UNCLASSIFIED

AD NUMBER
AD829143
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAR 1968. Other requests shall be referred to Arnold Engineering Development Center, Arnold AFS, TN 37389. This document contains export-controlled technical data.**
AUTHORITY
AEDC ltr, 23 Jan 1975

THIS PAGE IS UNCLASSIFIED

AEDC-TR-68-44

PROBING TECHNIQUES FOR USE IN HIGH TEMPERATURE REACTING FLOWS

R. P. Rhodes

ARO, Inc.

March 1968

This document has been approved for public release its distribution is unlimited.

Per AF Letter dtd 23 Jun. 75 signed William O. Cole

~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389.~~

ROCKET TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

PROBING TECHNIQUES FOR USE IN HIGH TEMPERATURE REACTING FLOWS

R. P. Rhodes
ARO, Inc.

~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389.~~

[illegible] ase
[illegible] mited.

Per AF Letter
dtd. 23 Jan. 75
Signed William O. Cole

AF - AEDC
Arnold AFS Tenn

FOREWORD

The work reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 6540215F, Project 4344, Task 434424.

The results of research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract AF 40(600)-1200. The research was conducted from July 1965 to December 1967 under ARO Project No. RW5803, and the manuscript was submitted for publication on January 30, 1968.

The author wishes to acknowledge the assistance of John Bartlett, Walter Delashmit, Gary Smith, Gerald White, and David Wright, who assisted in obtaining the experimental results shown in this report.

~~Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This report may be released to foreign governments by departments or agencies of the U. S. Government subject to approval of the Arnold Engineering Development Center (AETS), or higher authority within the Department of the Air Force. Private individuals or firms require a Department of State export license.~~

This technical report has been reviewed and approved.

Ian F. Flemming Captain, CAF Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

A basic probe has been designed which consists of a 1/8-in.-diam, water-cooled copper probe with an inside diameter of 0.050 in. These probes may be aspirated to take a gas sample and temperature reading, or used without aspiration to measure total pressure. Two systems currently being investigated to measure temperature are quartz-coated thermocouples and pneumatic thermometers. These probe designs were chosen because they should not include the heat of recombination of non-equilibrium gases in the temperature reading as would a calorimeter-type total enthalpy probe. The gases are analyzed on line with a bistable fluid oscillator having an oscillation frequency that is a function of the molecular weight of the sample. No quantitative theory of fluid oscillators is available; however, observations are given of the effect of some of the design parameters on performance. A study was made of the effect of probe shape and Mach number on the validity of samples taken in a supersonic stream. For hydrogen-nitrogen mixtures at a static pressure of 1 atm, no change between the free stream and the sample was seen in any of the tests.

~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389.~~

Per AF letter dtd
23 Jan., 75 signed
William D. Cole

CONTENTS

APPENDIXES

I. ILLUSTRATIONS

II. TABLE

NOMENCLATURE

A	Effective orifice area
C	Mass fraction
C_p	Specific heat
$f(\gamma)$	Flow function for choked flow, $\frac{\gamma}{R}\left[1+\frac{\gamma-1}{2}\right]^{-\frac{\gamma+1}{\gamma-1}}$
M	Molecular weight
P	Pressure
R	Universal gas constant
T	Temperature
t	Time
u	Velocity
V	Volume
$\dot{w}$	Probe mass flow rate
γ	$C_p/(C_p - R)$, ratio of specific heats
ϕ_α	$(\alpha - \alpha_{\text{unreacted}})/(\alpha_{\text{equilibrium}} - \alpha_{\text{unreacted}})$ where α is any property

SUBSCRIPTS

T	Total
1	Upstream
2	Downstream

SUPERSCRIPT

—	Average

SECTION I
INTRODUCTION

A knowledge of the fluid dynamic and chemical properties of gaseous combustion products is essential to the analysis of many systems where temperature, pressure, and composition fields occur which cannot be predicted theoretically. In general, no significant progress can be made in turbulent reactive mixing until more experimental data are available to guide the development of theories. These problems include:

1. Rocket nozzle boundary layers - where it is desired to evaluate boundary-layer losses. Existing boundary-layer calculations may not be sufficiently accurate when the flow is turbulent with a pressure gradient, has heat transfer, and is in an unknown chemical state.
2. Rocket exhaust plume mixing zones - where the amount of mixing with ambient air cannot be calculated and the chemical state of the mixing layer is unknown. This information is necessary to calculate the radiation from interfacial burning.
3. SCRAMJETS - where vehicle evaluation depends on a knowledge of fuel distribution and the state of the chemistry. Here no calculation procedures exist to provide this information.

The objective of this work is to develop techniques to measure fluid properties in high-temperature, high-speed reacting flows. Specifically, emphasis has been placed on the diagnostics of turbulent mixing zones, where the significant properties are time mean average density, velocity composition, and enthalpy. The choice of these properties is dictated by a desire to evaluate mixing data using the conservation equations (momentum, enthalpy, and elemental composition). The direct measurement of these properties is, however, not necessary since they may be calculated from any four nonredundant properties; for example, total pressure, static pressure, elemental composition, and temperature.

The choice of techniques to measure gas properties is dictated by physical considerations and by the range of properties to be measured. The physical considerations are:

1. In mixing systems, it is desired to meaningfully measure gradients of velocity up to 10,000 ft/sec/in. with comparable temperature and density gradients. Static pressure gradients may be very large around shock waves and expansion fans but in many systems can be assumed to be relatively small although not negligible compared with the stream momentum gradients. Therefore, small probes or other high resolution methods are necessary, and all the properties should be defined at one point to avoid the problem of spatially matching several measurements. This is particularly true when the desired properties must be calculated from a number of measurements.
2. Prandtl and Lewis numbers cannot, in general, be assumed to be unity so that equilibrium and frozen temperatures cannot be calculated from atomic composition or velocity.
3. The thermal effects of recombination must be accounted for if the technique stagnates the gas or exposes surfaces to mixtures not in equilibrium at the surface temperature.
4. The flow is turbulent with fluctuations in all properties; therefore, with time mean average measurements, care must be taken to avoid techniques which tend to weight averages toward high or low values.
5. The hardware geometry may be complex, and access to the point to be measured must be considered.
6. Because of the large number of points necessary to define a flow field, data must be taken rapidly, preferably on magnetic tape or on line to a computer so that it can be reduced automatically.

The instruments and techniques being considered here are to measure the properties of mixing zones between hydrogen and air or between mixtures of hydrogen (H_2), water vapor (H_2O), and nitrogen (N_2) (rocket exhausts) and air. The range of stream properties is:

1. Static pressure, 0.2 to 5 atm
2. Total temperature, up to 5500°R
3. Velocity, up to 10,000 ft/sec

Although it is desirable, it is not considered necessary that one instrument be able to cover this entire range.

The accuracy required in these measurements is dependent on their use. For example, a 100°R error at 2000°R would give a 5-percent error if used to calculate density and a 50-percent error in the rate of reaction $H + O_2 = OH + O$. If a large number of data points are used and the results smoothed, greater data scatter can be tolerated than if the result of a single point measurement is used. In either case, however, any consistent error is very undesirable.

A method of developing an instrument or technique is to determine by calculations whether it has a reasonable chance of success. These calculations must then be evaluated by preliminary experiments, which generally develop a number of problems that must be solved. The major problem in the work reported herein has been to provide a calibration source, i. e., a gas of known properties against which an instrument can be checked or calibrated. Several flat flame burners have been built in which the flame temperatures can be calculated from the fuel flow and heat loss measurements. Another approach has been to work on systems operating with different physical principles to determine if both methods give the same answer. This has not been successful because it is hard to get one system to work and so far nearly impossible to get two. This method is, however, necessary if temperatures are to be measured where nonequilibrium chemistry is important because there is no known way to create a flow not at equilibrium with a known temperature.

Each of the systems which have been examined experimentally is discussed individually with regard to the considerations listed above. The theory of the technique and the experimental results are presented. A general discussion of the flat flame burners used for instrument checkout and calibration is also included. Data and calculations are shown which indicate the validity of using a burner of this type for calibration.

SECTION II
PROBE DESIGN

If a probe can be built to measure total pressure and total temperature and to take a gas sample, the flow field of a constant pressure mixing zone could be defined by these measurements within the limits of the following assumptions:

1. The flow through the shock wave ahead of the probe can be modeled, for example, by a real gas normal shock calculation.
2. The compression from the shock wave to the stagnation point can be modeled, for example, by an isentropic assumption.
3. The gas specific heat and molecular weight are a function of the local temperature and elemental species composition only.
4. Time mean average properties are determined from the measurements.
5. Gas samples are not changed in composition by the flow fields between a normal shock wave on the probe and the inlet to the probe.
6. The measured total temperature does not include the effect of recombination.

Items 1, 2, and 3 are interrelated in that on their validity rests the accuracy of the calculation of density and velocity from total temperature and total pressure. Calculations based on the kinetics of the H_2-O_2-N_2 system made at AEDC indicate that a chemically frozen real gas normal shock wave is an adequate approximation. For a shock stand-off distance of 0.005 ft, typical times to stagnation would be on the order of 5 μsec. In this time at pressures of 1 atm or less, very little total temperature change can occur from chemical reaction. The effect of mixing between the shock wave and the probe might be important if the gradients of concentration were high enough to set up strong shear flows behind the shock wave. No attempt has been made to analyze the deviation from isentropic flow between a shock wave and a probe, and it is mentioned here only to point out that it may limit the range of application of a total pressure probe in reacting shear flows.

An analysis has been made of the effect of the reaction model on the molecular weight and specific heat of reacting hydrogen air mixtures. This modeling is necessary since there does not at the moment seem to be any way in which a nonequilibrium composition can be measured. Therefore, some assumption is necessary to relate the molecular weight and specific heat to the temperature in a nonequilibrium mixture. Two possibilities suggest themselves. The first is to use a chemical kinetics program to compute the temperature-gas properties relationship for the particular enthalpy, stoichiometry, and pressure of interest. The second is to assume that the properties are linear between those of the gas at equilibrium and unreacted gas. These two examples represent the extreme between a premixed system where the composition is controlled by the kinetics and a mixing model where the gas consists of local cells of equilibrium mixture interspersed with unreacted gas. The second model implies a linear relationship between T, C_p, and M. These relationships between a nondimensional temperature and the nondimensionalized specific heat and molecular weight are shown in Fig. 1 (Appendix I) for H_2-air mixtures over a range of temperature and equivalence ratio. Neither of these two models is a true representation of a turbulent mixing zone. However, since they give such small differences in properties, nothing more complicated than a linear assumption can be justified, considering the lack of knowledge of the structure of a reactive mixing zone.

Item 4, the effect of turbulence on probe readings, cannot be checked in detail since it is strongly dependent on the amplitudes of the turbulent fluctuations which are not known. In addition, composition and temperature measurements require a detailed knowledge of the phenomena which are occurring to be able to determine the relationship between the measured property and the average property in the stream.

Item 5 is discussed in Section 4.1, and item 6 is discussed in Section III.

The first problem in designing a probe is to build a probe to withstand the thermal environment encountered in reactive mixing systems. Experience has shown that a probe to be used in a high heat load situation in an oxidizing atmosphere should be made from copper and be strongly water cooled. There are a number of approaches to this problem. If venting cooling water into the stream is permissible, adequate cooling can be obtained with the designs described in Refs. 1 and 2 and shown in Fig. 2. Both of these designs do, however, have a rather large ratio of frontal area to internal flow area because of the water in the stream.

A copper probe has been designed (Fig. 3) which has a completely enclosed cooling-water system. The standard size of this probe is 0.125-in. OD and 0.050-in. ID, and it can be made with a square or rounded tip with a full bore or orifice tip section (Fig. 4). Any of these probes will give a reasonably accurate total pressure reading although some nose shapes are more sensitive to flow angle than others. In this study, the choice of the nose shape has been dictated by the use of the probe as a thermometer as discussed in Section III. One of these probes was used in the Mach 3 exhaust of an H_2-O_2 rocket motor operating at an O/F ratio of 3.2, a chamber pressure of 300 psia, and a total temperature of about 5500°R. A probe of this type, built with an OD of 0.040 in. and an ID of 0.010 in., withstood the full flame of an acetylene torch when cooled with water at 600 psi. Probes smaller than 0.125-in. OD are very difficult to build, however, and do not have a large enough bore for a thermocouple. The standard probes are cooled with filtered demineralized water at pressures from 150 to 400 psi. For atmospheric pressure, H_2-air flames, a cooling-water pressure of 150 psi is adequate. No study has been made of the maximum cooling-water pressure which can be used, but only one failure has occurred from cooling-water overpressure. Before a demineralized water system was installed, the majority of the probe failures occurred because of deposits in the cooling-water passages.

There were two possible thermal failures which occurred inside the probes just downstream of the nozzle. This section is quite thin (0.010 in. as designed and less if the tube bore is not concentric) and subject to mechanical damage. However, when one probe was cut open, it looked as though flame erosion had occurred. Both these failures occurred after about one hour of operation in H_2-air flames (from 3000 to 4300°R). Another probe with an 0.030-in. nozzle inlet has been run four hours under the same conditions without failure.

SECTION III
TEMPERATURE MEASUREMENTS

Three important considerations to be taken into account when selecting a method to measure temperature in a turbulent reactive mixing zone are:

1. The high temperature,
2. The turbulent fluctuations of properties and the effect of turbulence on heat-transfer rates, and
3. The heat of recombination of the partly reacted mixture.

The high temperature precludes using a thermocouple operating near the stagnation temperature since there are no materials which will withstand oxidizing conditions and which will not melt well below the expected flame temperatures.

Turbulent fluctuations have two effects on the design approach. First, it is desirable to have a method where the measured quantity, from which the temperature is deduced, is nearly a linear function of the temperature itself so that the fluctuating terms do not tend to weight the readings toward high or low temperatures. Second, the highly turbulent flow makes any theory, at best, approximate so that calibrations are necessary.

When a dissociated gas sample is taken into a probe, it will recombine, and the heat of recombination will be transferred to the probe walls. To make a reading independent of the degree of dissociation, it is necessary to avoid techniques which depend on the measurement of this transferred heat. There does not seem to be any way of evaluating this effect except to build two temperature measuring devices operating on different physical principles and to compare the readings in equilibrium and nonequilibrium gases. This has not been done up to this time because of difficulties with the calibrations of the individual probes.

3.1 THERMOCOUPLE PROBES

By coating a thermocouple junction with quartz, it is possible to markedly reduce the recombination that occurs on the surface of the junction (Ref. 3). The recombination will occur elsewhere in the probe, but except for that which occurs in the gas phase ahead of the junction, none of the heat of recombination should affect the junction temperature. A probe of this type was tested in a reactive hydrogen-air mixing zone and compared with a bare wire thermocouple probe. The results are qualitatively shown in Fig. 5. In the unreacted part of the stream, the quartz-jacketed thermocouple showed a regular transition from the hot hydrogen core to the cold outside air, whereas the bare wire thermocouple had maxima where the potential for heat release existed but where reaction had not yet occurred. Farther downstream both curves were similar in shape, but the bare wire probe gave a higher temperature. Near the end of the flame, both thermocouples indicated essentially the same temperature. The two probes were calibrated against each other in a premixed H_2-air flame, so that if the mixing zone were in equilibrium, the two probes should give the same temperature. There was no absolute calibration on either probe; therefore, the absolute value of temperature is not known.

The quartz-jacketed probe design is shown in Fig. 6. This probe consists of a basic water-cooled copper probe shell containing a platinum/platinum - 10-percent rhodium thermocouple supported by an alumina two-hole insulator and covered by a quartz thimble. No particular attempt was made to prevent the quartz tube from touching the copper wall although minor irregularities will prevent good thermal contact. The probe is aspirated to the sample system where the flow is controlled by a choked orifice.

