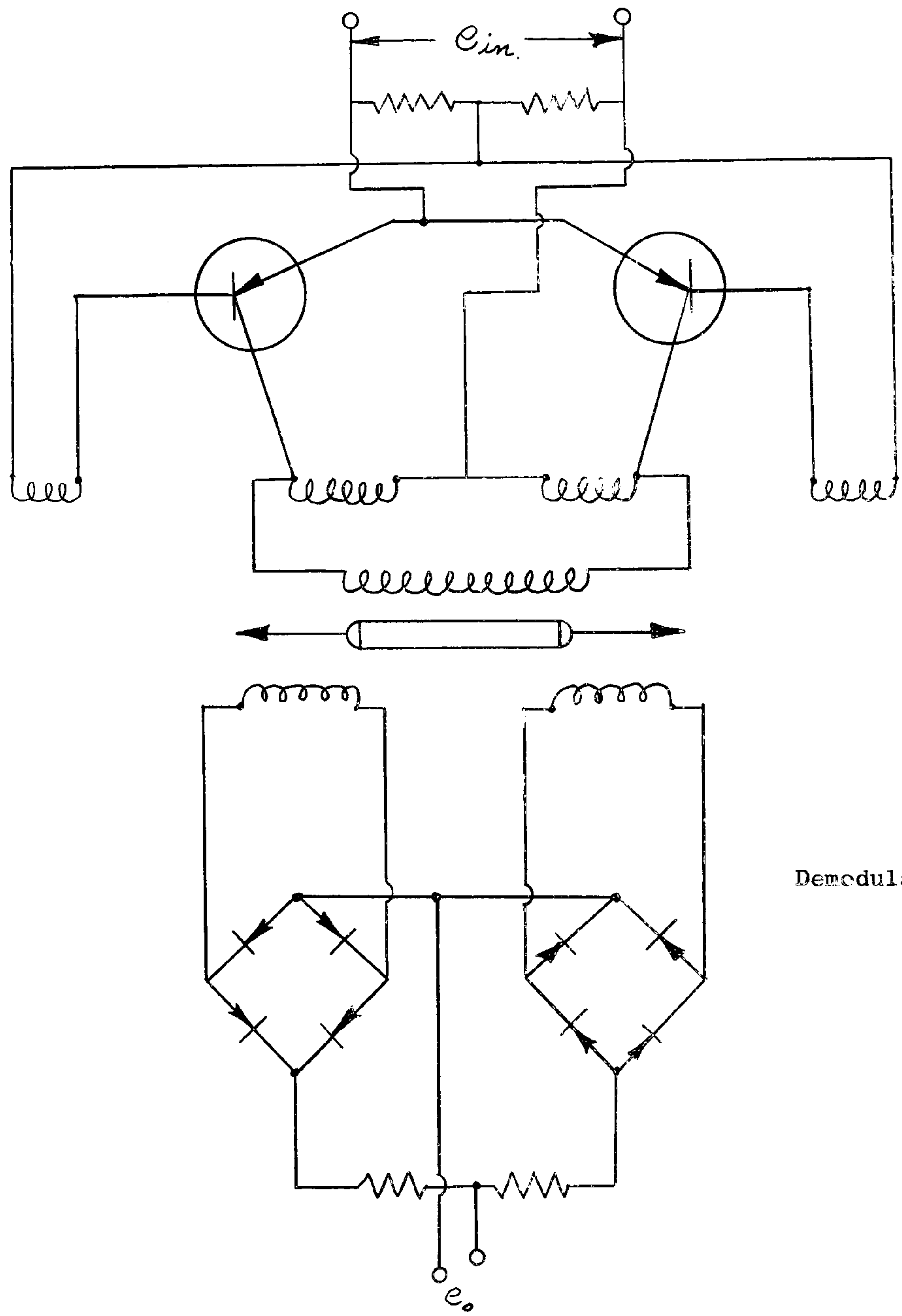
The output of this device can be connected directly to a high level PCM channel with no additional signal conditioning requirement.

An alternate approach for recording these parameters using considerably less complex circuitry, but with reduced resolution is shown in Figure 53. For recording with the PCM system the thrust system output signal must be either amplified to ±5 volts or attenuated to ±15 MV. For greatest accuracy and best signal-to-noise ratio, amplification to ±5 volts full scale is recommended. There are a number of commercially available amplifiers, such as Dynaplex Type 035B, which will be suitable for this application.

Accelerometer signals will require attenuation to bring the maximum signal level to the ±5 V range of the data system.

3.5.1.5 Flow Transducer Signal Conditioning

Each of the potential flow measurement systems considered feasible for this application requires an associated conversion system to provide a DC signal as a measure of flow. The specification for the design of this converter should include the characteristics required to connect to the ±5 V inputs to the system.



Schematic Circuit of L.V.D.T. Inverter, Sensor
and Demodulator

Figure 53

3.5.1.6 Dynamic Strain Gage Signal Conditioning

Dynamic strain data is necessary to monitor fatigue stress levels. Separate signal conditioning must be provided for dynamic stress measurements. A method used in flight engine evaluation on single element gages is shown in Figure 54. Several options are provided.

A high voltage power supply can be elected to provide higher gain from the strain sensitive element. This may not be necessary for the Ramjet testing.

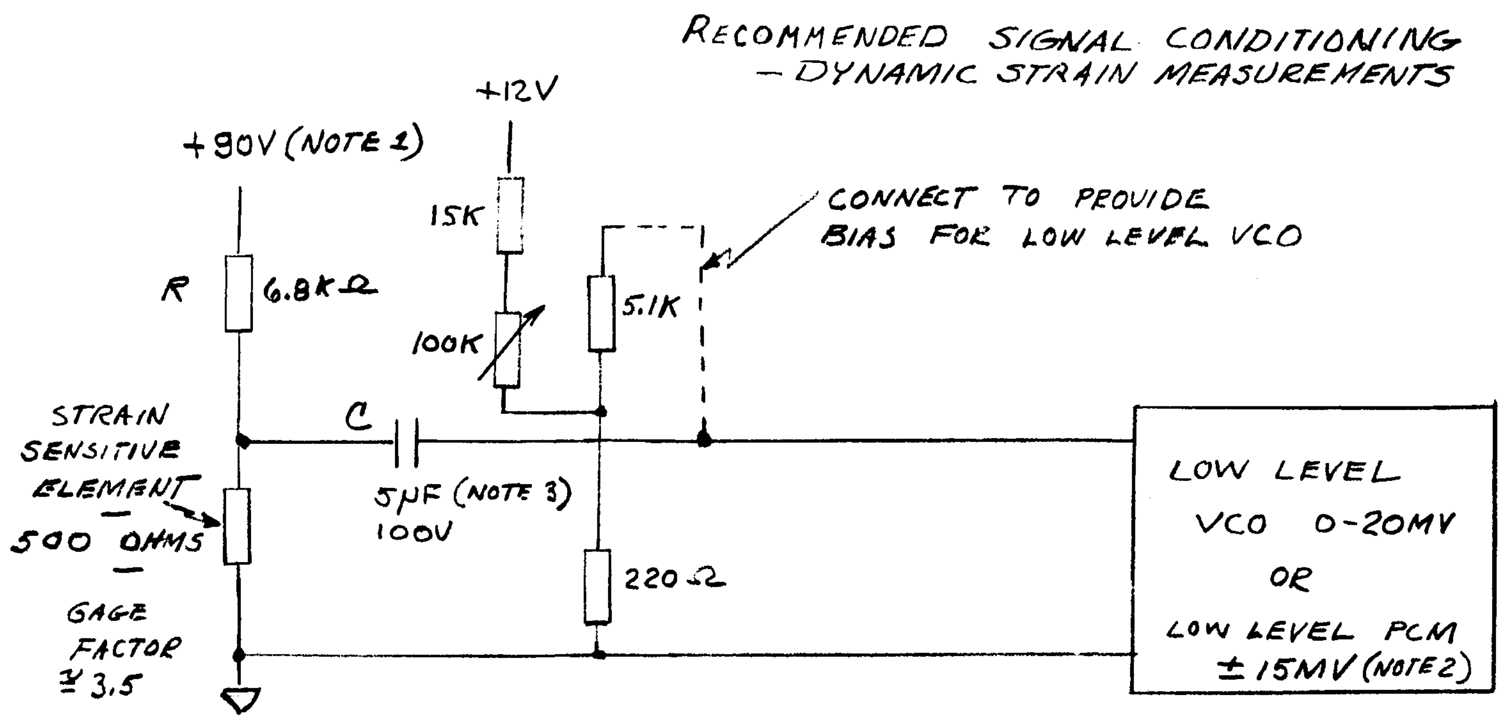
The recording system selected can be either the FM/FM system with a low level VCO or the P.C.M. package. For accuracy the P.C.M. system is required, but flight safety considerations indicate the necessity of telemetry to provide the ground station with dynamic levels of stress as well as some static information. IRIG channels from 11 up are suitable with this signal conditioner.