A typical calibration curve on the measured temperature against the calculated flame temperature is shown in Fig. 7. The data include hydrogen-air and hydrogen-oxygen combustion products at temperatures from 3000 to 4200°R. The gas temperature was obtained from an enthalpy balance around the burner as described in the section on the calibration system. The H_2-air data from this curve and other similar calibrations show a linear relationship between gas temperature and measured temperature for both rich and lean flames. There are insufficient H_2-O_2 data at this time to be sure, but these samples may give a somewhat higher temperature reading for a given gas temperature. This effect is not large since all the data can be fitted to a straight line with a maximum deviation less than 200°R. This would be a large deviation considering the chemical kinetics of the mixture, but in a fluid dynamic problem it would give about ±5 percent accuracy to a calculation of density.

The indicated temperature depends moderately on the flow past the thermocouple. This effect is shown for a different thermocouple probe of the same design in Fig. 8. Since the pressure at a choke point downstream of the thermocouple is a measure of the flow, this parameter can be used to evaluate scatter in the calibration data. Figure 9 is a graph of the choke point total pressure versus the measured temperature for the probe. These data show a similar scatter to the calibration curve without any particular point-to-point correlation, thus indicating that the scatter in the calibration data was probably not caused by mass flow fluctuations.

3.2 PNEUMATIC TEMPERATURE PROBES

The design of a pneumatic probe is shown in Fig. 10. This device contains two choked nozzles or orifices in series. The upstream nozzle is located at the probe tip, and the second nozzle is downstream at a station where the gas temperature is low enough to measure accurately with conventional thermometry. The temperature of the gas at the upstream orifice is calculated from the measured total pressures at the two nozzles and the temperature at the second nozzle using the one-dimensional mass continuity equation,

$$T_{T_1} = T_{T_2} \left(\frac{P_{T_1}}{P_{T_2}}\right)^2 \left(\frac{M_1}{M_2}\right) \left[\frac{f(\gamma_1)}{f(\gamma_2)}\right] \left(\frac{A_1}{A_2}\right)^2$$

Pneumatic thermometers of this type were developed in the late 1940's (Refs. 4 and 5). This idea is particularly interesting since

(1) the only temperature limit is in the design and cooling of the probe, and (2) if the change in molecular weight and γ can be accounted for, there seems to be no reason why this probe should not work equally well in equilibrium and nonequilibrium flow. This probe consists of a standard probe shell with an 0.020- to 0.030-in.-diam nozzle machined into the tip. An attempt is made to produce a smooth inlet with a short radius. There is no way to contour the nozzle exit section except to polish it to remove burrs formed in the drilling operation. The second nozzle is located in a constant temperature bath held at 200°F and is 12 to 18 in. downstream of the first nozzle. The probe is cooled with hot water so that there is no place in the system where water can condense from the combustion gases. The pressure just upstream of the second orifice is measured with a pressure transducer. As may be seen schematically in Fig. 10, if the valve (V_1) is open to vacuum and the three-way valve (V_2) to the transducer, the pressure transducer will measure P_{T2}. If V_1 is closed, the transducer will measure P_{T1}. The valve (V_2) may also be used to bypass the second orifice and provide a sample to the gas analyzer at a higher pressure than if the flow goes through the second orifice.

In spite of the apparent simplicity of this device, one major and several minor problems exist. The (A_1/A_2) term in the continuity equation is not a constant since it contains orifice coefficients as well as geometric areas. With this size orifice (0.020 to 0.040 in.), the diameter Reynolds numbers vary from a few hundred to a few thousand depending on the gas and the temperature. In this range, the orifice coefficient varies nonlinearly from 0.75 to 0.85 (Ref. 6), thereby causing changes in the effective area ratio. The effective area ratio may be calculated from the measured pressures and temperatures and the known gas temperature in the calibration burner by using the ratio of molecular weight times f(γ) calculated from the known gas properties. This parameter is shown in Fig. 11 as a function of gas temperature for rich and lean H_2-air mixtures and for very rich H_2-O_2 mixtures. There is a definite effect of composition on area ratio. An ideal probe would show no change in effective area ratio with temperature; however, it would be quite acceptable to have a variation with temperature which was not a function of composition. At this time, there does not seem to be any way to produce a general calibration curve for these probes since the functional form of the variation of effective area ratio with gas properties has not been found.

This problem is complicated by the possibility that heat can be removed from the front orifice making the flow thermally nondimensional and thereby making the flow coefficient vary with the heat transferred. This effect would be a complicated function of temperature and gas properties and would be added to the correction for nonuniform velocity profile which is given by the correlation between Reynolds number and orifice coefficient.

Another difficulty encountered was the change in effective area ratio resulting in a change of the size or shape of the front nozzle due to erosion from hot gases.

If the problems associated with variable nozzle coefficients could be corrected by a change in nozzle design, this probe still has some limitations. These are:

1. The pressure measurements must be very accurate because the two measured pressures appear as their ratio squared.
2. Water condensation in the probe can cause serious inaccuracies.
3. Some chemical reaction model must be assumed so that the molecular weight and specific heat can be specified as a function of temperature. This is not too serious a limitation since as shown in Section II these properties are relatively independent of the chemical model. There would be a catalytic burner between the two nozzles so that the gas at the second nozzle would be in equilibrium. An on-line gas analyzer would be necessary to obtain the overall stoichiometry.
4. With this probe design, care must be taken to prevent choking at some point between the two nozzles which would probably result in the nozzle on the probe tip running unchoked. This is a serious problem because it would probably occur only with some test conditions and is not detectable from the data analysis.

SECTION IV
COMPOSITION MEASUREMENTS

4.1 GAS SAMPLING

Two problems are associated with obtaining a gas sample in a flowing system. The first of these is the separation of low and high molecular weight species by the flow field behind a detached shock wave on a probe. A number of workers (Refs. 7 through 12) have reported this effect. However, no theory from which calculations can be made is available. As a result of this, a number of experiments were made with H_2-N_2 mixtures discharging to atmospheric pressure at several low supersonic Mach numbers. This range of Mach number and pressure is pertinent to other experiments being done at AEDC.

The apparatus is shown in Fig. 12. It consists of a bottle gas manifold in which the mixtures were prepared, a regulated flow system, a plenum and nozzle, and a sampling probe. Four different 0.125-in.-diam probes were investigated. These are shown in Fig. 13. Measurements were made of total pressure in the plenum, impact pressure measured by the probe, gas composition in the plenum, and gas composition in the probe. These compositions were deduced from measurements made with a fluidic oscillator which is described in Section 4.2. Although the absolute concentrations with various tests may not be exact, the change in oscillator frequency is a very reliable indicator of the change in composition. Table I (Appendix II) gives a summary of the results of these tests. In no case was any significant difference seen between the composition in the plenum and that in the probe. Most of the reported experiments in which this effect was seen were made at very low static pressure, and therefore, it may be concluded that this phenomenon is pressure sensitive and not important with probes of this size near 1 atm static pressure.

The second sampling problem results from fluctuations in concentration in the free stream ahead of the probe. The average concentration at a point in the free stream may be defined as

$$\bar{C} = \left(\int_0^t C\,dt\right)/t$$

whereas the average concentration of a sample is

$$\bar{C}_{\text{measured}}\Big| = \int_0^t C\,\dot{w}\,dt \Big/ \int_0^t \dot{w}\,dt$$

To evaluate this problem numerically, the flow to the probe must be modeled to get the instantaneous weight flow and also to obtain a distribution function for the fluctuations of weight flow and concentration. This has been done by very approximate methods and indicates that differences between $\bar{C}$ and $\bar{C}$ (measured) might be on the order of 1 percent of $\bar{C}$.

It should be noted that if the probe captures a stream tube equal to its total frontal area, then neither of these problems exists. This is not always possible since the probe tip design may be set by the temperature measuring function or cooling requirements.

4.2 GAS ANALYSIS

Two standard techniques are available for gas analysis: gas chromatography and mass spectrometry. Gas chromatography has the disadvantage of being slow. A minute or more is required for the analysis of even a simple mixture. A time of flight or a quadrupole mass spectrometer will give a very rapid analysis; however, the purge times on the vacuum chamber can be long, and water vapor is very hard to analyze accurately since it adsorbs on the chamber walls.

In many systems of interest, it is not necessary to know the complete composition. For example, in mixing zones between rocket exhaust gases and air, the gas properties which affect the fluid dynamics are defined if the percentage of exhaust gas and degree of reaction are known. For H_2-air and H_2-O_2 combustion products, the molecular weight will define the overall mixture ratio with adequate sensitivity.

The first method used to measure molecular weight was used for the analysis of cold H_2-air mixtures. It consisted of a nozzle and a tank in series as shown in Fig. 14. The weight flow through a choked nozzle is

$$\dot{w} = P_T \left(M f(\gamma)/T_T\right)^{1/2} A \tag{1}$$

and into the tank is

$$\dot{w} = \frac{d P_{tank}}{dt} \quad \frac{M V_{tank}}{R T_{tank}} \tag{2}$$

By equating the weight flow through the nozzle and that into the tank and solving for M,

$$M = \left[P_T/(dP_{tank}/dt) \; \frac{A R T_{tank}}{V_{tank}} \right]^2 \frac{f(\gamma)}{T_T} \tag{3}$$

The total pressure (P_T) and the rate of pressure change in the tank are measured. The rest of the terms are combined into a calibration factor which is nominally a constant (see Fig. 15). Some differences may occur in the effective area (A) because of the change in the nozzle coefficient when different gases are used.

A thermostatically controlled copper tube with a surface-to-tank volume ratio of about 6 in.^{2}/m^3 was placed in the tank to remove any possible heat of compression. Measurements of T_{tank} and T_T were made with fast response thermocouples and in no case changed during the fill time. A change in T_{tank} or M during the fill time would invalidate Eq. (3) by adding terms containing dM/dt and dT_{tank}/dt.

This system is simple to set up and operate. There are several disadvantages however. First, it is not a continuous process. The tank must be evacuated between tests. This limits the cycle time to about 1 per 10 sec. Second, it is difficult to measure the pressures with sufficient accuracy. Since the measurement depends on the square of the ratio of two readings, it is quite sensitive to errors.

A second technique which gives a measurement related to molecular weight is to use a fluidic oscillator that has been calibrated to relate the frequency of the oscillation to the composition. This method was used by Prokopius (Ref. 13) to analyze H_2-steam mixtures. The type of oscillator investigated in the work reported herein was based on a bistable fluidic amplifier connected with the output which was fed back to the control jets (Fig. 16). Although good qualitative descriptions of bistable fluidic amplifiers exist (Ref. 14), there is no quantitative theory that will predict the switching time and, therefore, the frequency of the oscillator. The approach to the design of a fluidic oscillator analyzer has been "cut and try." Some outstanding successes have been achieved, but so far it is not possible to describe an optimum configuration. Two basic configurations are shown in Fig. 16. These are (Fig. 16a) an unvented design with a hot-wire bridge detector and (Fig. 16b) a vented design with a pressure detector.

The parameters which have been found to affect frequency and stability (absence of random fluctuations in frequency) are vents, feedback loop length, back pressure valve setting, inlet pressure, oscillation detectors, temperature, and composition.

4.2.1 Vents

One unvented oscillator has been built. It will operate down to an inlet pressure level of 7 psia and is very stable (±1 Hz in 500 over a period of several hours). A duplicate of this model could not be made to operate at all.

The vented oscillators all have had a much wider range of oscillation in terms of input and back pressure but seem to be less stable.

4.2.2 Feedback Loop Length

This has a small effect on frequency since frequency seems to depend on switching time, which is quite a bit longer than the time it takes a pressure pulse to travel the return loop.

4.2.3 Back Pressure Valve Setting

The back pressure controls the pressure ratio across the inlet nozzle and has a large effect on the oscillator frequency. The unvented oscillator will run at only one setting. Figure 17 shows the frequency with air and helium as a function of back pressure for a vented oscillator.

4.2.4 Inlet Pressure

This parameter has a moderate effect on frequency and does affect the amplitude of the oscillation and also the presence or absence of oscillation. It is desirable to be able to operate with an inlet pressure as low as possible. If the probe must be operated choked, then this pressure cannot be more than one half the minimum total pressure in the system. Oscillators have been run as low as 3 psia; however at this pressure, they are very sensitive to changes, and the conditions cannot always be duplicated. At the present time, 6 to 7 psia seems to be the minimum pressure at which a unit can be expected to operate reliably. Figure 18 shows the effect of inlet pressure on frequency. Although this change is not large, it does require pressure control if the unit is to be used as an accurate analytical tool.

4.2.5 Oscillation Detectors

Two types of detectors can be used with fluid oscillators: velocity sensitive detectors and pressure pickups.

Velocity sensitive detectors (hot wires) may be used for frequencies up to 2000 Hz. Miniature light bulb filaments make very suitable hot-wire detectors. Four 28-v bulbs were wired as a Wheatstone bridge with two active legs formed by removing the glass from the bulbs and potting them into the feedback loops. The other two bulbs which form the dummy legs of the bridge are left enclosed. The bridge is excited with 1.5 v dc. A balancing resistor may be placed across one leg to reduce the direct current in the output. This is generally not necessary if the output is capacitively coupled to the amplifier. The only real disadvantage to this system is the low output (typically 30 μv, peak to peak). This requires a gain of at least 1000 before the signal can be discriminated. The low bridge impedance (about 100Ω) makes it fairly easy to eliminate pickup-induced noise. There seems to be very little inherent noise in the system, and the waveform is sinusoidal, which makes it easy to discriminate or count.

Two types of pressure transducers have been tried. The first of these was an earphone of the type used with transistor radios. It contains a permanent magnet, coil, and diaphragm and can be used in heated systems if the plastic case is removed and the parts are potted in a metal case. This device gives a reasonably large output and is simple to use since it requires only an amplifier. The major disadvantage is that it resonates at its natural frequency (about 2000 Hz) and requires the output to be filtered strongly to remove this component of the signal. The second transducer was of the variable capacitance type. It produces a large signal and has a frequency response flat to 10kHz. This becomes a disadvantage since the high frequency components in the pressure wave make the signal hard to count accurately. Neither pressure transducer is subject to pickup-induced noise, but all oscillation detectors should be filtered to remove noise and overtones that can make accurate counting impossible.

4.2.6 Temperature

It is desirable to be able to operate an analyzer at a temperature of about 600°R so that condensation of water from H_2-O_2 combustion does not occur. No detailed study of the effect of temperature on frequency has been made; however, the effect of a given percentage change in temperature should be the same as the same percentage change in molecular weight. A constant temperature box was built and heated by steam condensing at atmospheric pressure. This will give a variation of less than ±1°R (±0.2 percent with the normal variation of atmospheric pressure) and can be held much closer with a simple pressure control, or corrections can be made for changes in atmospheric pressure, assuming $\Delta T/T = -\Delta M/M$.

4.2.7 Composition

Figure 19 is a calibration curve of an unvented oscillator. There does not seem to be any simple, exact correlation between frequency and molecular weight, or speed of sound (γ/M), but the frequency of oscillation with a mixture of H_2 and air is nearly proportional to $(1/M)^{1/2}$.

SECTION V
CALIBRATION SYSTEM

The calibrations and evaluation of various probes are made by using a flat flame burner such as the one shown in Fig. 20. Hydrogen, air, and oxygen are supplied from pressure regulators and metered with choked orifices. The orifices are calibrated with a dry gas meter at the pressure levels used during the tests. The design flow gives a bulk gas velocity at approximately 50 ft/sec at the probe tip. The heat convected back to the burner grid is calculated from the burner cooling water flow rate and temperature rise. A combustion chamber section larger than the burner diameter and secondary air was found necessary to provide a stable flame.

A radial traverse of this burner was made 0.75 in. from the burner grid with the combustion chamber removed. Typical thermocouple probe outputs are shown in Fig. 21. There is in the burner an area of constant temperature with a diameter of 0.5 to 0.75 in. Axial traverses showed no gradient from 0.5 to 1 in. from the grid on the axis of the burner.