For lower frequency response a change in capacitors will be necessary. The values required are:

Capacitor (Microfarads)	Low Frequency Cutoff
5	7 cps
10	3.5 cps
15	1.75 cps

The proposed signal conditioning method can be installed by modifying the present strain gage units to accomodate the few additional circuits required for dynamic strain data.

This signal conditioning method provides for a D.C. bias to be supplied for certain types of V.C.O. systems.



NOTE 1; 12 VOLTS CAN BE USE AS SUPPLY FOR STRAIN SENSITIVE ELEMENT AT SOME REDUCTION IN SENSITIVITY - FOR 12 VOLTS - R = 500 OHMS

- REDUCTION IN SENSITIVITY - APPROX 1/2

NOTE 2: PCM MUST BE SUPERCOMMUTATED TO PROVIDE ANY SATISFACTORY FREQUENCY RESPONSE - 2 PRIME CHANNEL FOR A SINGLE STRAIN MEASUREMENT - 7 CPS to 100 CPS

NOTE 3: CAPACITOR LIMITS FREQUENCY TO ABOVE 7 CPS.

Figure 54

3.5.2 X-15 Interface

There are two major interfaces concerned with the instrumentation of the Ramjet.

a. Ramjet/X-15 Bulkhead Disconnect
b. Recording requirements.

3.5.2.1 Bulkhead Disconnect

The bulkhead disconnect is the primary item concerned with design of the ramjet. A preliminary evaluation of instrumentation wiring is shown in Table I . It indicates a weight of one pound per foot and must be considered in determining the weight budget. Reduction of the number of wires in the 4-wire strain gage pressure system is desirable from this point of view. This can be accomplished by using a single pair of wires to supply instrumentation power. It has many advantages as discussed in the signal conditioning section on pressure transducers and will decrease the wires required from 507 to 377.

If, as it appears likely, the total pressure probes will be limited in number, the actual number of transducers for pressures can be between 51 and 55. The disconnect requirements for this recommended approach are shown in Table II . This also indicates, as shown by the study, requirements for monitoring in the ramjet temperatures of measurements as follows:

Central Instrumentation Package Temperature		3
Accelerometers:	Piezoresistive	3
	Inertial	1
Temperature Reference - RTD		1
Dynamic Pressure Transducers		3
	Total	11

The specifications on the Ramjet disconnect and associated instrumentation wiring are as follows:

Copper wire used throughout.
Maximum contact and thermal gradient EMF generated - less than 30 microvolts with thermal gradient of 200° across plug.

The use of a thermally lagged temperature reference source on the Ramjet permits all wire entering the Ramjet/X-15 disconnect to be copper. This is of great advantage in the design of the actual hardware in meeting the 30 microvolt specification. This level of contact and thermal gradient voltage represents approximately 0.2% of full scale and is required to meet reasonable instrumentation accuracies.

TABLE I

RAMJET/X-15 BULKHEAD DISCONNECT

	TRANSDUCER	# REQUIRED	# WIRES
Pressure	4-Wire strain gage	67	268
Temperature	Thermocouples	76	152
Enthalpy		1	6 (est)
Force	4-Wire E-core	4	8
Accelerometers:			
static	4-wire inertial	2	8
dynamic	Piezoresitive	3	3 coaxial plugs
Special inputs	For controls, power, etc.	(separate plug)	12 (est)
Static strain	2-Wire	25	50
		TOTAL	507 Wires

Estimated Weight - 1.0#/ft. (assuming #26 wire on transducers)

TABLE II

RAMJET/X-15 BULKHEAD DISCONNECT - PROPOSED APPROACH

	TRANSDUCER	# REQUIRED	# WIRES
Pressure	4-Wire strain gage (Instrumentation Power Bus)	55	114
Temperature:			
Measurements	Thermocouples	67	134
Transducer Mon-toring	Thermocouples and RTD	11	22
Enthalpy		1	6 (est)
Force	4-Wire E-core	4	8
Accelerometers:			
Static	4-wire inertial	2	8
Dynamic	Piezoresistive	3	3(coaxial)
Special Inputs	For controls, power, etc.	(separate plug)	12(est)
Static Strain	2-wire	25	50
		TOTAL	357 Wires

Estimated Weight - 0.7#/ft. (assuming #26 wire on transducers)

3.5.2.1 Bulkhead Disconnect - cont'd

Disconnects should be tested with a 200°F gradient across the unit making this evaluation. There appears to be no problem but specially plated pins may be required, and the materials for the contacts should be from the same alloy melt to prevent the existence of thermocouples within the disconnect. If insertion pins are used they should be identified as to batch number in packaging. These problems have been ovserved recently in flight test aircraft in the case of bulkhead connectors that had a high thermal gradient across special pins for iron-constantan thermocouples. This is a real accuracy problem for thermocouple connectors but with copper wiring all that is required is good quality control practice in procuring and minimizing of the thermal gradient across the connector.

Special inputs for instrumentation power will be required. The study indicates the following are needed:

	Wires
Instrumentation Power Bus - 115 volts, 3.5 amps	2
Instrumentation Power Bus - 28 volts, 6 amps	2
Instrumentation Power Control Wires (2 amps each) for gas sampling, Scanivalve and special tests.	8

The power should be in a separate plug from the low level instrumentation signals as represented by thermocouple and strain gage signals.

3.5.2.2. Recording Requirements

The high accuracy of the PCM system makes it the most feasible method to meet the measurement requirements to provide for good ramjet performance data. This recording system meets the objective on all but the very high frequency measurements.

Some modification must be made to the PCM filter system when recording above 50 cps to provice a suitable frequency response. Presently there is in the PCM system a filter that consists of a single R-C element with the standard roll off of 6 db per octave. Practical controls on phenomena such as frequency folding indicate its cutoff frequency should be about one-fourth of the sampling rate. The PCM filters should be set to the following values, depending on measurement frequency response:

FREQUENCY RESPONSE	SAMPLING RATE (3 db down)	FILTER CUTOFF	PRIME CHANNELS
50 cps	200 S/S	50 cps	Standard (1)
100 cps	400 S/S	100 cps	Supercommutate (2)
200 cps	800 S/S	200 cps	Supercommutate (4)

3.5.2.2 Recording Requirements - cont'd

There is only one channel restriction involving the 50 S/S rate (10 cps). As previously indicated, the total pressure measurements required will be less because of the internal engine shock problem. This will decrease the need for the number of 50 S/S channels by around 10 to 12. If further channels for other purposes are needed at the 50 S/S rate, an additional subcommutator should be provided.

The high frequency requirements on certain parameters are difficult to meet. The measurements in question are:

a. One combustor pressure signal 0 - 2000 cps.
b. Three vibration signals 200 - 2500 cps.

The high frequency recording system on the X-15 consists of a standard IRIG FM-FM system. The characteristics of the wide bands are given below:

BAND	C+ FREQUENCY	SIGNAL RESPONSE
A	22,000	660
B	30,000	900
C	40,000	1200
D	52,500	1600
E	70,000	2100

In addition, in the NASA FM-FM system the accuracy is in the order of ±7% of full scale. This, combined with the frequency response, does not meet measurement requirements. Some other equipment must be supplied to meet these needs. A single frequency identification approach using a discriminator was considered. It is not really suitable since the measurements in question will have a wide frequency spectrum. A possible candidate is a wide band FM recorder system installed in the aircraft. The details of such a system are beyond the bounds of this report.

4. Program Conclusions and Recommendations

4.1 Overall Results

The major study results are:

a. The preliminary design of a direct thrust/drag measurement system for the experimental ramjet after identification of important design criteria, a preliminary thermal and mechanical performance analysis, and identification of development programs leading to an in-flight measurement. (Volume 2)

b. Conceptual design of instrumentation systems and techniques for performing desired measurements during flight testing on the X-15A-2. Preliminary error analyses of candidate systems have been developed as well as identification of reasonable accuracy to be expected, and special considerations for calibration and installation procedures to insure maximum accuracy. Programs for development of advanced components are suggested, and where possible, vendor equipment which meets specifications and is readily available has been identified.

c. A proposed overall program for development, cost, and lead times of important instrumentation systems. The instrumentation systems which are considered to be feasible are listed below as well as their recommended function.

Engine Performance	Diagnosis	Safety
Fuel Flow	..Internal Static Pressure(steady state and fluctuating)	..Fuel Pressure
Mechanical Measurement of direct Thrust/Drag	..Fuel temperature and pressure	..Structure temperature
External static pressure.	..Exhaust gas sampling	..Vibratory stress
	..Optical gas analysis	..Vibration
	..Structure temperature	
	..Vibration	

4.2 Specific Program Conclusions and Recommendations

Program conclusions and recommendations are summarized according to the primary areas of measurement covered during the study. Detailed information is included in Volumes 2 and 3.