Figure 22 is a schematic of the measuring system used with the probes. This equipment is mounted in a box and heated with saturated atmospheric steam. The heating prevents condensation of any water at total pressures less than two atmospheres for H_2-air mixtures and for H_2-O_2 mixtures richer than twice stoichiometric. Also, all probe cooling water is heated to remove the possibility of condensation in the probe.

Pressures and temperatures are measured with pressure transducers and thermocouples and recorded on strip-chart recorders. The data taken consist of:

A. Probe Data
    1. The thermocouple temperature of a thermocouple probe
    2. The burner total pressure
    3. The total pressure downstream of the probe and upstream of any orifice
    4. The gas temperature at the orifice
    5. The oscillator frequency
    6. The rate of pressure change in the tank

B. Burner data
    1. Fuel and oxidizer orifice pressures
    2. Fuel and oxidizer temperatures

3. Burner grid cooling water flow
4. Burner grid cooling water temperature rise.

The flame temperature is calculated assuming the gases are in equilibrium with an enthalpy equal to the enthalpy of the supply gas minus the measured heat loss to the burner per pound of gas. It is estimated that these temperatures are correct to ±100°R. This error is the sum of fuel flow measurement errors, the nonequilibrium effects, the errors in heat loss, and radiation losses. The probe data give directly the temperature of a thermocouple probe and the pressure ratio of a two-orifice probe. The parameters which may be determined over and above the direct measurements given by the probe are:

1. Molecular weight of burned and unburned samples from the fuel flows or the oscillator.
2. Probe mass flow from the orifice or the rate of pressure change in the tank.

SECTION VI
SUMMARY

The objective of this report is to describe the status of research leading to measuring systems with small (0.125-in.-diam) probes that will measure total pressure and total temperature and will take and analyze gas samples in chemically reactive mixing zones. Physical probing was chosen to make these measurements because:

1. The large property gradients in mixing zones make it necessary to obtain all measurements, used in a given calculation, at one location in the flow field. This can be done most easily with a single multipurpose probe.
2. Probe measurements should minimize errors from turbulent fluctuations of composition, velocity, temperature, and pressure which are expected in the mixing zones.

The basic design consists of an 0.125-in.-diam water-cooled copper probe with an inside diameter of 0.050 in. These probes may be aspirated to take a gas sample and temperature reading or shut off to measure total pressure. A probe of this design was successfully used at Mach 3 in the exhaust of an H_2-O_2 rocket with a chamber pressure of about 300 psia.

Two systems are currently being investigated to measure temperature. These are:

1. Quartz-Coated Thermocouples. To survive the temperature being measured, the thermocouples must be cooled by conduction loss to the probes. Calibrations made on a flat flame burner indicate that the difference between the gas temperature and the thermocouple temperature is nearly independent of the composition of the gas and almost wholly dependent on the gas total temperature.
2. Pneumatic Thermometer. In this system, an orifice is placed at the tip of the probe, and a second orifice is located in the cooled flow downstream. The gas temperature is calculated from the continuity equation when the total pressure at the first orifice and the total pressure and total temperature at the second orifice are measured. A calibration is necessary because the area ratio between the orifices includes the orifice coefficients and cannot be calculated. This area ratio appears to be a function of composition because of the change in Reynolds number with a change in the gas. The effect makes it very difficult to obtain a calibration curve for this probe over a large range of composition. For nonequilibrium flow, it is necessary to establish a relationship between the temperature, molecular weight, and specific heat and to solve the continuity equation including these relations.

These probe designs were chosen because they should not include the heat of recombination in the temperature as a calorimeter-type total enthalpy probe would. The validity of this assumption has not been checked but could be by comparing the output of two measurements operating on different physical principles. Further work is necessary on both of these temperature measurement techniques before their accuracy and reproducibility is adequately defined. Specifically, calibrations should be made over a wider range of composition and pressure than has been done to date. Based on the results to date, the thermocouple probe appears to be the more satisfactory temperature sensing device.

The gases are analyzed on line with a bistable fluid oscillator with an oscillation frequency that is a function of the molecular weight of the sample. No quantitative theory of fluid oscillators is available; however, observations have been of the effect of some of the design parameters on performance. Further experimental work is necessary to define these parameters in more detail so that an optimum design can be selected.

A study was made of the effect of probe shape and Mach number on the validity of samples taken in a supersonic stream. For hydrogen-nitrogen mixtures at a static pressure of 1 atm, no change between the free stream and the sample was seen in any of the tests.

REFERENCES

1. Rhodes, R. P., Rubins, P. M., and Chriss, D. E. "The Effect of Heat Release on the Flow Parameters in Shock-Induced Combustion." AEDC-TDR-62-78 (AD275366), May 1962.
2. Peters, C. E., Peters, T., and Billings, R. B. "Mixing and Burning of Bounded Coaxial Streams." AEDC-TR-65-4 (AD458348), March 1965.
3. Swigart, R. W. "A Study of the Kinetics of the Hydrogen-Oxygen Reaction in a New Flow Reactor." AEL Report No. 432, Princeton University, 1958.
4. Moore, D. W., Jr. "A Pneumatic Method for Measuring High Temperature Gases." Aero Eng. Rev., Vol. 7, No. 5, May 1948, pp. 30-34.
5. Blackshear, P. L. "Sonic Flow Orifice Temperature Probe for High Gas Temperature Measurements." NACA TN 2167, September 1950.
6. Bloom, G. "Errorless Orifices." Product Engineering, October 25, 1965, pp. 61-64.
7. Reis, V. H. and Fenn, J. B. "Separation of Gas Mixtures in Supersonic Jets." J. Chem. Physics, Vol. 39, 1963, pp. 3240-3250.
8. Waterman, P. C. and Stern, S. A. "Separation of Gas Mixtures in a Supersonic Jet." J. Chem. Physics, Vol. 31, 1959 pp. 405-419.
9. Stern, S. A., et. al. "Separation of Gas Mixtures in a Supersonic Jet II: J. Chem. Physics, Vol. 33, 1960, pp. 805-813.
10. Chow, R. R. "On the Separation Phenomenon of Binary Gas Mixture in an Axisymmetric Jet." University of California, IER Tech. Report HE-150-175, November 1959.
11. Kogan, A. J. Int. Heat Mass Transfer, Vol. 9, 1965, pp. 1-10.

12. Alpinieri, L. J. "An Experimental Investigation of the Turbulent Mixing on Non-Homogeneous Coaxial Jets." PIBAL Report 789, August 1963.

13. Prokopius, P. R. "Use of a Fluidic Oscillator as a Humidity Sensor for a Hydrogen-Steam Mixture." NASA TM X 1269, August 1966.

14. Kirshner, J. M. Fluid Amplifiers, McGraw-Hill Book Company, New York, 1966.

APPENDIXES

I. ILLUSTRATIONS
II. TABLE

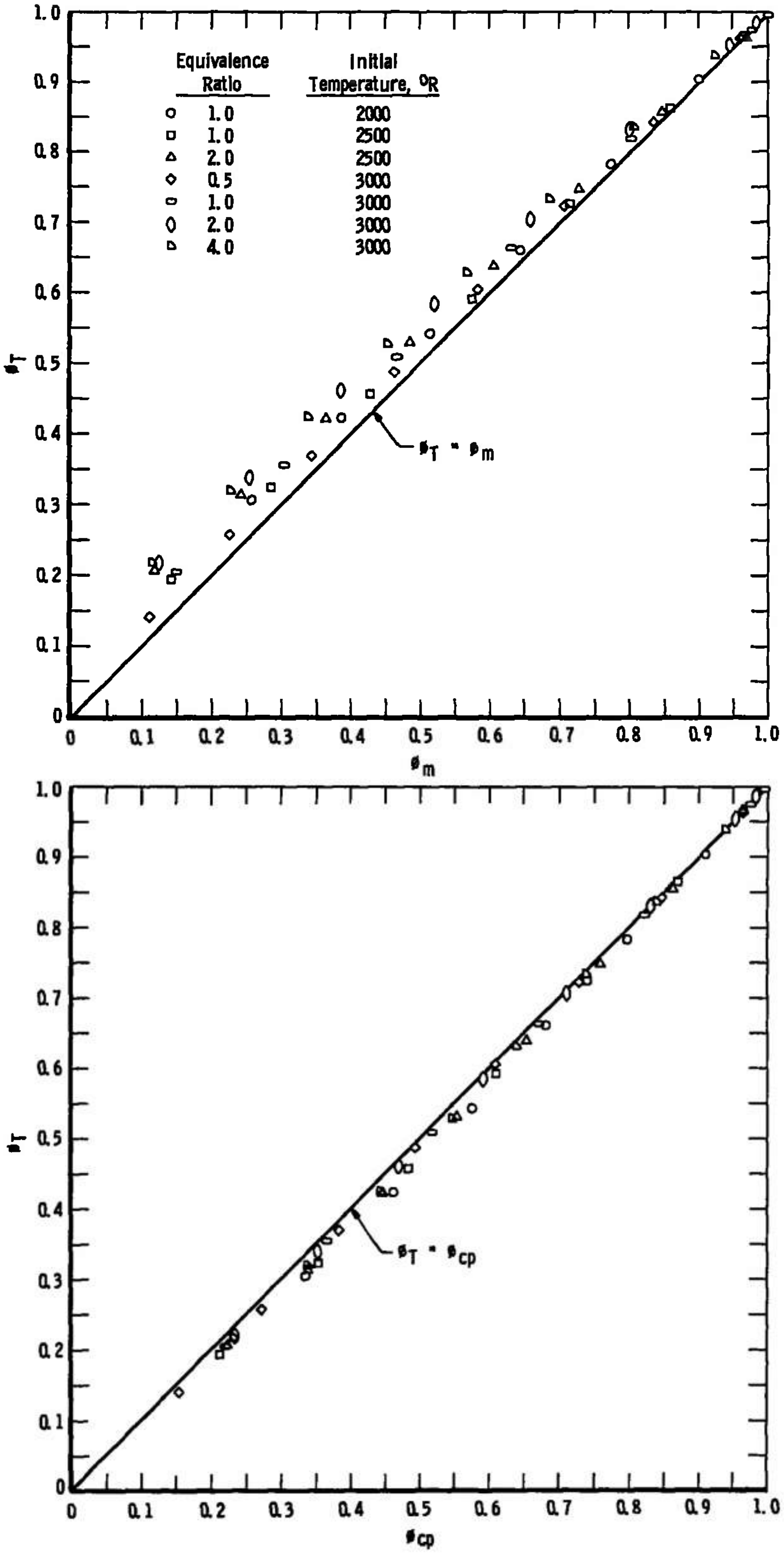
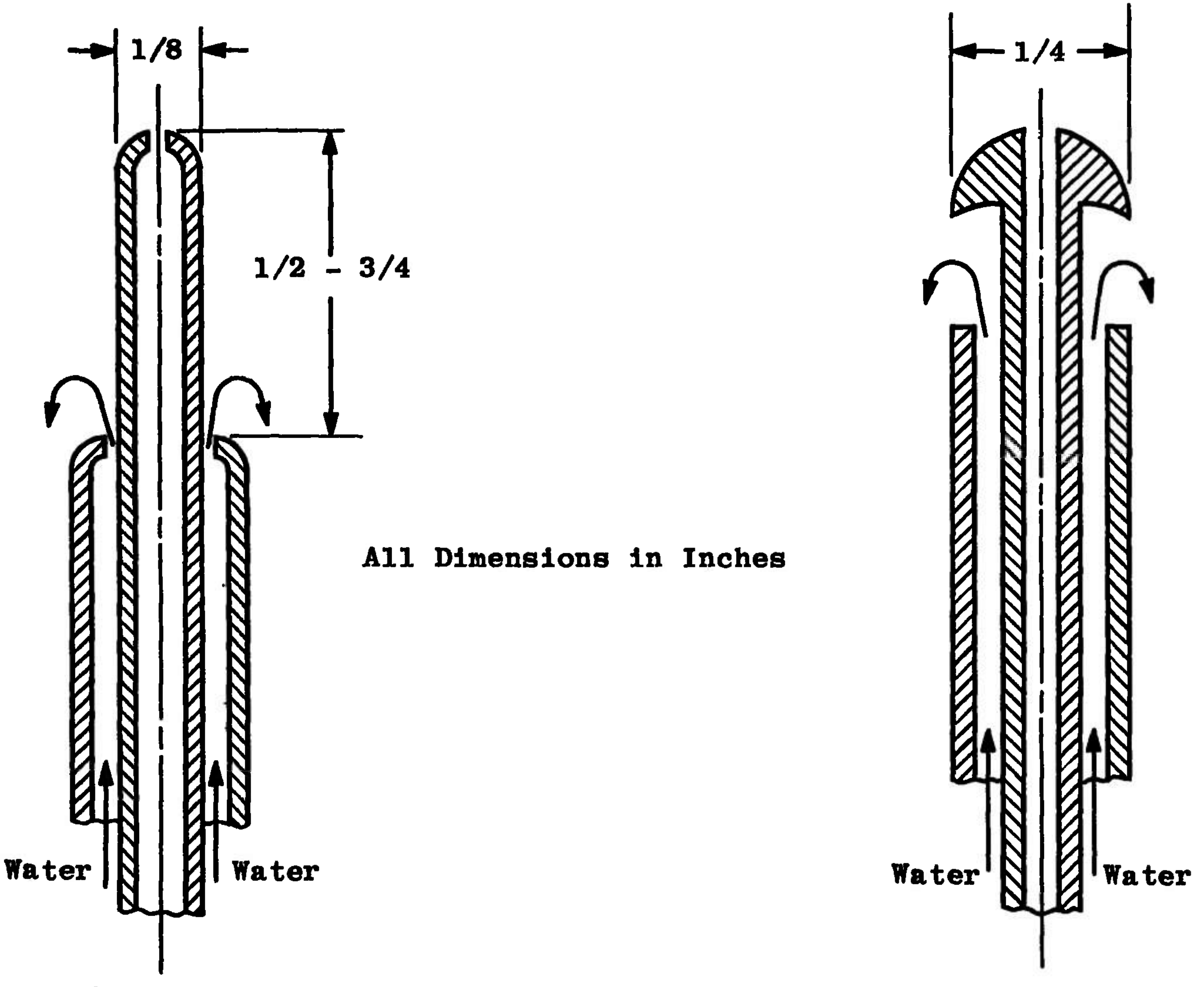


Fig. 1 Nonequilibrium Properties of H_2-Air Mixtures



(Ref. 1)

(Ref. 2)

Fig. 2 Probe Configurations with Vented Cooling Water

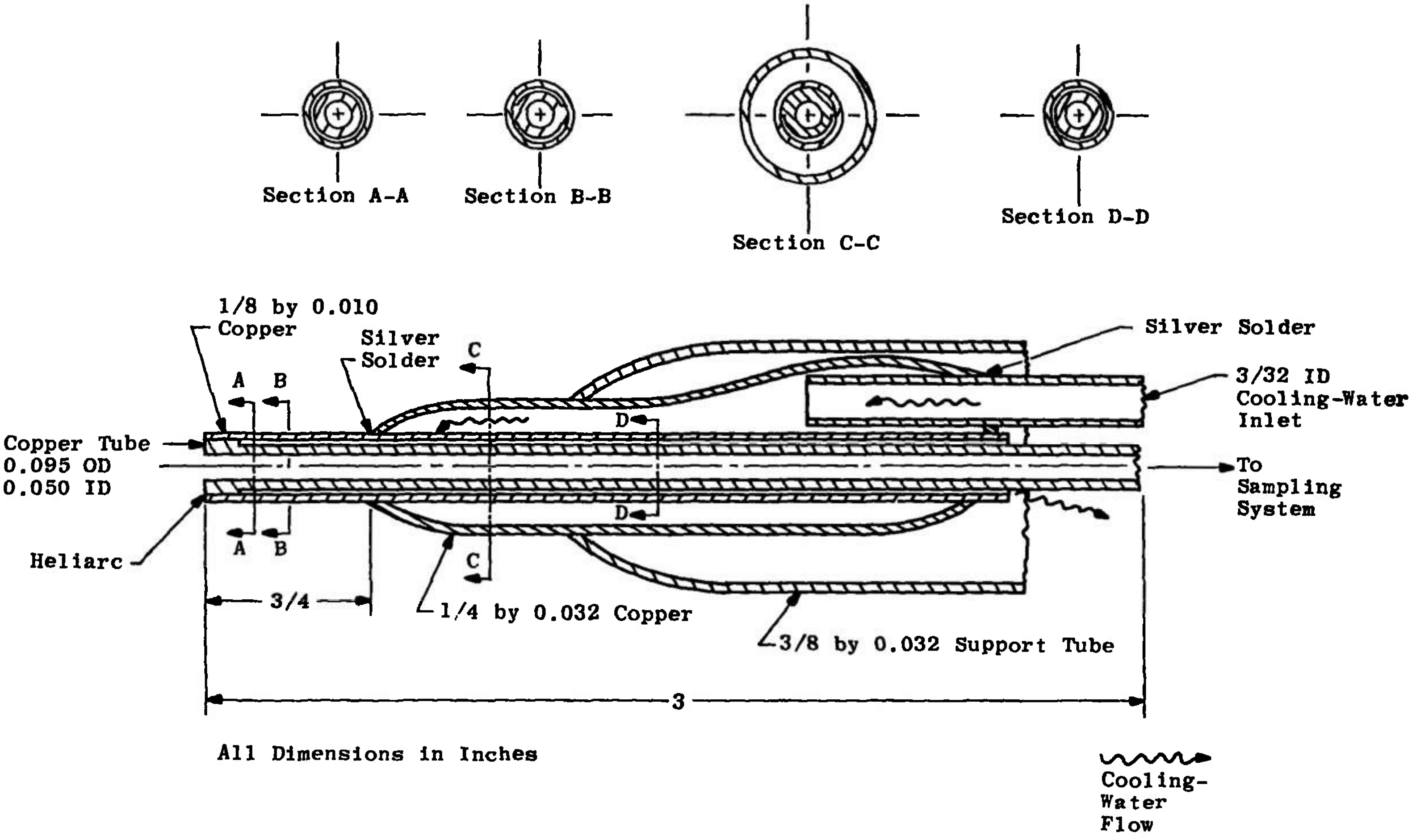
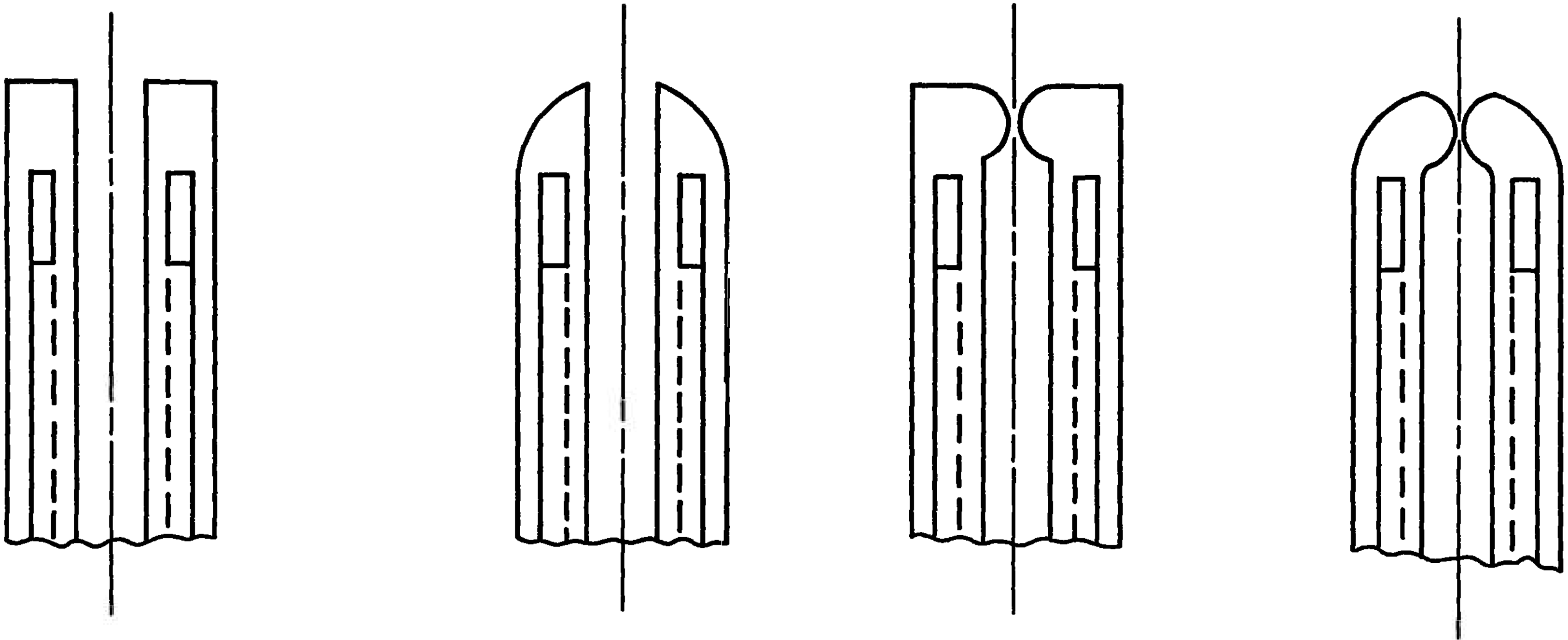


Fig. 3 Copper Probe Design Details



Full Bore

Orifice Tip

Fig. 4 Probe Tip Configurations

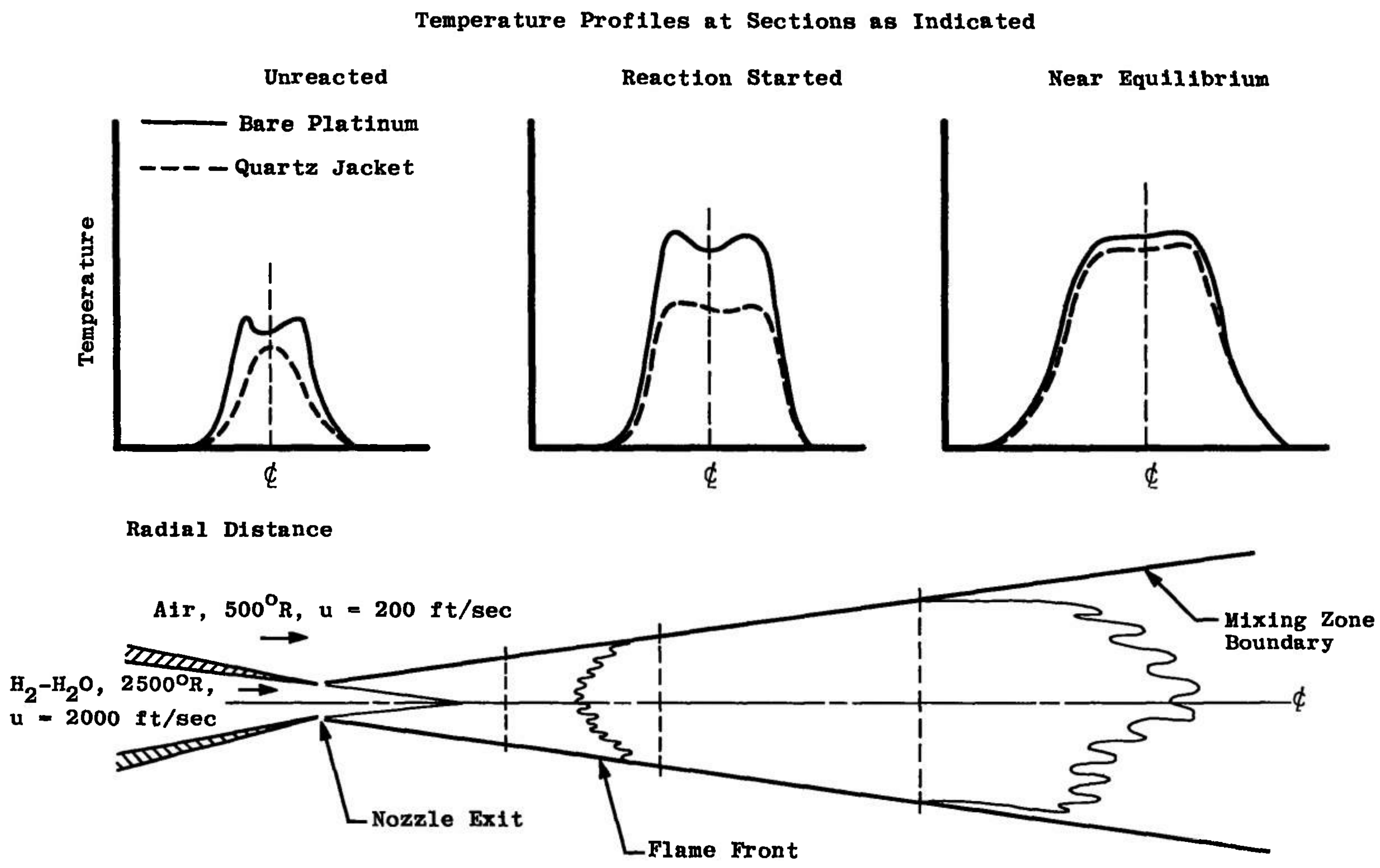


Fig. 5 Effect of Thermocouple Catalysis on Profiles

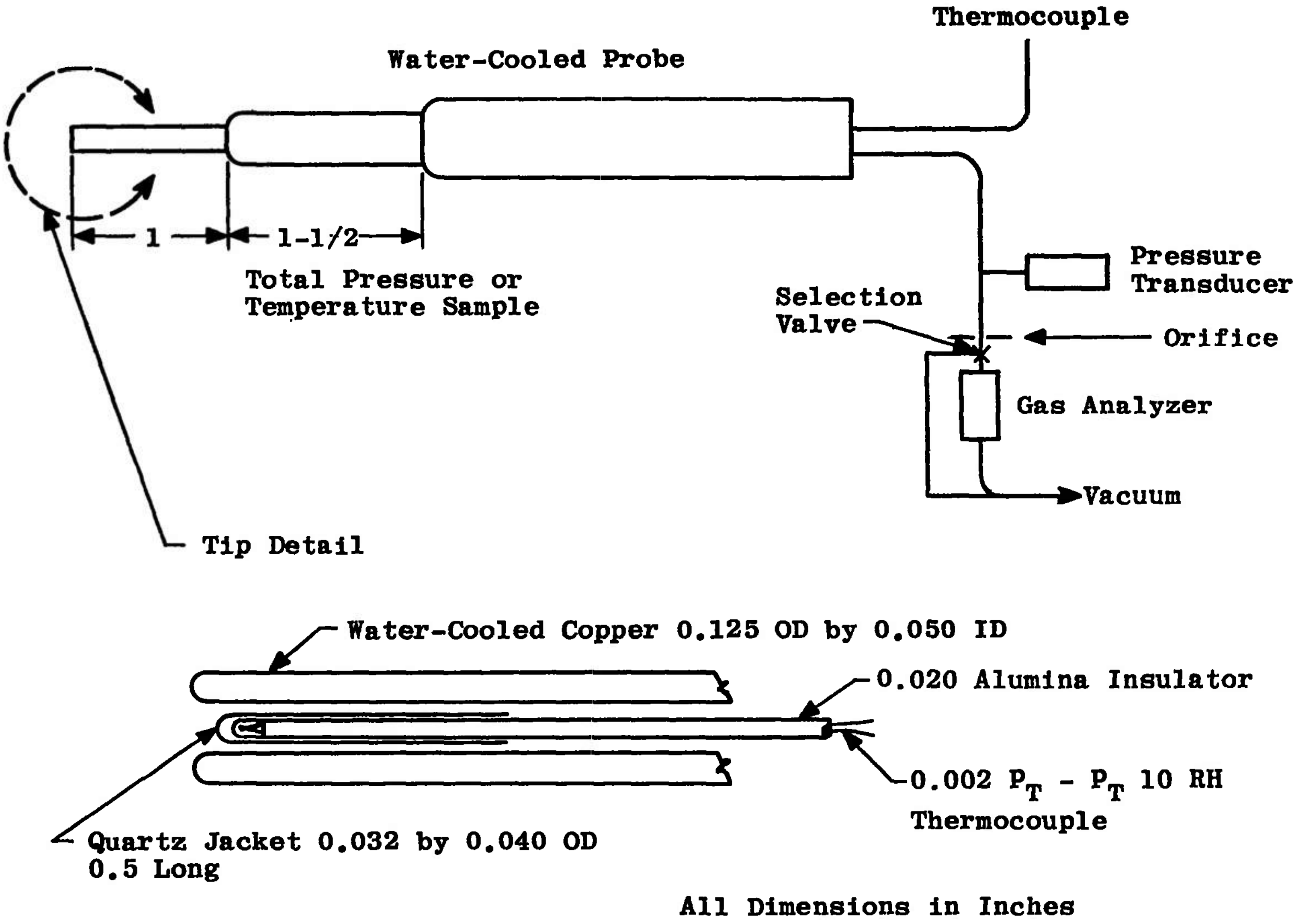


Fig. 6 Pressure-Temperature Sampling Probe (Thermocouple)