THRUST/DRAG SENSING DEVICE

Conclusions:

a. Minimize magnitude of extraneous forces mechanically by two point support; one flexible, the other fixed, and measure at all support points.

b. Provide for electro-mechanical compensation of remaining forces within the thrust sensing element.

c. Measure all remaining axially extraneous forces for correction by proper electrical circuitry, or by correction in data reduction.

d. Measure deflection rather than strain.

Recommendations:

a. Conduct study of dynamic compatibility of ramjet X-15A-2 attachment.

b. Optimize single thrust measurement element.

c. Evaluate a prototype thrust measurement system under simulated loads.

d. Design and manufacture flyable thrust measurement system.

FUEL MEASUREMENTS

Conclusions:

a. Density correction of volume flow meters is difficult and seriously limits their application for liquid hydrogen measurements.

b. Current methods to protect turbine type meters from overspeed during two phase hydrogen flow are unreliable for flight application.

c. Orifices and venturies are limiting in flow range unless large fuel systems pressure drops can be accomodated.

d. Adequate cryogenic facilities are available for meter calibration.

e. Cryogenic pressure and temperature measurements as required in this program are within the current state-of-the-art.

Fuel Measurements - cont'd

Recommendations:

a. Liquid hydrogen mass flow measurement should be made with a mass flowmeter.

b. The mass flowmeter should be calibrated at six month intervals using liquid hydrogen and fuel system mockup.

c. Meter calibration should have a minimum of 15 points over the range 0-5 lbs. per second.

d. Pyrophoric fuels can be metered with conventional turbine-type flowmeters provided materials are compatible. Calibration can be conducted with selected fuel on Edwards Air Force Base Rocket Site.

STATIC PRESSURE MEASUREMENTS

Conclusions:

a. Static pressure measurements along the internal wetted surface provide the most feasible method of indicating internal aerodynamic conditions over the complete range of ramjet operation.

b. Repeatable correlation between free stream and wall surface pressure is questionable unless smooth surfaces with no abrupt changes can be provided.

c. Complete range of pressure cannot be measured with a single transducer without severe accuracy, number, or weight penalties.

d. Transducers will require thermal and vibration protection.

e. Several pressure measurement system concepts are available to provide adequate compromise between number of measurements, system weight, and pressure range.

Recommendations:

a. Establish location of internal static pressure taps during component ground tests to insure repeatable correlation between free stream and wall surface pressure.

b. Fluctuating and steady-state pressure should be measured separately but simultaneously.

c. Record steady state and quasi-steady state data on Pulse Code Modulation (P.C.M.) and fluctuating pressure with non-resonant probe systems.

4.2 Specific Program Conclusions and Recommendations - cont'd

Static Pressure Measurements - cont'd

Recommendations - cont'd

d. Provide for centralized instrument compartment with temperature regulation to ±25°F.

e. Provide for pre-flight system calibration.

STRUCTURAL MEASUREMENTS

Conclusions:

a. Regression rate, surface temperature and pressure measurements of ablation materials cannot be made with sufficient accuracy to satisfy ramjet test requirements.

b. Sheathed thermocouples imbedded in metal surface will provide adequate accuracy and reliability with current calibration and installation procedures.

c. Steady state and vibratory strain measurements are temperature limited. Practical limit for steady-state is 650°F; for vibratory 1500°F.

d. Vibration measurements as required in this program are within the current state-of-the-art.

Recommendation:

Apply current practices associated with installation of sheathed and flame sprayed thermocouples to ramjet metal surfaces.

EXHAUST GAS MEASUREMENTS

Conclusions:

a. Uncooled probes represent a better than 5 to 1 weight advantage over cooled probes.

b. Refractory metals such as tungsten, columbium, and molybdenum with their coatings are unsatisfactory probe materials in oxidizing gas streams at high velocities and enthalpies.

c. Pyrolytic graphite is a feasible protection for high temperature probes.

d. Most reliable technique for analyzing exhaust gases appears to be on-board sample collection with subsequent analysis on the ground.

e. Optical techniques for measuring exhaust gas temperatures and constituents are feasible.

f. Probe interference effects will limit the use of probes to locations aft of the exit nozzle.

4.2 Specific Program Conclusions and Recommendations - cont'd

Exhaust Gas Measurements - cont'd

Recommendations:

a. Conduct experimental program to establish design and fabrication procedures of probe supports with pyrolytic graphite protection.

b. Design and demonstrate minimum volume gas collection system for mounting on ramjet engine.

c. Conduct applied research program to evaluate application of infra-red emission and absorption.

d. Design, manufacture, and demonstrate flight weight optical system for exhaust gas measurements.

e. Demonstrate practical application of polarographs for on-board gas analysis.

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APPENDIX 1

Description of Wyle Laboratories LH_2 Flowmeter Calibration System

In selecting the principle for developing the precision calibration system, a great deal of emphasis was placed upon Wyle's prior experience in the use of time-weight calibration systems and the desirability of directly comparing the indicated total output of the various meters with accurately known increments of test fluid weight. Based upon these criteria and experience, the time-weight calibration principle was selected for use in the design of the primary calibration system.

The system basically consists of a 650 gallon calibration tank mounted on a mechanical scale system. Fluid is removed from the calibration tank through the use of helium pressurization of the calibration system. In order to eliminate the requirement for the measurement of pressurization gas added to the calibration system during the calibration test, the helium pressurization system is contained on-board the scale system. Calibrated drop weights were selected for use which permit the use of the scale system as a null balance device rather than as an absolute weight measurement device.

Fluid is removed from the scale system through a three inch, vacuum-jacketed flexible hose assembly, and subsequently into a fluid piping system containing the flowmeters to be calibrated. At the end of each calibration run the liquid hydrogen test fluid is transferred by backflow through the test line to refill the 650 gallon calibration tank.

A special vacuum test chamber is incorporated into the test system so that most non-vacuum jacketed flowmeters with variable configurations can be easily installed in the calibration system.

A typical flowmeter calibration is performed in the following manner: With the calibration tank and transfer lines precooled and filled with liquid hydrogen, and stabilized at atmospheric pressure, the vent valve of the 650 gallon calibration tank is closed and the tank rapidly pressurized to approximately 50 psig using helium pressurization gas.

The downstream flow control valve is opened and the predetermined flow rate is rapidly established. Following establishment of the pre-selected flow rate, the mechanical beam balance system (which has been previously adjusted to an over balance condition) approaches an initial balance condition, thus actuating the capacitance switch which senses the beam pointer position. Following the initial switch actuation, a 200 pound calibrated drop weight is lowered on to the scale system, thus producing an overbalance condition. As the flow rate through the flowmeter proceeds, a second balance condition is attained which causes the final actuation of the switch sensing the beam pointer position. The initial and final capacitance switch actuations trigger a totalizing counter and standard timer to indicate the total output of the flowmeter undergoing test and the test time period.

Appendix 1 - cont'd

Following the completion of the calibration period, the 650 gallon tank is vented and the test fluid is transferred at a reduced flow rate through the transfer lines to refill the calibration tank in preparation for subsequent calibration tests.

The accuracy of the calibration system may be assessed by a combination of evaluation of all possible sources of error and the results obtained during the calibration of turbine type flowmeters.

The sources of error which contribute to the inaccuracies of the calibration system are scale repeatability, dynamic lag, standard weights, and extraneous loading of the scale system.

A. Scale System

The scale system is a specially designed mechanical beam balance scale capable of supporting the total system weight and possessing a sensibility reciprocal of less than one ounce. Since the scale system is used as a null balance device, the inaccuracy introduced by the scale may be attributed solely to the repeatability of the scale system. Static and dynamic tests of the scale system have indicated that repeatability of the scale is better than one ounce, thus producing an error at the initial and final balance points of ±0.03% for a 200 lb. weight change.

B. Dynamic Lag

The dynamic lag of the scale system may be predicted utilizing the techniques outlined in Reference

$$T = \left[\frac{6H\overline{W}}{Kg}\right]^{1/3} \qquad (1)$$

T = Actuation time of scale system (sec.)
H = Distance traveled by the beam pointer before actuation of the capacitance switch (ft.)
$\overline{W}$ = Gross system weight (lb.)
K = Flow rate (lb/sec)
g = Graitational constant (ft./sec./sec.)
W = Incremental error resulting from dynamic lag (lb.)

Based upon a capacitance switch sensitivity of 0.002", a repeatability of ±0.0012, and a flow control of ±2%, the error due to dynamic lag may be shown to be:

$$W = (102\%)(K)(T_1) - (98\%)(K)(T_2) \qquad (2)$$

where:

$$T = \left[\frac{6H_0\overline{W}(1+\Delta H/H)}{gK_0(1-\Delta K/K)}\right]^{1/3} \tag{3}$$

$$T = \left[\frac{6H_0\overline{W}(1-\Delta H/H)}{gK_0(\pm\ K/K)}\right]^{1/3} \tag{4}$$

Evaluation of the system parameters yields:

$\Delta H/H = (0.0012)/(0.002) = 16.7\%$

$\Delta K/K = 2\%$

$\overline{W} = 2000$ pounds

Substitution of equations (3) and (4) into equation (2) yields:

$$\Delta W = (0.05)(K_0)^{2/3} \tag{5}$$

ΔW = gravimetric error

The error for a total weight change of 200 pounds is:

$$\text{Percent error} = 2.5 \times 10^{-2}(K_0)^{2/3} \tag{6}$$

C. Standard Weights

The standard weights which are used in the calibration system have been calibrated to an accuracy of ±6 grains with a resultant error for each individual 50 pound weight of ±0.002%.

D. Extraneous Loading

The effects of horizontal and vertical loading of the scale system have been evaluated experimentally by the application of loads in excess of those encountered during system operation. This evaluation has demonstrated that the scale system performance is not degraded during operation by extraneous loading.

Appendix 1 - cont'd

E. Total System Accuracy

The total system accuracy may be established at a maximum flow rate of 300 pounds per minute as shown in the table below:

	Error(%)	$(Error)^2$
Initial scale balance	0.03	0.0009
Final scale balance	0.03	0.0009
Dynamic lag and capacitance switch	0.07	0.0049
Standard weight	0	0
Extraneous loading	0	0
Total:	0.13%	0.0067

Maximum error of ±0.13%
RMS error ±0.82%

The above error analysis indicates an expected performance in the order of ±0.1%. Actual operation of the system during the past 24 months period and numerous static and dynamic evaluations of the system substantiates the above analysis.

APPENDIX II

THERMAL ANALYSIS OF INSTRUMENTATION SUPPORT WITHIN A RAMJET ENGINE

P. CLINE, SUPV. ENGINEER, RSD - THERMODYNAMICS, VALLEY FORGE, PA.

Introduction

A thermal analysis was made of a total temperature on pressure probe located in the gas stream of a supersonic ramjet engine. The results of this analysis are reported within this appendix.

The probe was to be six inches long, of minimum weight and the cross-sectional area end was to be capable of withstanding the heating environment for at least 90 seconds without failure. The environment was to range from a Mach number of 5.5 at the inlet to 8 at the exit and the fuel (hydrogen) to air ratio could go as high as four times the stoichiometric values.

The results that are reported are those of a preliminary investigation of the problems. Before actual probes are manufactured and inserted into a ramjet, a more detailed analysis would have to be made, along with a rather extensive experimental program. Not only must the heat transfer to the probe be evaluated, but the increased heating to the walls of the ramjet engine must be determined.

Results

An ablative thermal protection system for the probe appears to be lighter in weight and simpler than either a transpiration or convective cooling system, if the cooling must be obtained from another source other than the hydrogen fuel for the engine. Since the possibility of using the fuel was ruled out, only the ablative system was analyzed. The results which follow are based upon using pyrolytic graphite as the ablation material. It was selected due to its low thermal conductivity in the "C plane" and its capability to withstand high temperatures with little mass loss. Therefore based solely upon thermal considerations, pyrolytic graphite appears to be an excellent choice of thermal protection materials. However, before a final selection could be made, it is necessary to consider manufacturability, thermal stresses and system compatibility.

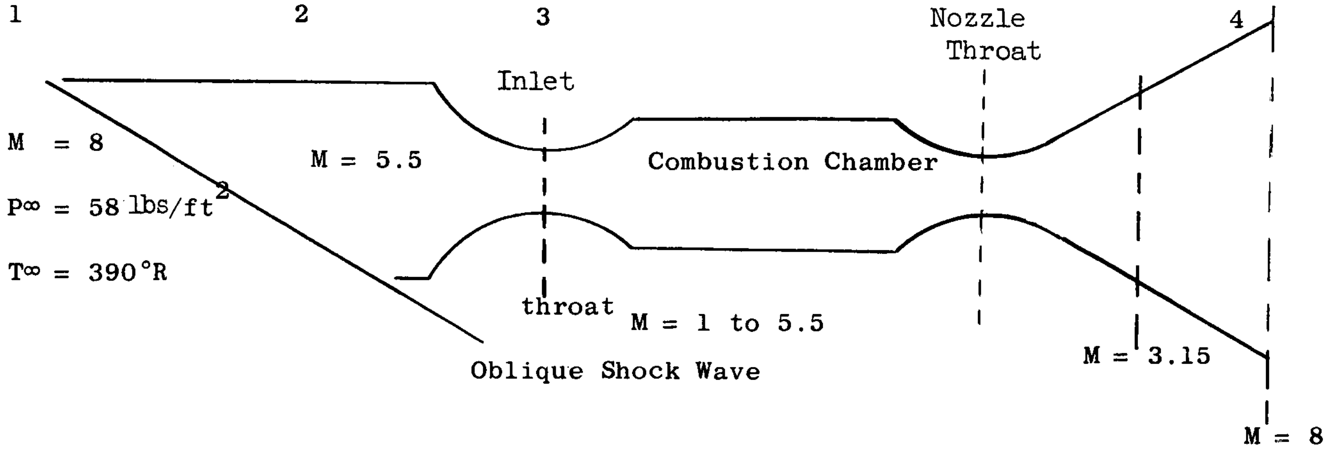
A sketch of the probe configuration is shown in Figures 1 and 2. The base of the probe has been curved outward to smooth into the wall of the ramjet in an attempt to reduce the high interaction heating observed at the base of fins attached to bodies in supersonic flow. Heat transfer to the surface adjacent to protuberance in supersonic flow has been investigated by Wisniewski (1), Bloom and Pallane (2), Warren, Harris and Kaegi (3) and Shaw and Nestler (4).

These tests indicated heat transfer rates to the surface adjacent to the protuberance were a factor of approximately 4-12 times the values predicted for an equivalent surface without the probe in the presence of a locally laminar boundary layer. The interaction heating to the adjacent surface is shown in Figure 3. The values plotted are the ratios of the actual film coefficients divided by the predicted film coefficients assuming laminar flow and no probe. This interaction heating may be decreased if the probe was like a swept protuberance rather than a vertical fin. By rounding the foreward base region of the probe as shown in Figure 1, a similar decrease in the interaction heating should be realized without having flow disturbances and separation shocks interact with the sensor as might happen if the entire probe was allowed to be at an angle of attack to the flow stream. The heating problem can be reduced by a factor of two. The actual flow performance around the probe would have to be evaluated in a wind tunnel test. The allowable size of the radius will depend on the height of the probe and upstream flow conditions. A summary of the thermal analysis is shown in Table 1. The convective heating (q_c) given in Table 1 is the theoretical stagnation line value assuming a zero wall temperature. The heating on the side of the probe is approximately 0.18 of the stagnation heating value. It has been found (Reference 4) that the actual heat transfer to a protuberance in hypersonic flow may exceed the theoretical value by a factor of 2 at the separation shock impingement point. The material temperatures given are those after 90 seconds of heating. Shown in Figure 4 is a typical set of temperature distributions within a probe at the stagnation point. The total gas temperature and/or heat transfer to the probe are sufficiently low for pyrolytic graphite that the computed mass loss due to ablation is insignificant. However, tests conducted by GE-RSD (Reference 4) have shown that severe erosion will take place at the intersection of the body and probe if there is a shape corner, this should be minimized due to the rounding of the base of the probe into the wall of the ramjet engine.

For the thermal analysis described here two thicknesses or probe radii have been considered: one having a total thickness at the sensor of one inch (this is the one shown in Figures 1 and 2) and the other one half inch thick. Each are adequate from a thermal standpoint provided the sensor tubes can be heated to the tube temperatures given in Table 1.

Discussion

The flow Mach numbers within the ramjet engine upon which the thermal analysis was based is shown in the following sketch:



The freestream temperature and pressure are those corresponding to an altitude of 80 thousand feet as taken from Reference 5. The conditions at station 2 were calculated assuming the flow had crossed an oblique shock of sufficient strength to decrease the flow Mach number to 5.5. The conditions at the throat were determined by allowing the air to be compressed isentropically to a Mach number of one. The heat addition within the combustion chamber and the flow conditions downstream of the chamber were determined from the Rayleigh Line Tables given in Reference 6. The properties of air at the various stations were determined from Reference 7 and those for the hydrogen air mixture were from Reference 8.