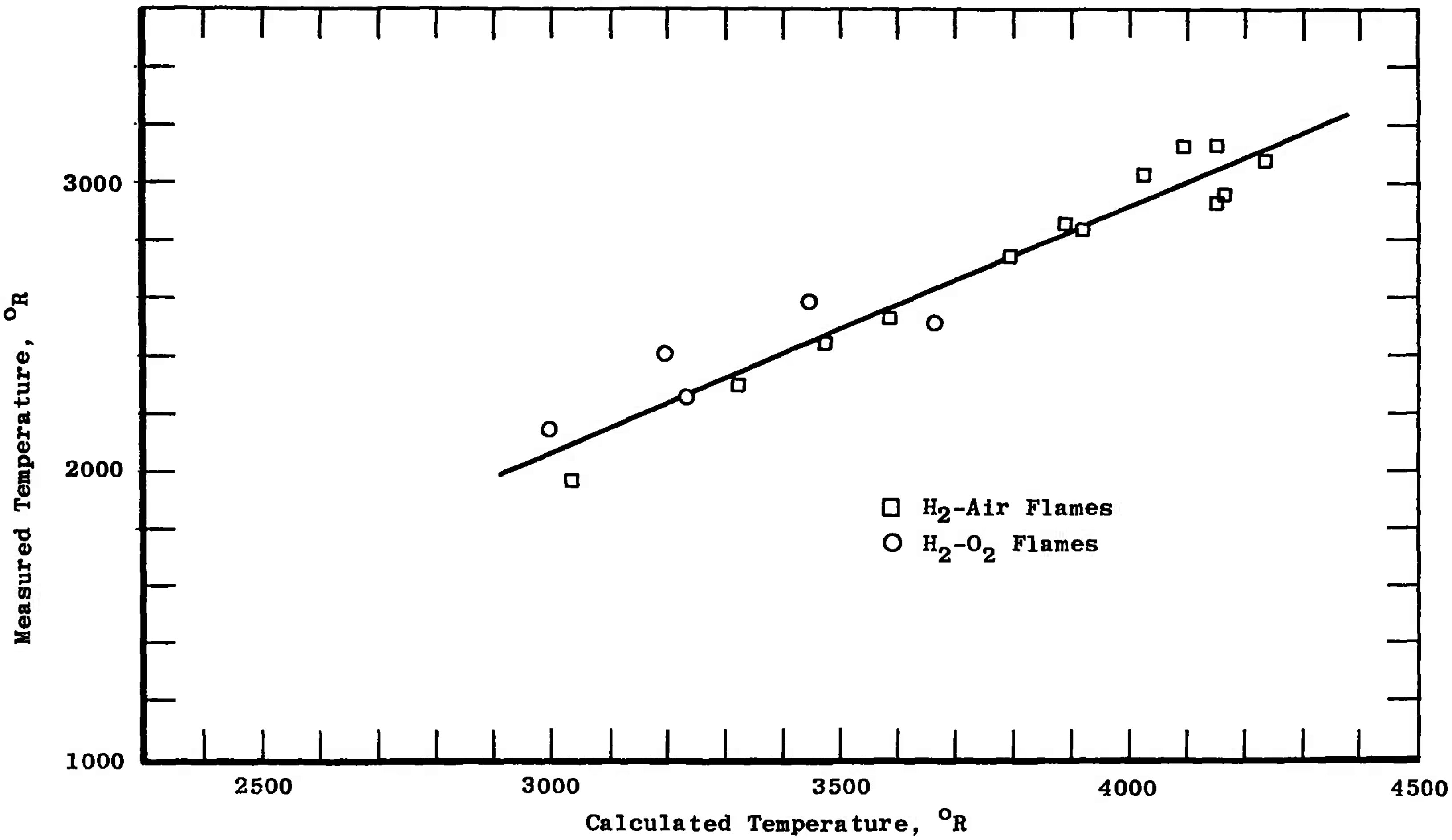


Fig. 7 Calibration Curve for a Quartz-Jacketed Thermocouple Probe

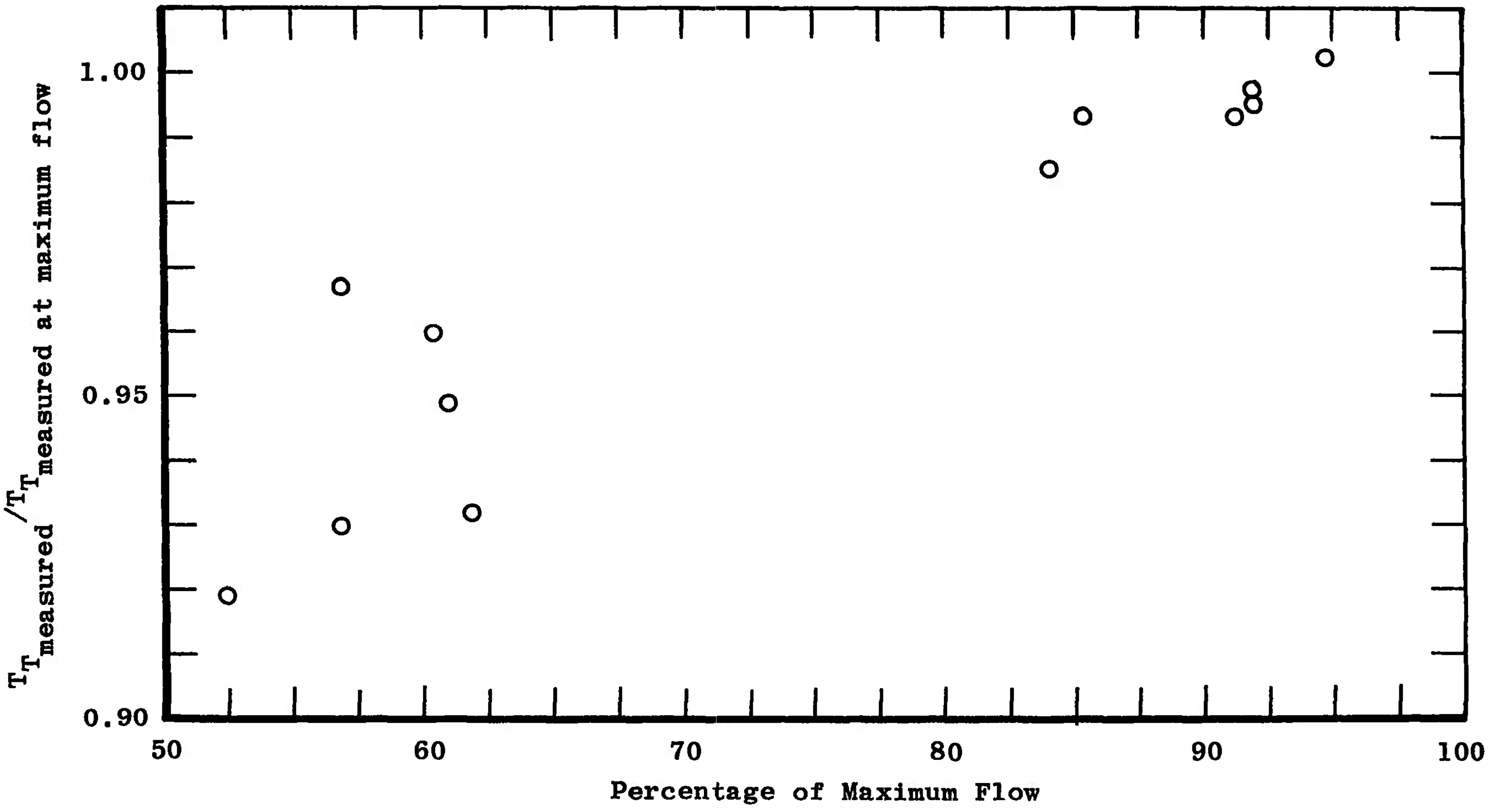


Fig. 8 Effect of Probe Flow Rate on Probe Readings

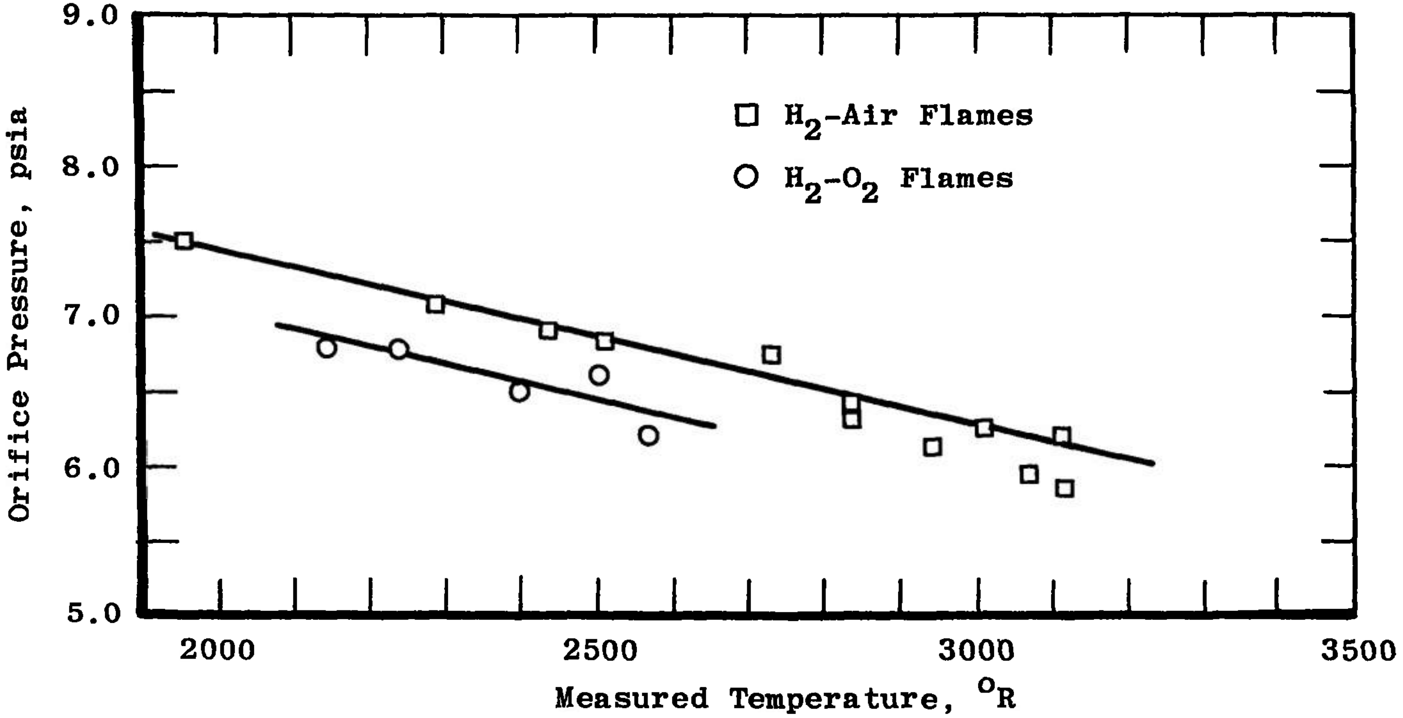
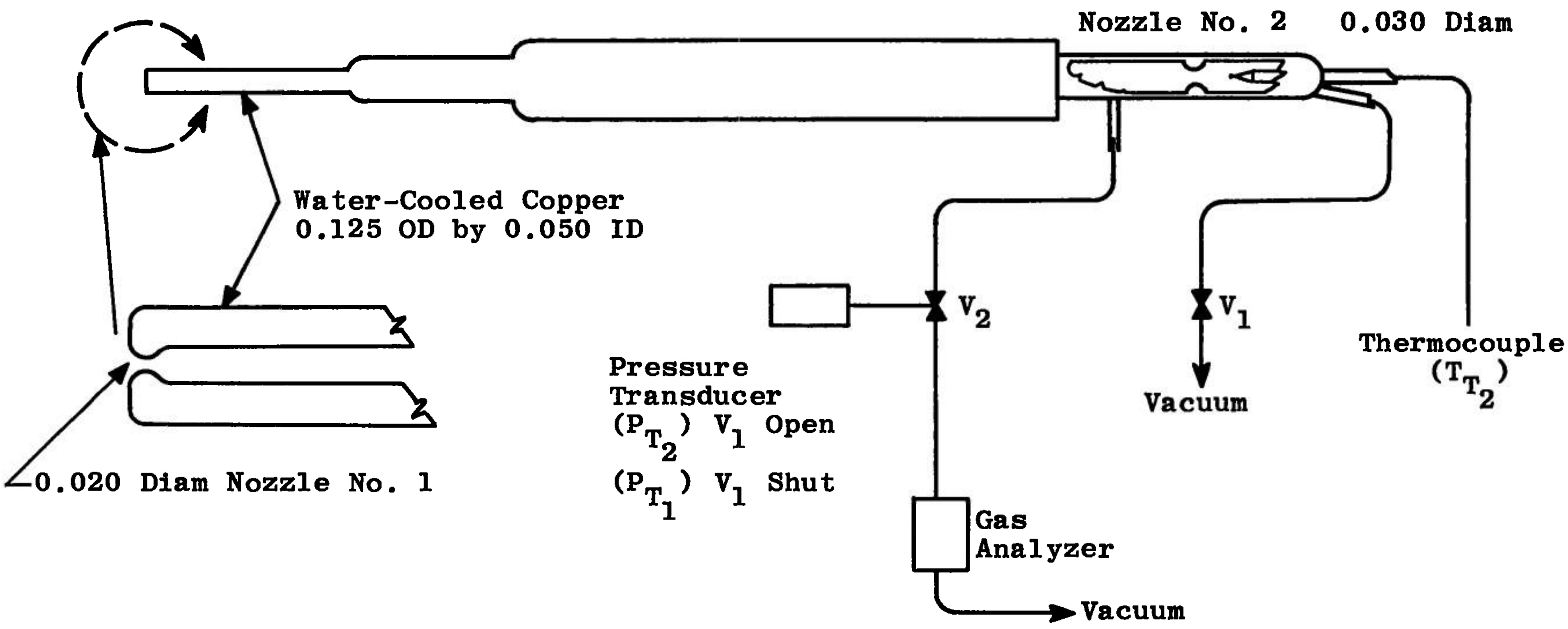


Fig. 9 Correlation between Measured Temperature and Probe Orifice Pressure



$$T_{T_1} = T_{T_2} \left[\frac{P_{T_1}}{P_{T_2}}\right]^2 \left[\frac{M_1}{M_2}\right] \left[\frac{f(\gamma_1)}{f(\gamma_2)}\right] \left[\frac{A_1}{A_2}\right]^2$$

Fig. 10 Pressure-Temperature Sampling Probe (Pneumatic)

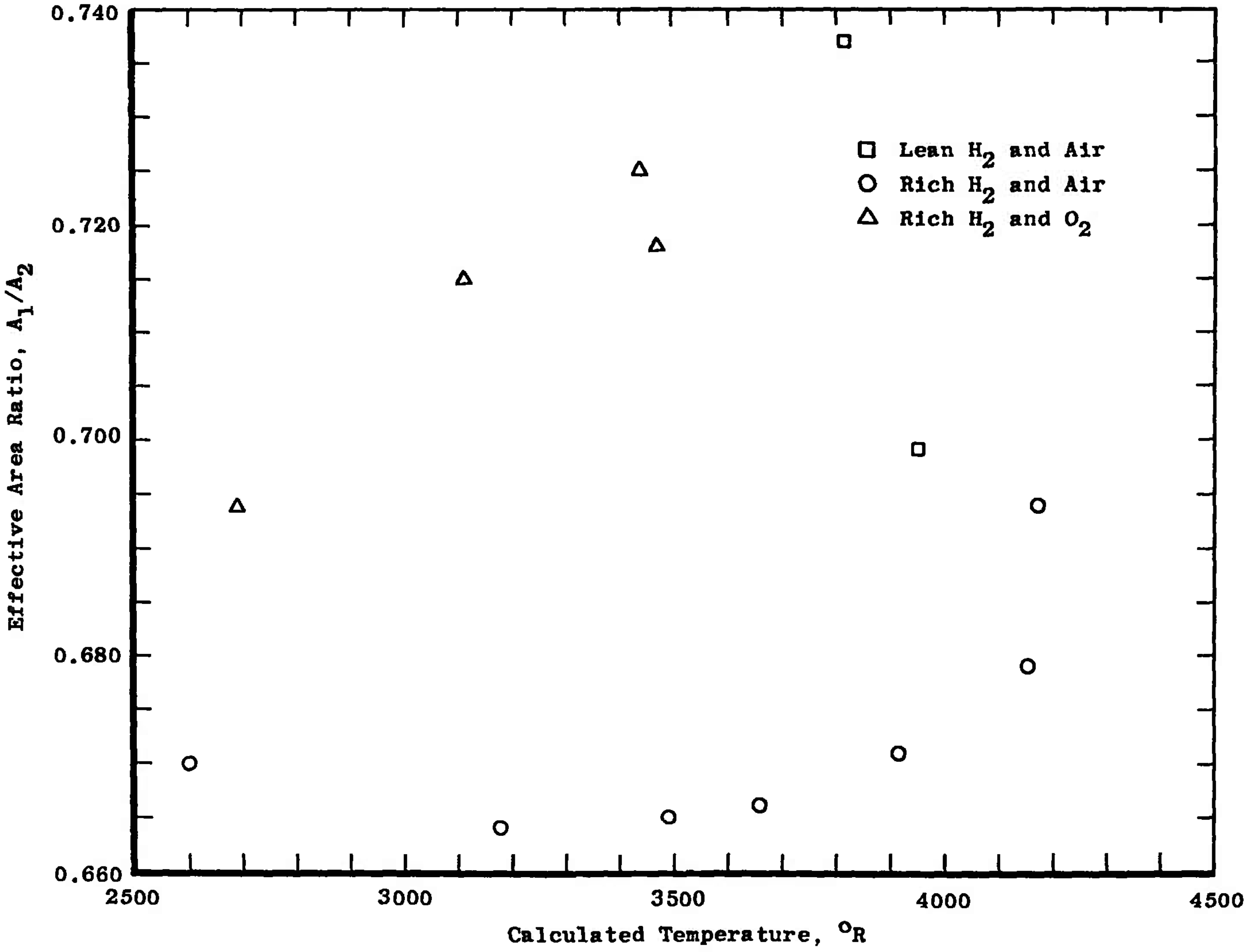


Fig. 11 Effect of Composition and Temperature on the Effective Area Ratio of a Pneumatic Temperature Probe