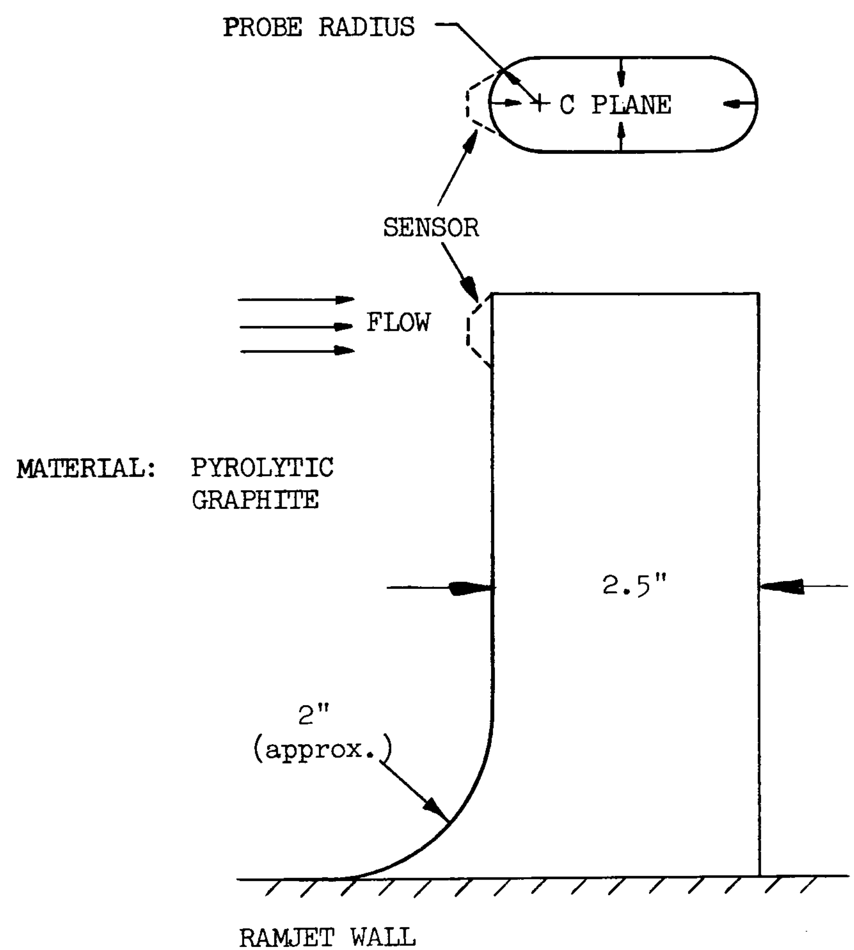
The heat transfer to the probe was determined using Lees' method modified by Echert's reference enthalpy tehcnique. The temperature response and ablation of the pyrolytic graphite was determined using the Reaction Kinetic and Ablation Program (Reference 9).

Conclusions and Recommendations

It appears that a pyrolytic graphite probe can be placed within a ramjet engine and it will last for at least 90 seconds. However, before an actual probe is designed it is necessary to investigate the possibilities of using other high temperature materials and an experimental program must be conducted to determine the extent of the interaction heating and to evaluate the flow disturbances caused by rounding the base of the probe.

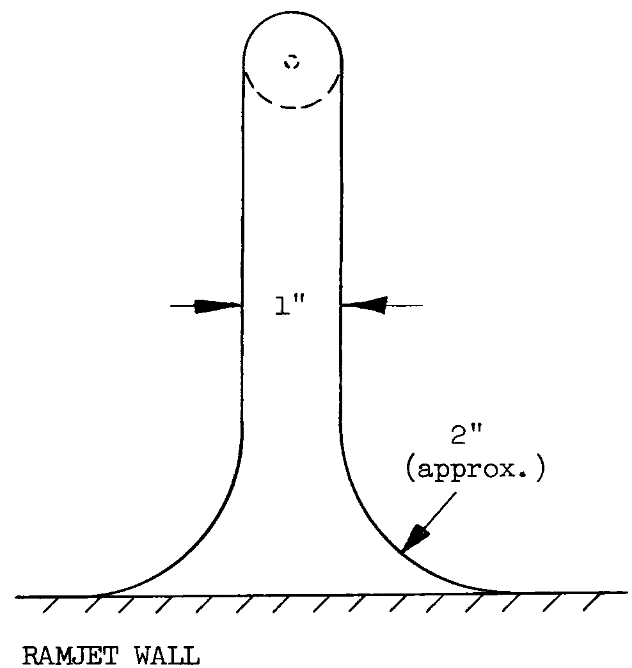
TABLE I

PROBE LOCATION	MACH NUMBER	TOTAL TEMPERATURE OR	TOTAL PRESSURE PSF	EQUIVALENCE RATIO	1/2 Inch Probe Radius			1/4 Inch Probe Radius		
					q_c (BTU/ft^{2}sec)	$T_{surface}$ (°R)	T_{tube} (°R)	(BTU/ft^{2}sec)	$T_{surface}$ (°R)	T_{tube} (°R)
Inlet	5.5	4400	13950	0 (Air)	386	4093	1170	547	4120	1870
Throat 1	5.5	4400 to 4500	13950 to 171000	0 (Air)	386 to 33.6x10^3	4093 to 4253	1170 to 1195	547 to 47.5x10^3	4120 to 4330	1870 to 1915
Nozzle	8	6610	6.82	4	25.9	5720	2330	36.8	5890	2920
Nozzle	3.15	6240	2055	1	409	5830	2410	578	5960	2990



SIDE VIEW OF RAMJET SENSOR PROBE

FIGURE 1



FRONT VIEW OF RAMJET SENSOR PROBE FIGURE 2

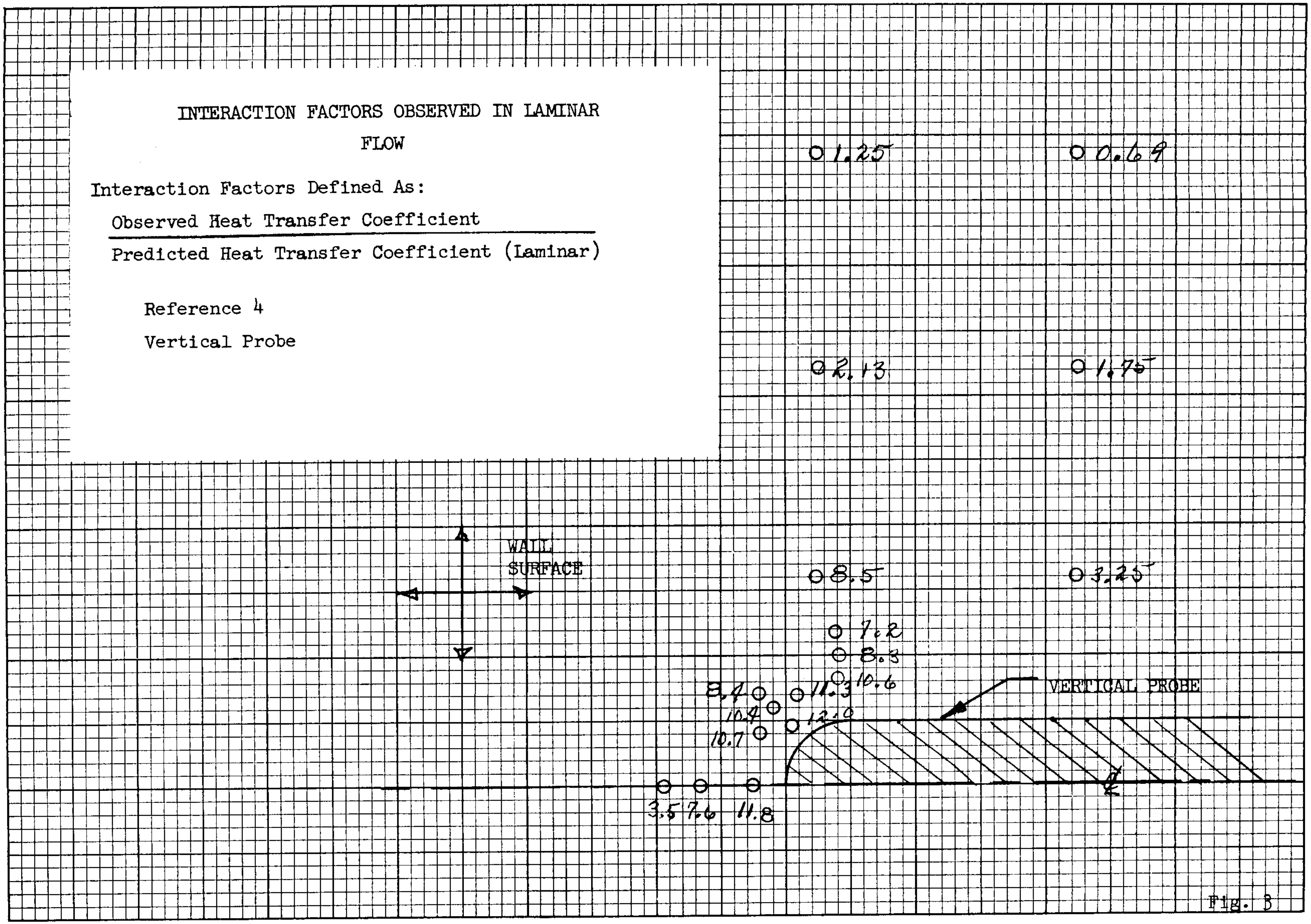
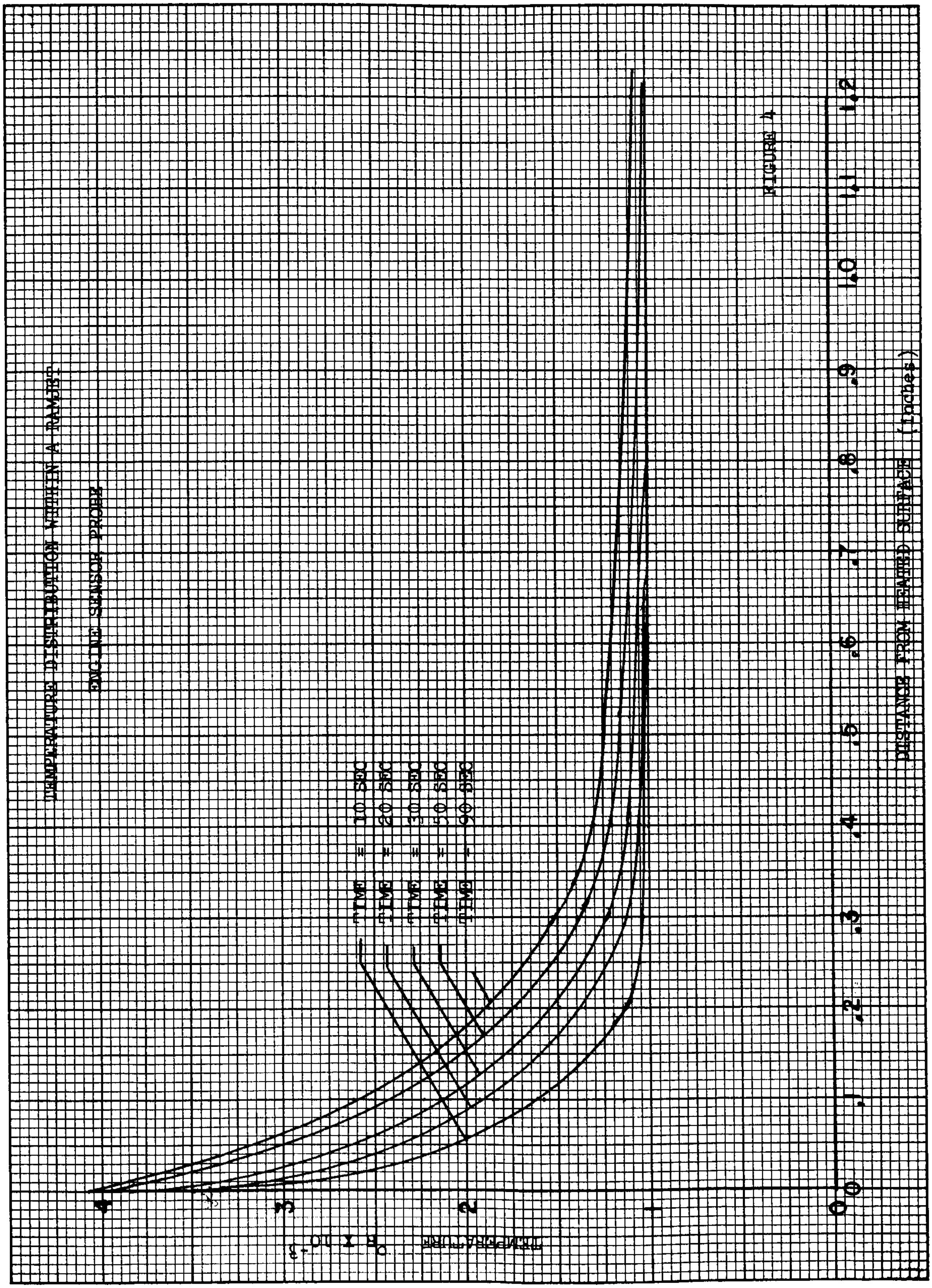

INTERACTION FACTORS OBSERVED IN LAMINAR FLOW
Interaction Factors Defined As:
Observed Heat Transfer Coefficient / Predicted Heat Transfer Coefficient (Laminar)
Reference 4
Vertical Probe
WALL SURFACE
VERTICAL PROBE
1.25
0.69
2.13
1.75
8.5
3.25
7.2
8.3
10.6
11.3
12.0
8.4
10.4
10.7
3.5
7.6
11.8

Fig. 3


TEMPERATURE DISTRIBUTION WITHIN A RAMJET
ENGINE SENSOR PROBE
TIME = 10 SEC
TIME = 20 SEC
TIME = 30 SEC
TIME = 50 SEC
TIME = 90 SEC
FIGURE 4
TEMPERATURE °R X 10-3
4
3
2
1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
DISTANCE FROM HEATED SURFACE (inches)

References

1. Wisniewski, R. J., "Turbulent Heat Transfer Coefficients in the Vicinity of Surface Protuberances", NASA Memo 10-1-58E, October 1958.

2. Bloom, M. and Pallone, A., "Investigation of Heat Transfer Coefficients in The Vicinity of Circular Cylinders on a Flat Plate," Heat Transfer and Fluid Mechanics Institute, 1957.

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7. Moeckel, W. E., and Weston, K. C., "Composition and Thermodynamic Properties of Air in Chemical Equilibrium", NASA TN 4265, 1958.

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APPENDIX III

RAMJET SENSOR PROBE STRENGTH AND VIBRATION - J. MCGLINCY, S. BENNET AND T.E. HESS, STRUCTURAL MECHANICS TECHNOLOGY COMPONENT MISSLE AND SPACE DIVISION, PHILADELPHIA, PA.

Thermostress Considerations

A preliminary study was conducted in order to determine feasible structural approaches to the subject casing. Thermodynamics studies defined the need for a low conductivity material, such as pyrolytic graphite. This is considered necessary in order to maintain a relatively moderate operating temperature environment for the stainless steel probes.

Figure I shows representative temperatures of a pyrolytic and a commercial grade graphite (ATJ) casing. These temperatures are shown as a function of distance from the heated, or forward, surface.

Three materials concepts were determined to be feasible. These are shown in Figure 2. The first configuration was made by depositing pyrolytic graphite in the elliptical form indicated. While this procedure is not beyond the state of the art, it is not an off the shelf item and some developmental work would be necessary. It is expected that a considerable amount of random delamination would occur, however, the piece, as shown, would be expected to maintain its integrity under thermal and pressure loadings for the duration of the test. The delamination anticipated may however create problems under the dynamic load environment or by the impingement of foreign particles (if this latter condition is probable).

Configuration 2 is also a pyrolytic graphite composition; however, in this case the casing has been machined from two flat plates. The thickness of the forward piece would depend on the temperature requirements at the bond line. The bond line temperature can be controlled by tailoring the thickness (x) of the front plate. The minimum temperature possible (from figure 1) is 600^{o}F using a .60 inch thick plate. This is within the usable range of C-10 bonding cement. In fact, a higher bond temperature is feasible and therefore a thinner plate may be used.

A third configuration, similar to the second, but fabricated from a solid piece of ATJ graphite was investigated. The temperature at the inner surface dut to the higher thermal conductivity of ATJ. A preliminary thermal stress analysis of a 1/2 inch deep beam using the ATJ temperatures of Figure 1 indicates marginal performance. This assumes internal support is provided to help withstand bending forces. The internal temperature can also be expected to be approximately 2000^{o}F - a rather severe environment for the probe tubes.

As previously shown, each of the three concepts have inherent advantages and disadvantages. The preliminary evaluation described herein, however, indicates an advantage to the pyrolytic graphite plate approach. This approach provides the preferred orientation of P. G. where needed, can be more easily fabricated and adapt to an internal support structure readily. Design development, fabrication and test studies are, however, necessary for this structural concept.

Vibration Considerations

The subject probe will encounter severe dynamic excitations during the test run, and this fact must be taken into account during the design phase.