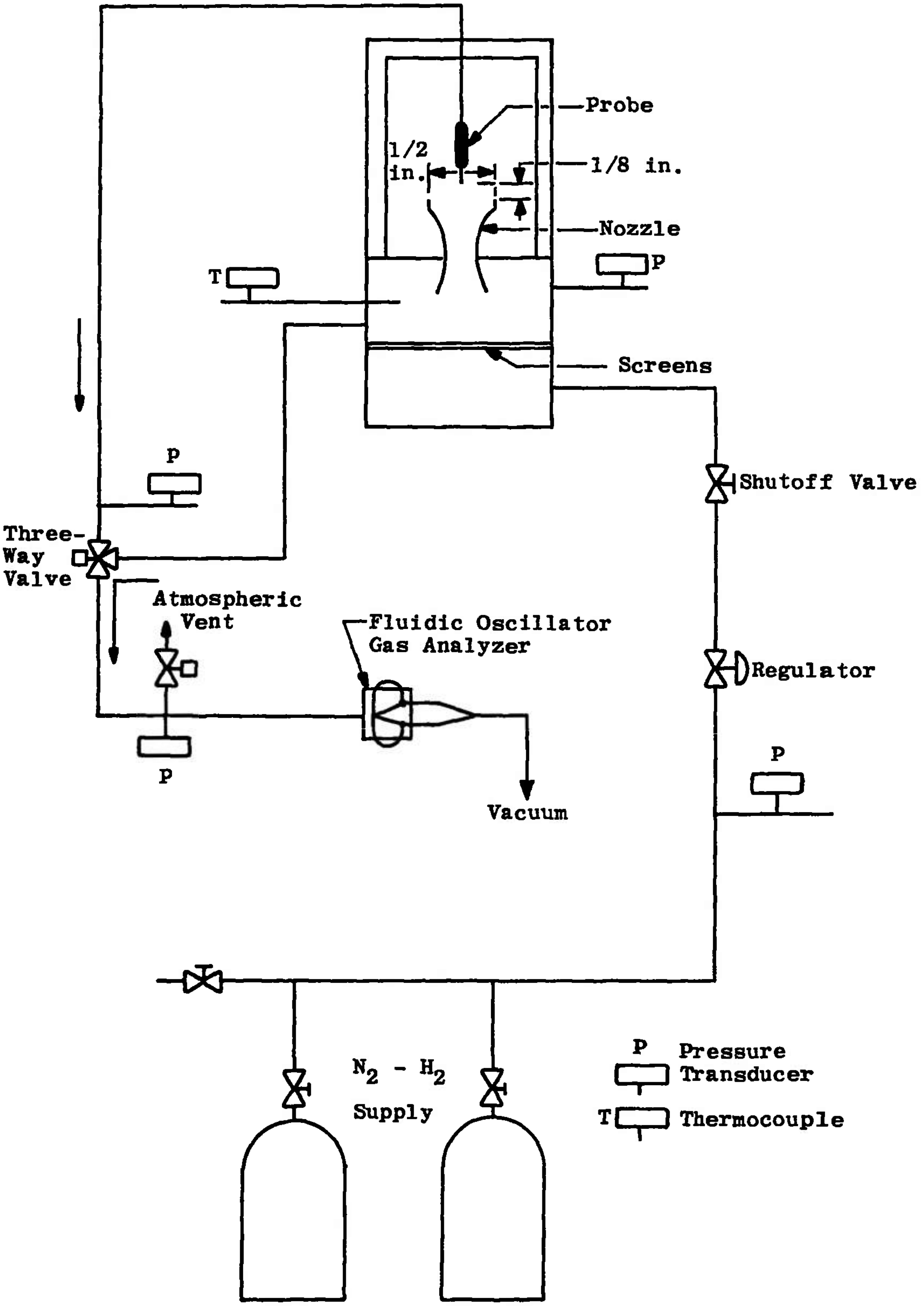


Fig. 12 Gas Separation Test Schematic

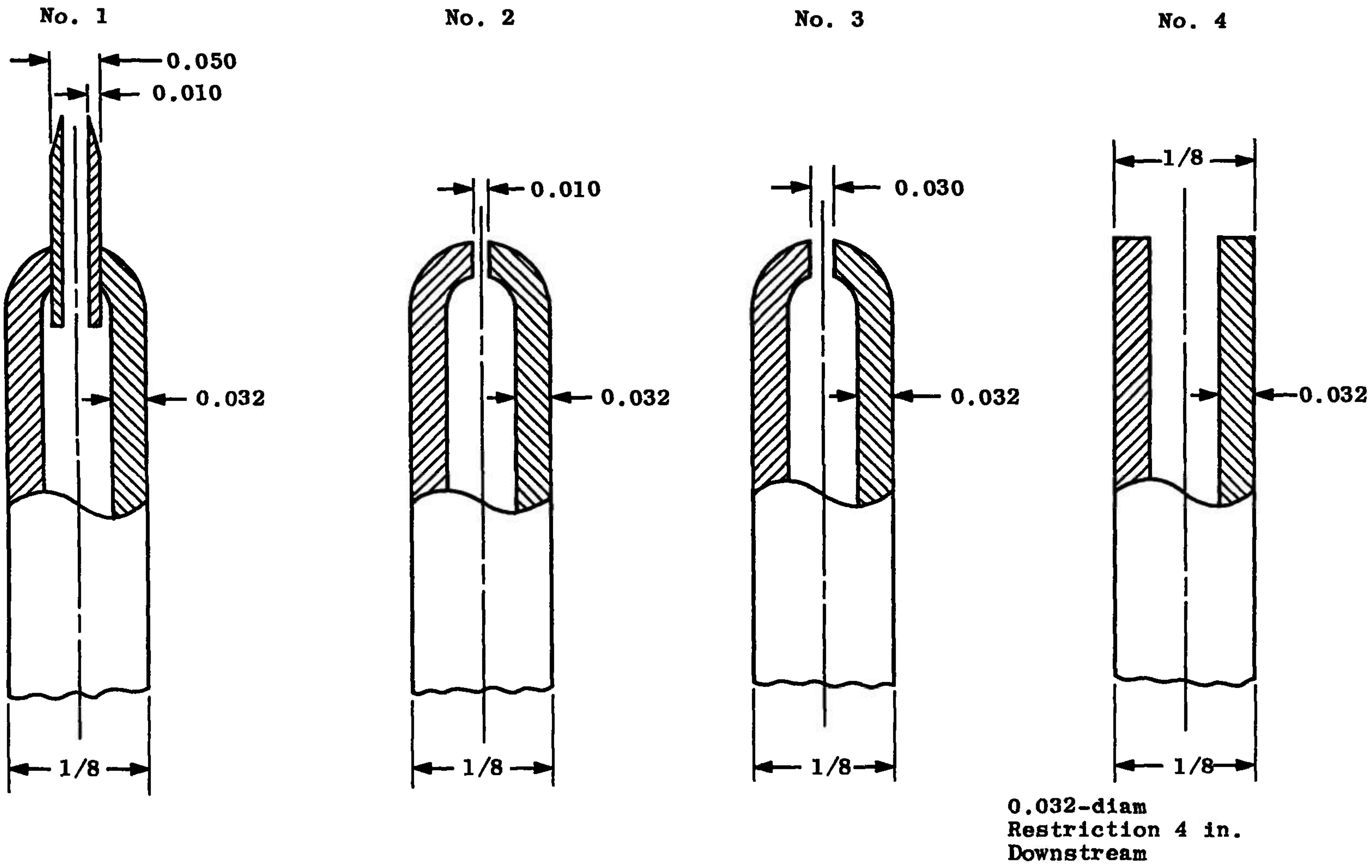


Fig. 13 Probe Tips Used in the Gas Separation Test

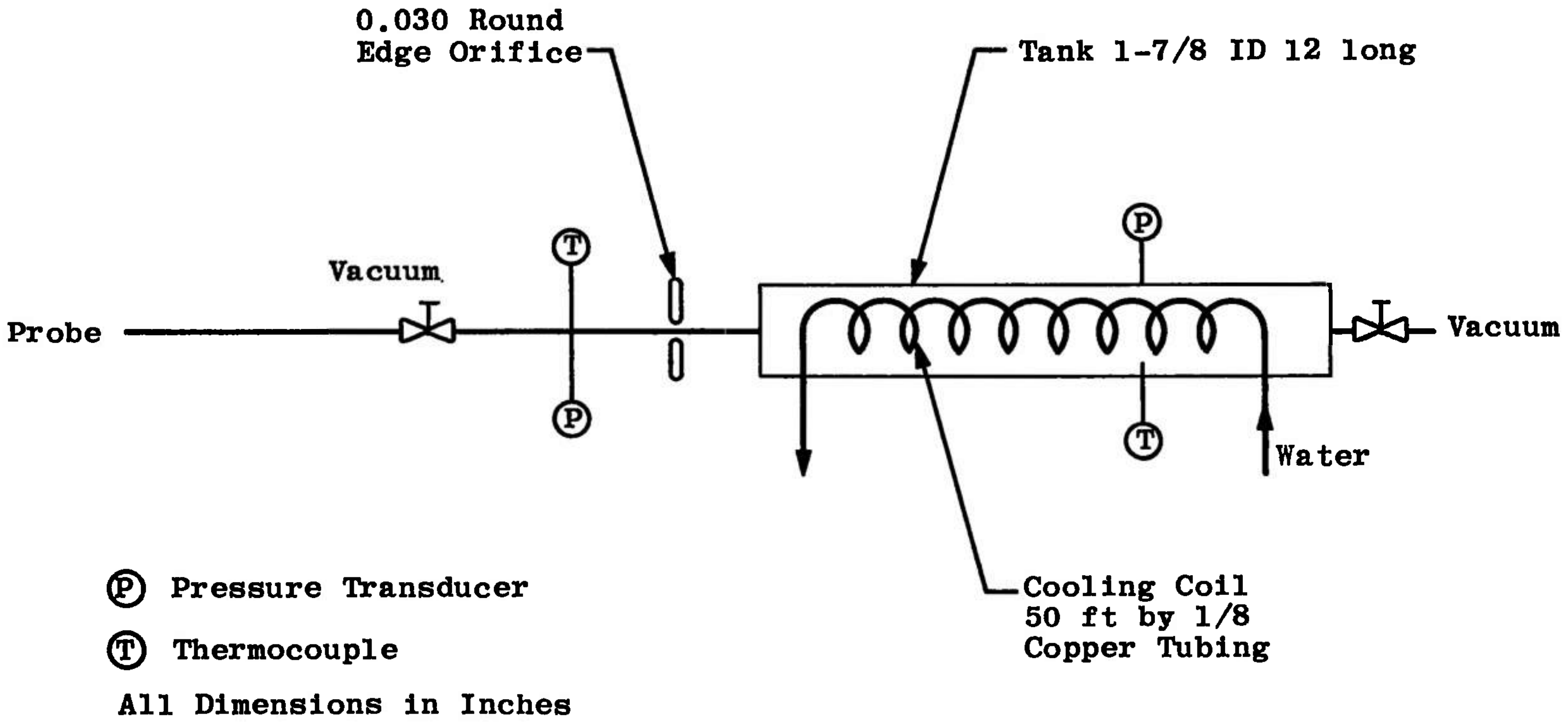


Fig. 14 Orifice-Tank Molecular Weight System