The probe may be treated analytically as a cantilevered beam clamped to the wall of the ramjet. The cantilevered beam configuration has been analyzed for almost any class of loading functions, by either exact or approximate techniques.

The dynamic loading of the probe will include both deterministic and random excitations. The more important sources include:

1. Excitation due to motion of ramjet wall. Presumably the limits of this excitation are given by Section 5.9.1 of the Study Work Statement (50G from 200-2500 cps steady state harmonic + 200G step pulse). Standard techniques of solution are available for these problems. See, for example, References 1, 2, and 3.

2. Excitation due to boundary layer turbulence on the surface of the probe. This excitation is random in amplitude and occurs across a wide frequency band. The pressure fluctuations are usually uncorrelated over any significant structural lengths. This problem has been solved in the technical literature if the power spectrum of the pressure fluctuations can be determined. See Reference 4.

3. If the probe is mounted down stream of the combustion area the possibility of vibration due to combustion instability exists. This is also a random excitation and it too can be solved providing the power spectrum of the excitation is known. For this problem the correlation factor over the length of the beam is unity. This is a special case of the uncorrelated fluctuation and has also been solved. See Reference 5.

4. The possibility of shock oscillations near the tip of the probe where there is a structural discontinuity exists. This shock can interact with the turbulent boundary layer and cause a boundary layer separation which will also induce an oscillatory response. This is another random process which can be analyzed if the power spectrum of excitation is known.

5. If the probe is mounted down stream of the combustion area, uneven heating of probe during the start up transient stage of operation could cause a boundary layer separation and subsequent dynamic loading.

6. Another source of vibration arises from the possibility of the beam going into a flutter mode. The stability of the probe can be analyzed using standard techniques. See, for example, Reference 6.

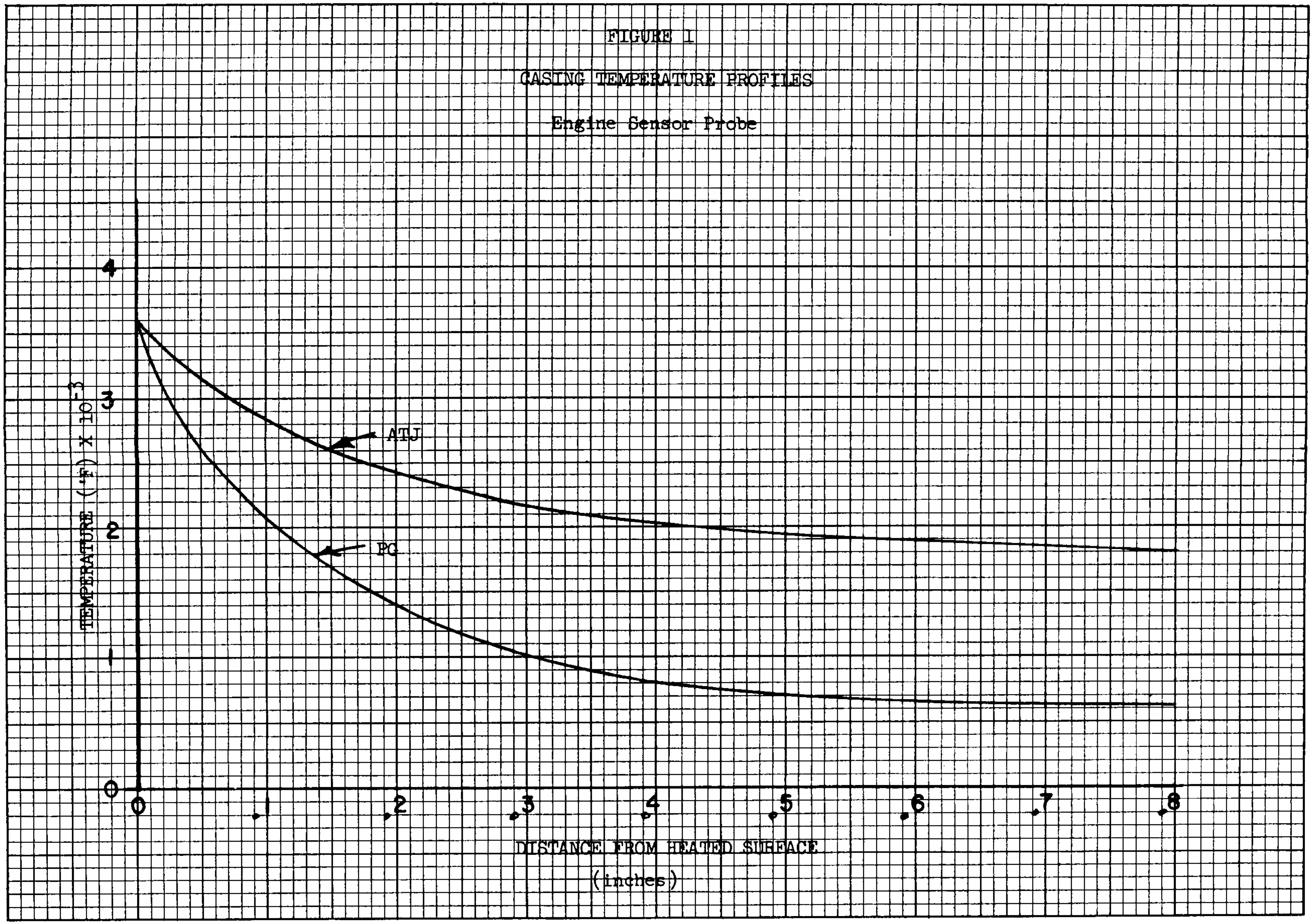
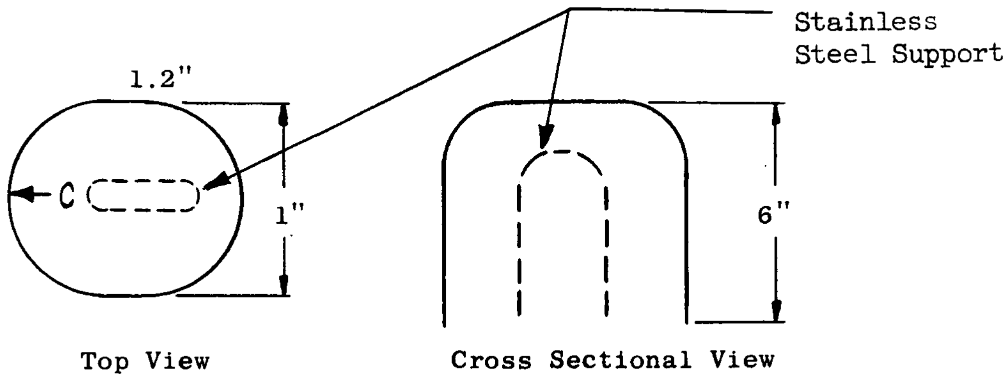


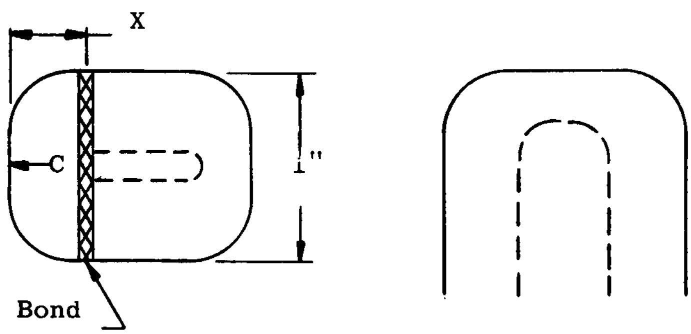
FIGURE 1
CASING TEMPERATURE PROFILES
Engine Sensor Probe
TEMPERATURE (°F) X 10^-3
4
3
2
1
0
ATJ
PG
0
.1
.2
.3
.4
.5
.6
.7
.8
DISTANCE FROM HEATED SURFACE
(inches)

CONFIGURATION I



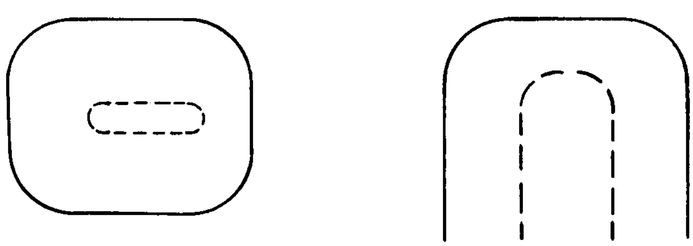
Pyrolytic Graphite

CONFIGURATION II



Pyrolytic Graphite

CONFIGURATION III



ATJ Graphite

Figure 2

References

1. Mindlin, R. D., and L. E. Goodman; "Beam Vibrations with Time-Dependent Boundary Conditions". Journal of Applied Mechanics, Vol. 17, #4, 1950.