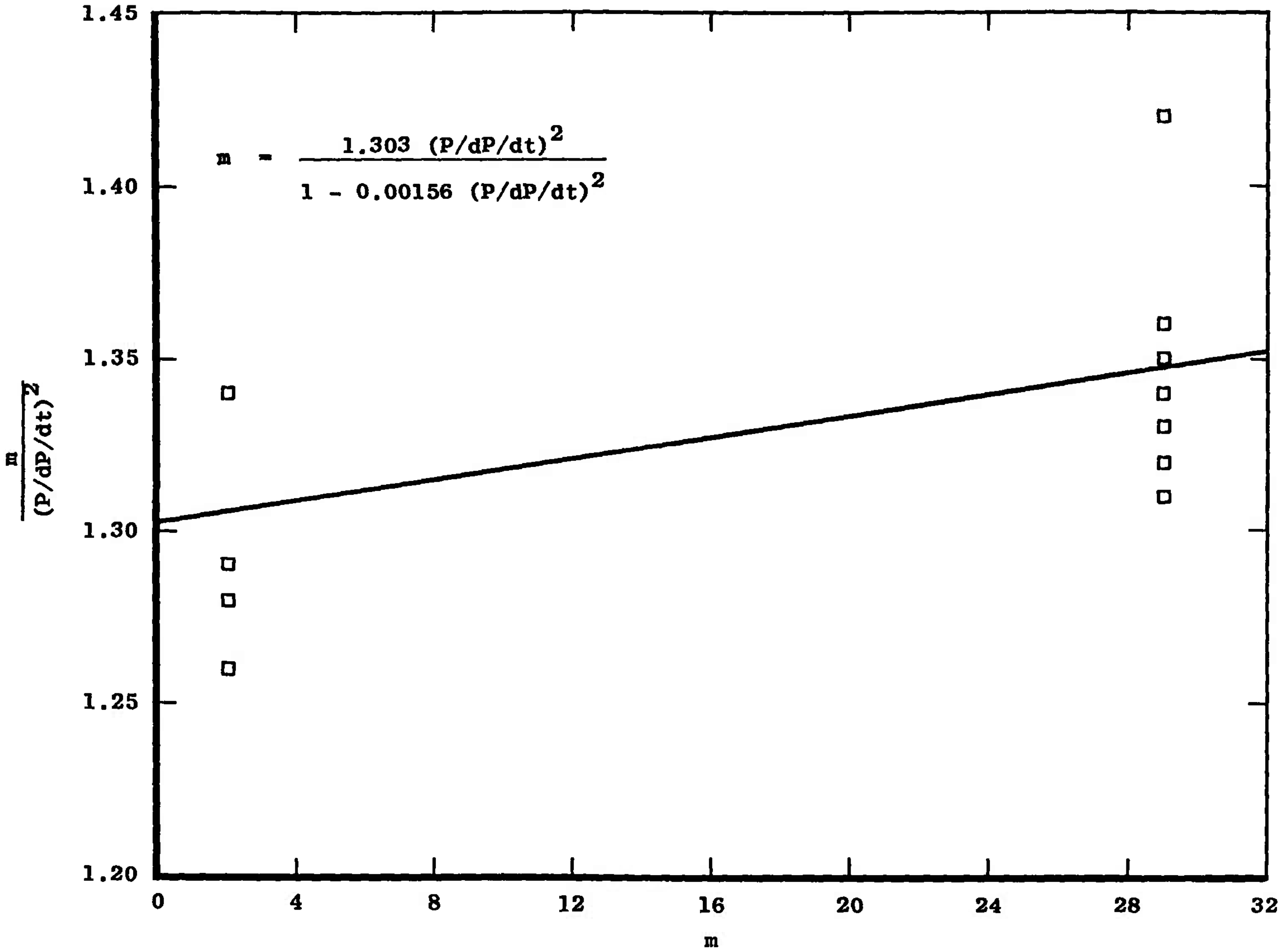


Fig. 15 Orifice-Tank Calibration Curve

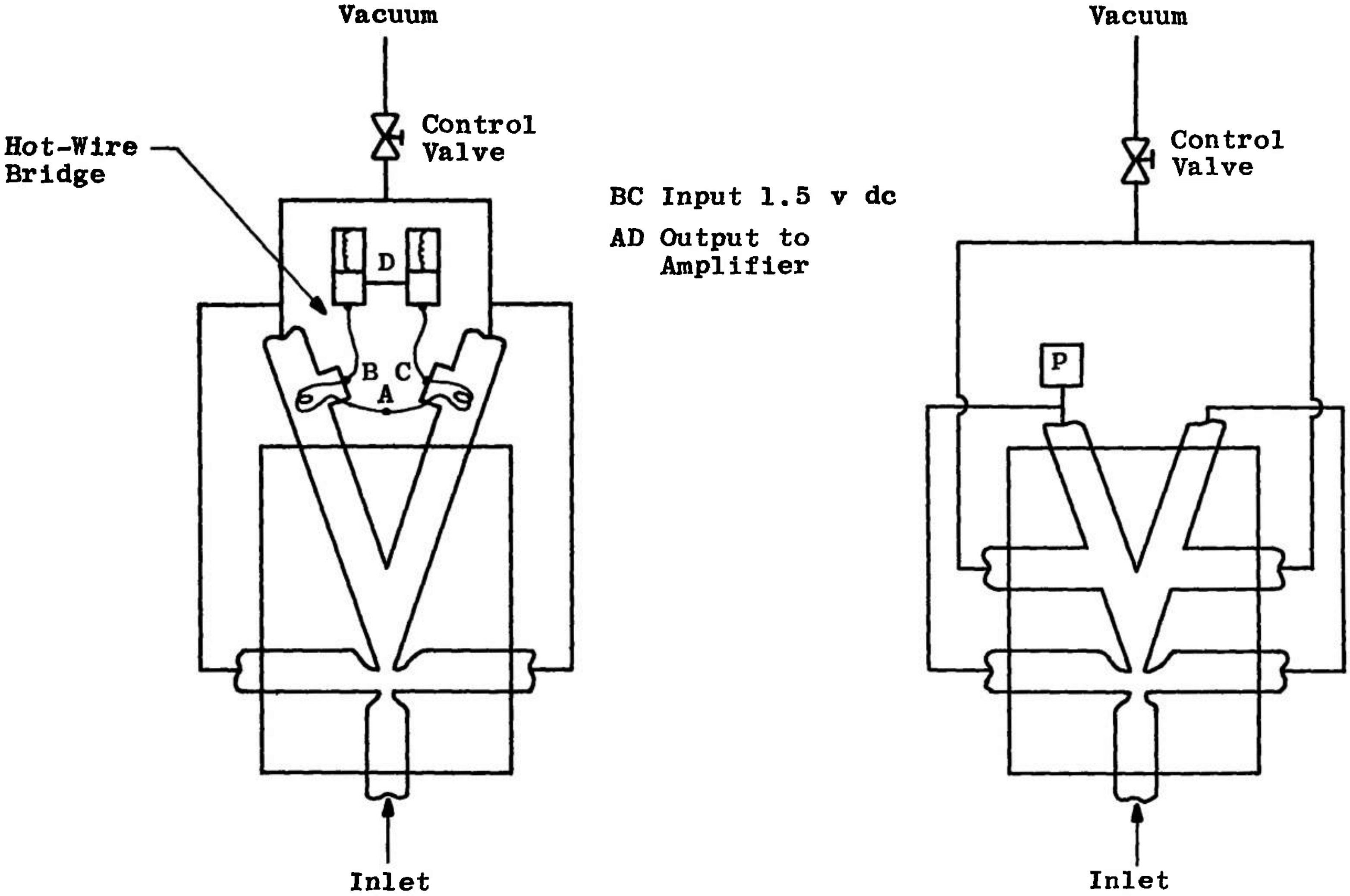


Fig. 16 Fluidic Oscillator Schematic

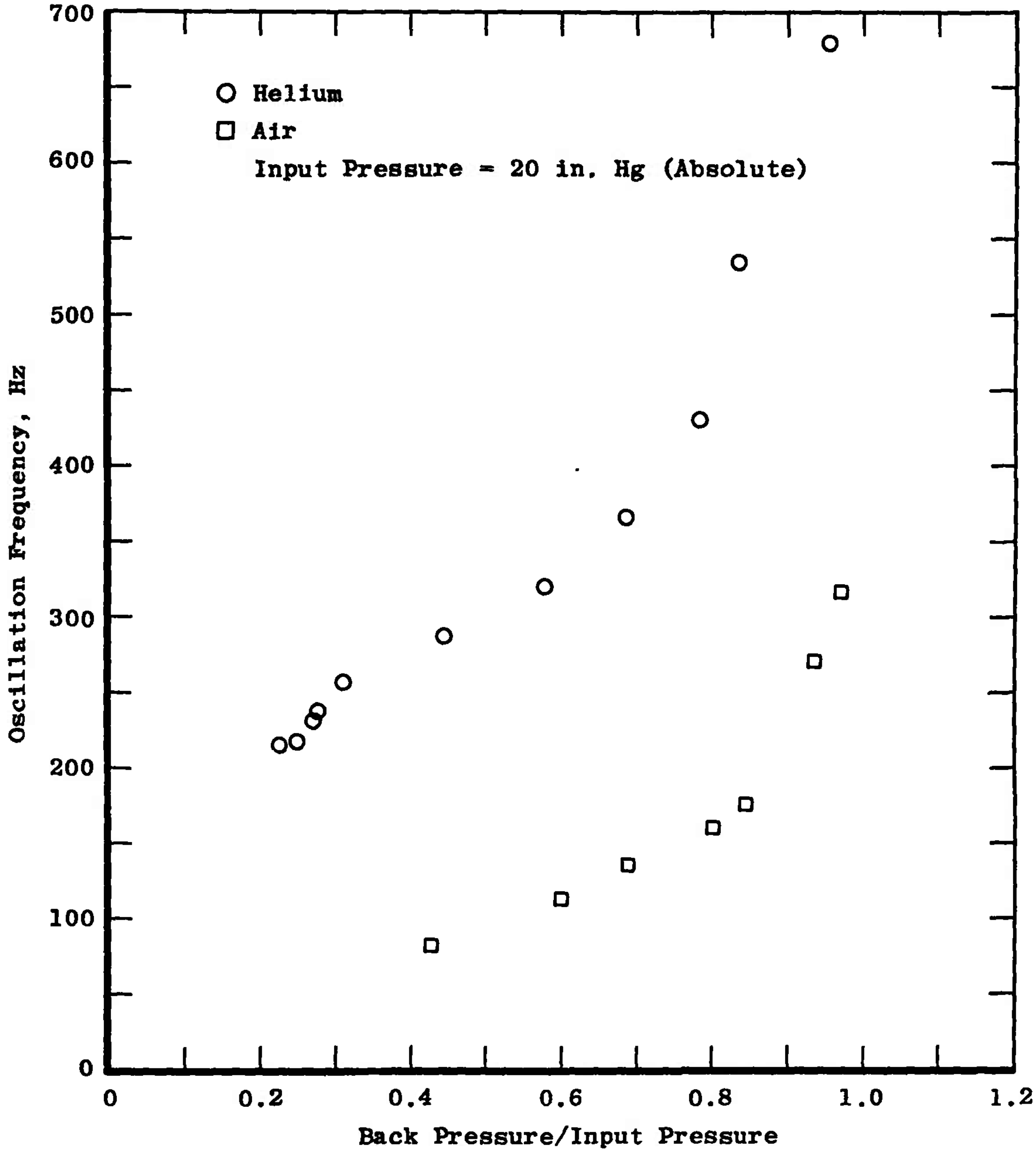
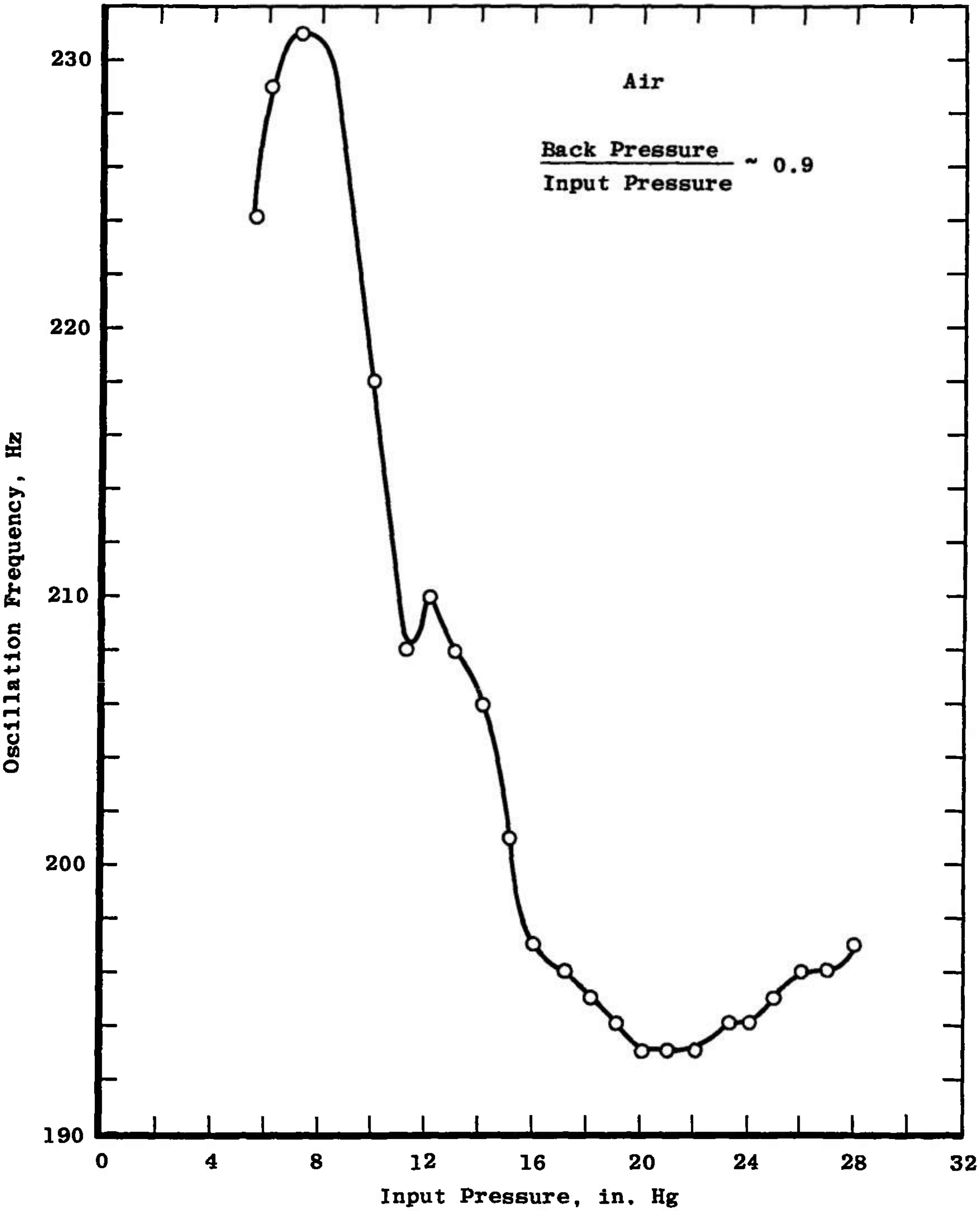
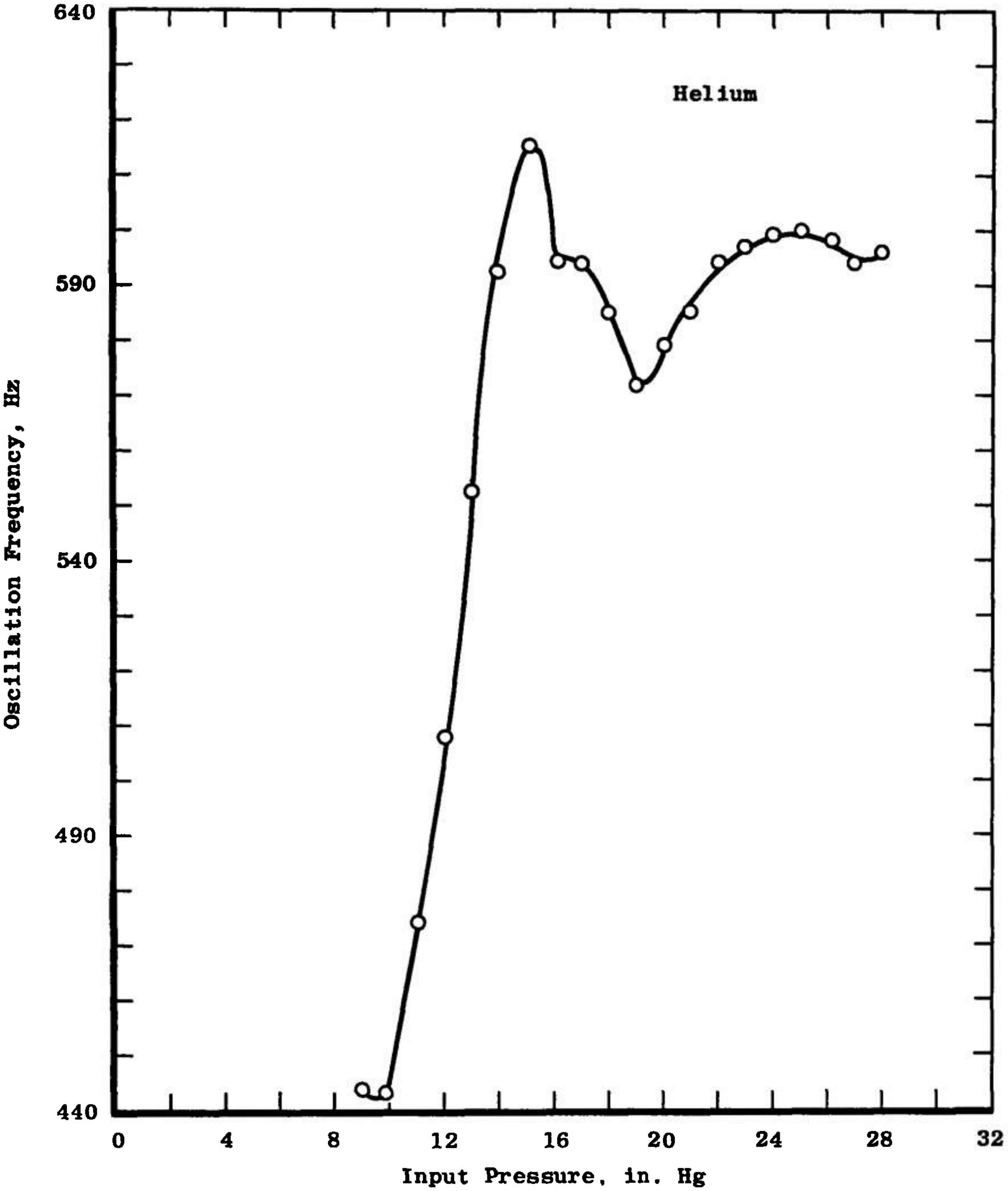


Fig. 17 Effect of Control Valve Setting at Constant Input Pressure



a. Air

Fig. 18 Effect of Input Pressure on Frequency at Constant Control Valve Setting



b. Helium

Fig. 18 Concluded

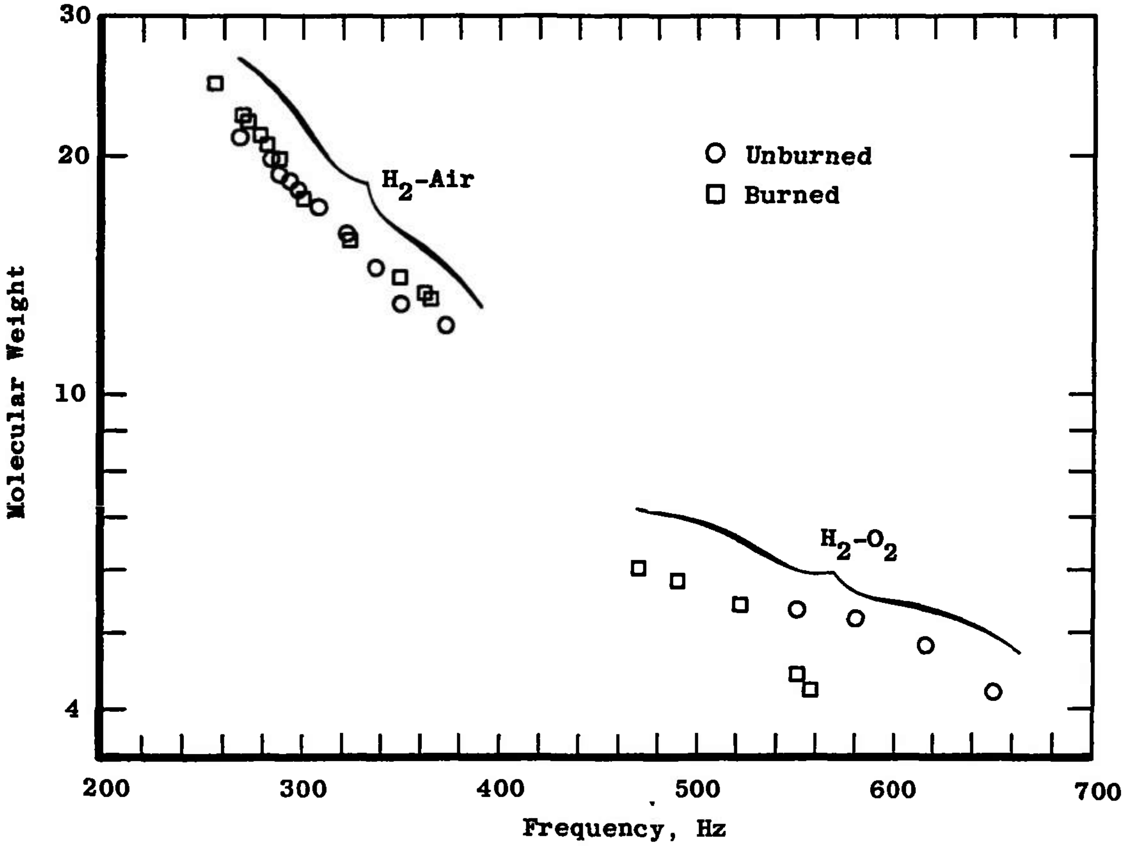


Fig. 19 Oscillator Calibration

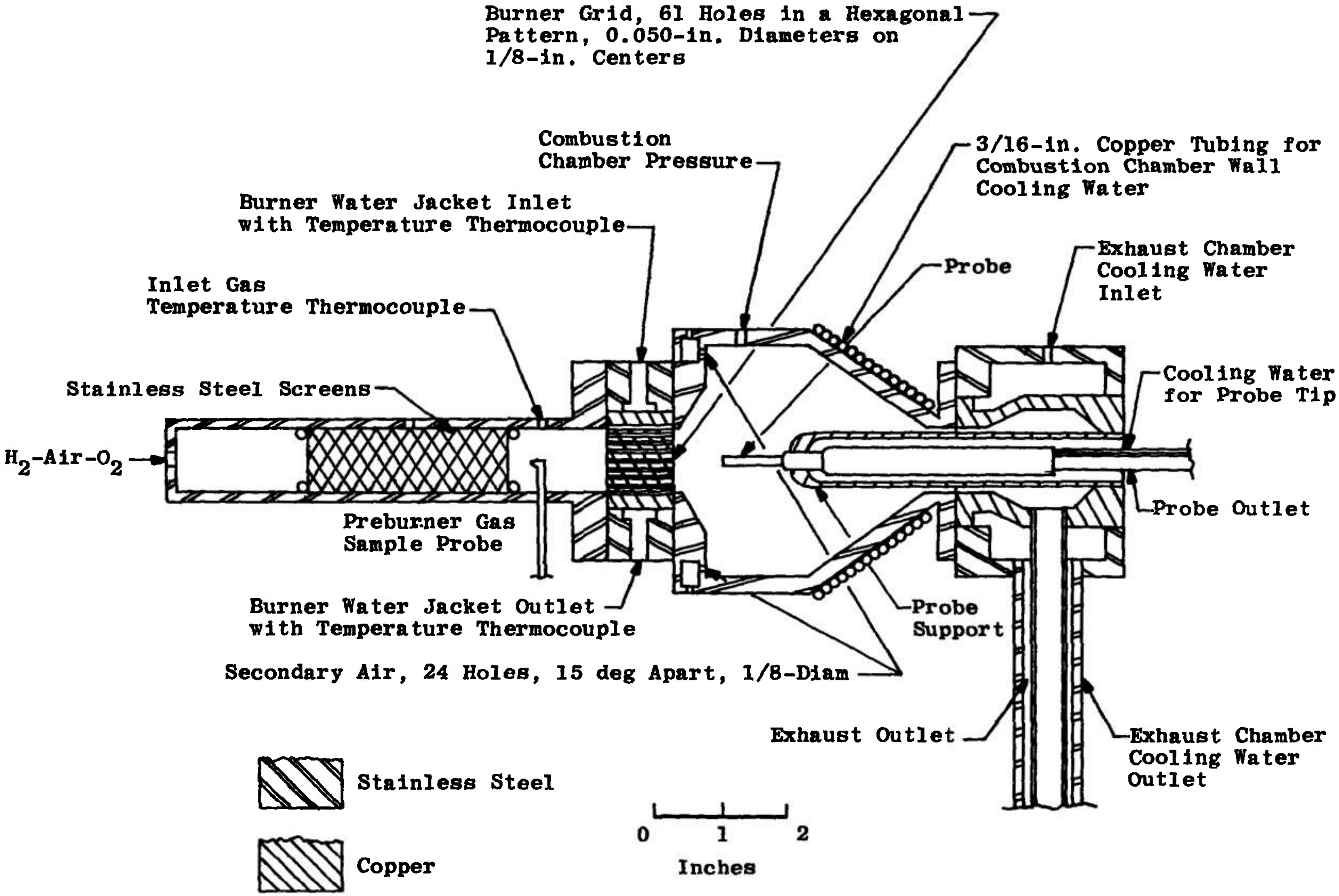


Fig. 20 Calibration Burner Schematic

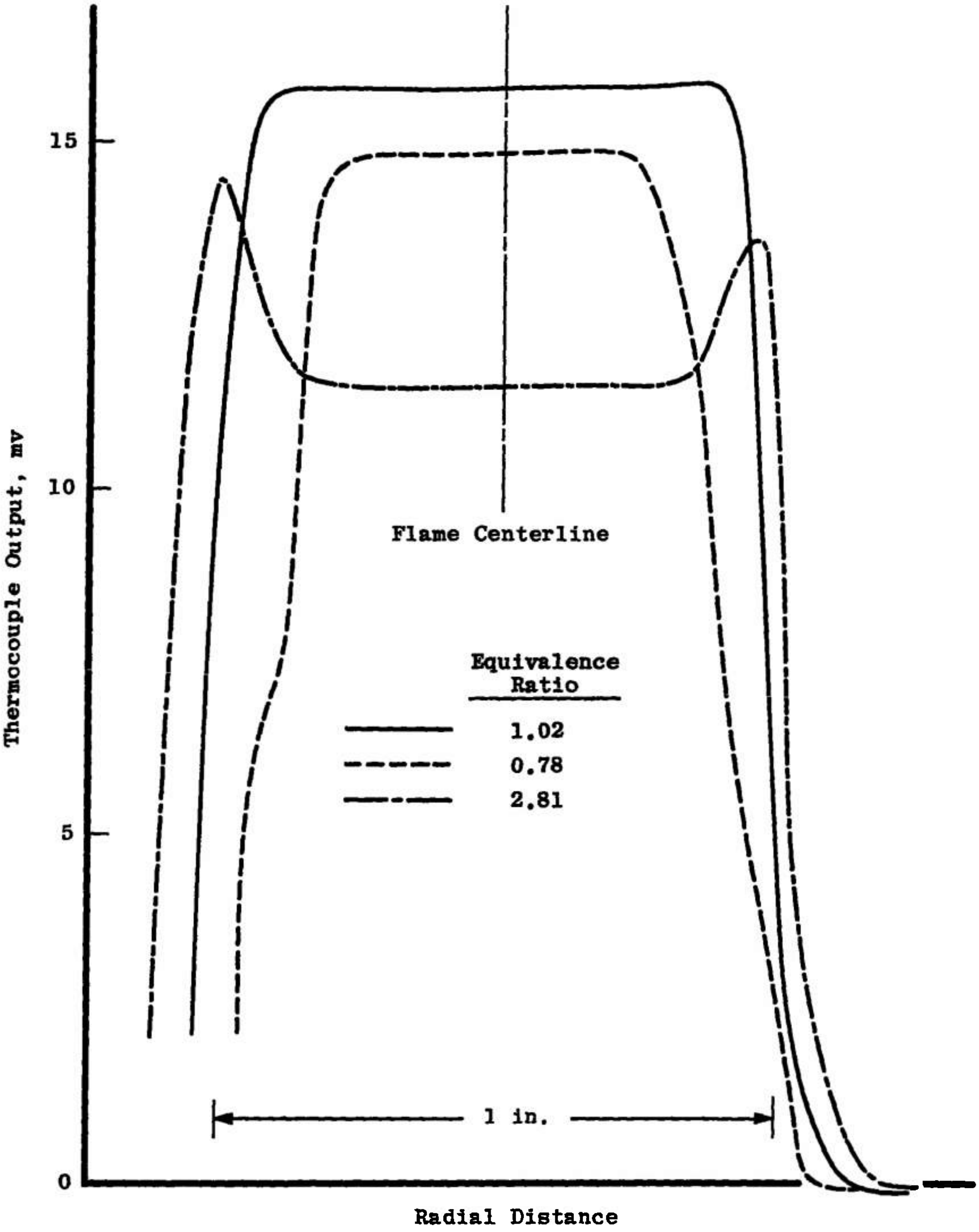
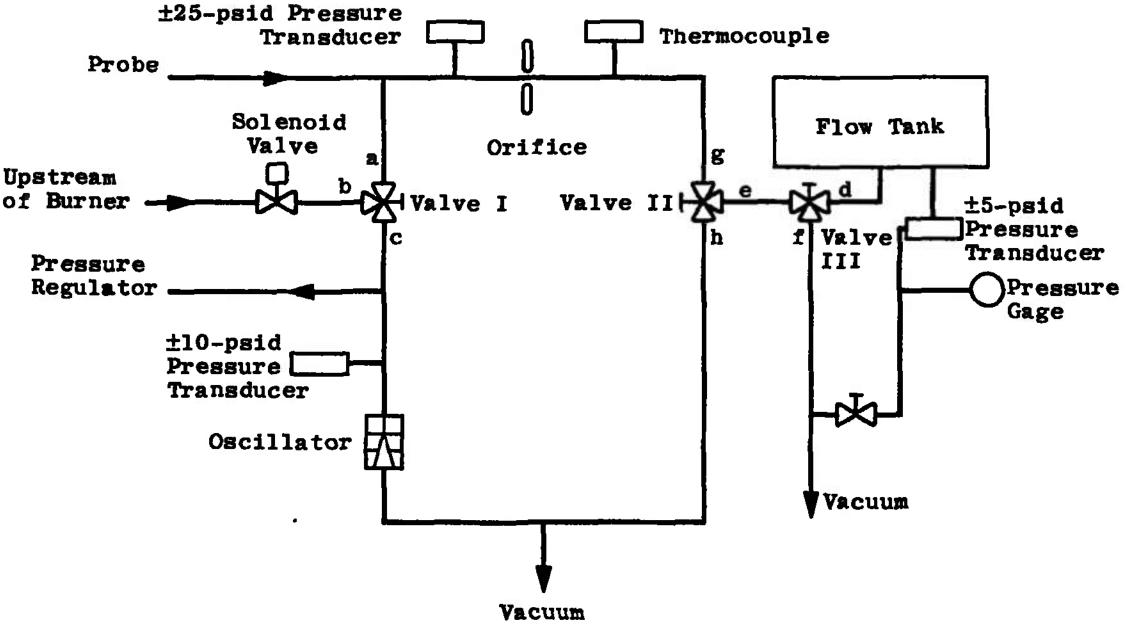


Fig. 21 Typical Flame Profile



Function	Valve Position I	II	III
Oscillator Flow from the Downstream Probe	ac	df	ge
Total Pressure on the ±25-psid Transducer and Oscillator Flow from the Upstream Probe	bc	df	ge
Tank Flow	bc	de	ge
Orifice Flow	bc	de	gh

Fig. 22 Probe Measuring System Schematic

TABLE I

PROBE SEPARATION OF H_2-N_2 MIXTURES

Volume Percentage H_2	Nozzle Mach Number	Nozzle Total Pressure, psia	Probe Number	Percent Change in Molecular Weight
20	2.5	250	1	0.64
20	2.5	250	2	0.4
20	2.5	250	3	0.48
20	2.5	250	4	-0.12
20	2.0	115	1	0.24
20	2.0	115	2	0.68
20	2.0	115	3	0.16
20	2.0	115	4	1.00
20	1.5	54	1	0.08
20	1.5	54	3	0
20	1.5	54	4	0.12
50	2.5	250	1	1.44
50	2.5	250	2	1.33
50	2.5	250	3	0.35
50	2.5	250	4	0.09
50	2.0	115	1	0.17
50	2.0	115	2	0.13
50	2.0	115	3	0.26
50	2.0	115	4	0
50	1.5	54	1	-0.13
50	1.5	54	3	0.40
50	1.5	54	4	0.40
50	1.0	28	1	0.13
50	1.0	28	3	0.26
50	1.0	28	4	0.26

TABLE I (Concluded)

Volume Percentage H_2	Nozzle Mach Number	Nozzle Total Pressure, psia	Probe Number	Percent Change in Molecular Weight
75	2.0	115	1	1.10
75	2.0	115	2	−0.44
75	2.0	115	3	0.66
75	1.5	54	1	−0.15
75	1.5	54	2	0.22
75	1.5	54	3	0.22
75	1.5	54	4	0.51
75	1.0	28	1	0.22
75	1.0	28	2	−0.14
75	1.0	28	3	−0.51
75	1.0	28	4	−0.51
93	2.0	115	1	0.47
93	2.0	115	2	2.28
93	2.0	115	3	0.94
93	2.0	115	4	0.40
93	1.5	54	1	1.08
93	1.5	54	2	1.62
93	1.5	54	3	1.79
93	1.5	54	4	0.66
93	1.0	28	1	−0.14
93	1.0	28	2	0
93	1.0	28	3	0.45
93	1.0	28	4	0.26

Average	1	0.40
	2	0.61
	3	0.42
	4	0.26
	All	0.41

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE
PROBING TECHNIQUES FOR USE IN HIGH TEMPERATURE REACTING FLOWS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report July 1965 to December 1967

5. AUTHOR(S) *(First name, middle initial, last name)*
R. P. Rhodes, ARO, Inc.

This document has been approved for public release its distribution is unlimited. Per AF Letter dtd 23 Jan 75 Signed William O. Cole

6. REPORT DATE March 1968	7a. TOTAL NO. OF PAGES 54	7b. NO. OF REFS 14

8a. CONTRACT OR GRANT NO. AF 40(600)-1200 b. PROJECT NO. 4344 c. Program Element 6540215F d. Task 434424	9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-68-44 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* N/A

10. DISTRIBUTION STATEMENT ~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389.~~

11. SUPPLEMENTARY NOTES Available in DDC.	12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tenn.37389

13. ABSTRACT

A basic probe has been designed which consists of a 1/8-in.-diam, water-cooled copper probe with an inside diameter of 0.050 in. These probes may be aspirated to take a gas sample and temperature reading, or used without aspiration to measure total pressure. Two systems currently being investigated to measure temperature are quartz-coated thermocouples and pneumatic thermometers. These probe designs were chosen because they should not include the heat of recombination of non-equilibrium gases in the temperature reading as would a calorimeter-type total enthalpy probe. The gases are analyzed on line with a bistable fluid oscillator having an oscillation frequency that is a function of the molecular weight of the sample. No quantitative theory of fluid oscillators is available; however, observations are given of the effect of some of the design parameters on performance. A study was made of the effect of probe shape and Mach number on the validity of samples taken in a supersonic stream. For hydrogen-nitrogen mixtures at a static pressure of 1 atm, no change between the free stream and the sample was seen in any of the tests.

~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389.~~

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1 probes						
2 thermometry						
gas analysis						
high temperature						
3. Gases -- analysis						
4 " -- Sampling						
5. Temperature -- Measurement						
6 Pressures -- "						

17- S.