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3. Eagle, H. A.; "TRAMP- A Digital Computer Program for the Transient Response Analysis of Lumped Parameter Systems," RDS 64SD529, February, 1964.

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5. Bennett, S. H.; "The Response of Structures to Random Excitation," RSD Struct. Mech. Tech. Memo No.8156-84, July, 1964.

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APPENDIX IV

Specifications for Metal Sheathed, Ceramic Insulated Thermocouple Wire

1. Purpose and Scope

   1.1 This instruction is to establish the limits of acceptability for the mechanical and electrical properties of metal sheathed, ceramic-insulated thermocouple wire used in the Flight Propulsion Division.

   1.2 The instruction shall pertain to that group of thermocouple materials employing a continuous integral sheath in which the thermoelectric element or elements are insulated from the sheath and each other by an inert metal oxide.

2. User's Option

   2.1 It shall remain the option of the user to specify the type of sheath material, thermoelements, insulation, length of material, nominal O.D. and shipping condition.

   2.2 Unless otherwise specified by the user, the following specifications will prevail.

3. Physical Properties

   3.1 Sheath

   3.1.1 The outside diameter of the sheath shall be held within the following limits in the finished product:

Nominal O.D.	O.D. Limits
.010"	.0095 - .0105"
.020"	.019 - .021"
.040"	.039 - .041"
1/16"	.0615 - .064"
1/8"	.124 - .127"
3/16"	.1855 - .190"
1/4"	.248 - .253"

   3.1.2 The sheath wall thickness shall be controlled to fall within the following limits in the finished product:

Nominal O.D.	Minimum Wall Thickness
.010"	X
.020"	.003"
.040	.006"
1/16"	.009"
1/8"	.011"
3/16"	.014"
1/4"	.020"

3.1.3 While seamless tubing is preferred for the sheath, it is not mandatory. Welded (drawn) tubing is quite acceptable.

3.1.4 The sheath surface shall be free from cracks and gouges and shall exhibit a finish of 32 micro-inches or better.

3.2 Thermoelements

3.2.1 The individual minimum wire gauge size for a two-conductor configuration shall conform to the following:

Nominal O.D.	B and S Gauge
.010"	X
.020"	38
.040"	34
1/16"	28
1/8"	22
3/16"	18
1/4"	16

3.2.1.1. The final surface condition of the contained conductors shall not have scratches, dents, pits, etc., greâter in depth than five percent of the starting diameter or 1.5 mils (0015") whichever is least.

3.2.2 Wires shall be uniformly spaced and centered throughout the length of the sheathed material.

3.3 Insulation

3.3.1 The insulation shall be electrical furnace-fused magnesium oxide (MgO) of minimum 99.1% purity with a boron content of no more than 30 parts per million by weight.

4. Electrical Properties

4.1 All conductors must exhibit complete continuity from end to end regardless of length, and shall not have a resistance deviation of more than ±10% from that calculated for the actual wire diameter, length, and resistivity of the material.

4.2 Insulation Resistance

4.2.1. Ambient:

4.2.1.1 The insulation resistance between wires and between wire and sheath shall not be less than 150 megohms per linear foot of material at 1.5 to 3 volts D.C.

4.2.1.1 (cont'd)

Note: The resistance per linear foot is determined by multiplying the resistance of "X" number of feet (meter indication) by "X", the length of the specimen.

4.2.1.2 For the .020 thermocouple wire, the insulation resistance shall not be less than 100 megohms per linear foot.

4.2.1.3 For the .010 diameter thermocouple wire, the insulation resistance is still experimental.

4.2.2 High Temperature

4.2.2.1 All sizes of sheathed thermocouple material of 1/16 O.D. and larger shall exhibit a minimum average insulation resistance between sheath and wire and between wires of 100,000 ohms with an applied potential of 1.5 volts D-C when 12 inches of the specimen, open-circuited, is elevated to a temperature of 1500°F.

4.2.2.2 For the .040 O.D. thermocouple the resistance shall be 40,000 ohms when tested under the conditions of paragraph 4.2.2.1.

4.2.2.3 For the .020 thermocouple wire, the resistance shall be 30,000 ohms when tested under the conditions of paragraph 4.2.2.1.

4.2.2.4 Copper-Constantan is excluded from this test.

4.3 Thermoelectric

4.3.1 The thermoelectric elements will have been annealed and aged to the extent that they will meet the thermoelectric specifications of the Instrument Society of America's Recommended Practice, ISA RPI.3.

4.3.2 When checking calibration of the thermelements, a sample piece of wire three to five feet long from each spool or roll shall be used.

4.4 Spurious EMF

4.4.1 The final product is to be treminated with an ambient junction and reference. (See sketch) It is then to be heated along its length with a 1500°F sharp gradient (approximately 1/2 to 1-1/2 inch). Under this impetus, the wire shall not produce a spurious EMF greater than:

continued....

Appendix IV - cont'd

4.4.1.1 ±100 microvolts for chromel-alumel (ISA-K)

4.4.1.2 ± 25 microvolts for platinum-platinum rhodium 10%(ISA-S)

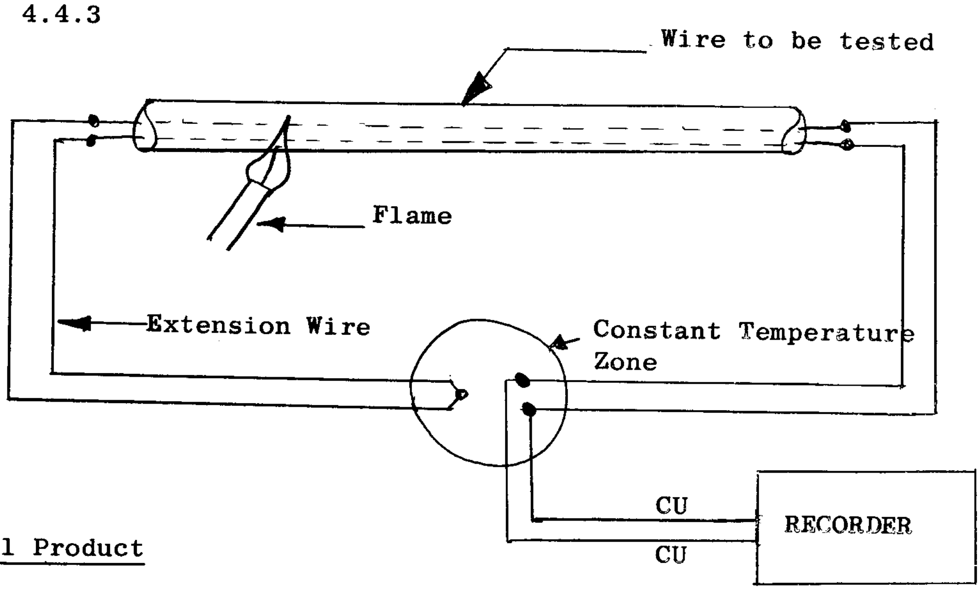
4.4.1.3 ±100 microvolts for iron-constantan (ISA-J)

4.4.1.4 ±100 microvolts for Platinel II

4.4.1.5 ±100 microvolts for chromel-constantan

4.4.2 Vendor substantiation certificate required that all wire shipped has been checked to meet paragraph 4.4.1.

4.4.3



5. Final Product

5.1 All metal sheathed thermocouples shall be fully annealed (air or bright anneal).

5.2 Materials as received must be capable of bending 360° around a mandrel diameter equal to three times the sheath nominal outside diameter without loss of insulation resistance or fracture of the sheath.

5.3 A sample end of metal sheathed thermocouple material, dressed square, shall be firmly clamped vertically at a point 12 diameters above the dressed end. There shall be no appreciable fallout of the insulating material when the O.D. of the dressed end is subjected to repeated taps of sufficient force to visibly move the dressed end at least one half of the sheath diameter.

5.4 All exposed ends shall be sealed with a waterproof electrical compound which shall be cured or dried to a hard form bonded securely to the sheath.

Appendix IV - cont'd

6. Shipping

6.1 All material of sufficient length shall be shipped in coils, the diameters of which will be no less than shown in the following table:

Nominal O.D.	Coil Diameter	Preferred Length	Minimum Length
.010	Convenience	X feet	3 feet
.020"	20"	60 feet	20 feet
.040"	20"	60 feet	30 feet
1/16"	24"	60 feet	60 feet
1/8"	30"	60 feet	60 feet
3/16"	48"	X feet	10 feet
1/4"	60"	X feet	10 feet

6.2 Coils are to be held together in at least four places by reinforced paper or plastic ribbon.

7. Identification

7.1 Each piece shall be identified as to:

Sheath Material
Sheath O.D. (Nominal)
Type of Insulation
Thermoelement Identification
Size of Thermoelements
Length
Manufacturer's Name