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A HOT-WIRE VACUUM GAGE FOR TRANSIENT MEASUREMENTS

Prepared by

V. A. Sandborn

RESEARCH AND ADVANCED DEVELOPMENT DIVISION
AVCO CORPORATION
Wilmington, Massachusetts

Technical Memorandum
RAD-TM-63-41
Contract AF04(694)-264

THIS REPORT WAS PREPARED IN ACCORDANCE WITH AIR FORCE CONTRACT AF04(694)-264. IT IS SUBMITTED IN PARTIAL FULLFILLMENT OF THE CONTRACT AND IN ACCORDANCE WITH AFBM EXHIBIT 58-1 (PARAGRAPH 4.2.1).

15 July 1963

Prepared for

AIR FORCE BALLISTIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Norton Air Force Base, California

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APPROVED

S. Georgiev

S. Georgiev, Manager
Aerophysics Department

H L Bell

H. L. Bell, Director
Advanced Vehicle Development

Prepared for

AIR FORCE BALLISTIC SYSTEMS DIVISION
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SUMMARY

The application of a hot-wire manometer to the measurement of transient static pressures on a wind tunnel model is outlined. A tungsten and a platinum-iridium wire were evaluated as the sensing elements, both from a steady state and a transient viewpoint. An instrument with a frequency response of over 300 cps and a sensitivity of approximately 10.5 volts/psia over the range from 0.02 to 0.08 psia is demonstrated. The total useable range of the instrument extends down below 0.001 psia and up to approximately 0.2 psia.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

Symbols

a	Accomodation coefficient
C	Specific heat of hot wire material (joule/gm °K)
D	Hot wire diameter, (cm)
h	Heat transfer coefficient, $(W/cm^2\ °K)$
I	Hot wire current, (amps)
k	Thermal conductivity of hot wire material, (W/cm °K)
ℓ	Hot wire length, (cm)
M_a	Molecular weight of ambient gas, (gm/gm - mole)
P	Pressure, (psia or mm Hg)
q_c	Local rate of heat flow due to conduction in hot wire material, (W/cm)
q_g	Local rate of molecular heat conduction in the ambient gas, (W/cm)
q_j	Local rate of heat production due to Joulean heating,(W/cm)
Q_c	Heat flow rate from hot wire due to conduction to wire supports, (W)
Q_g	Heat flow rate from hot wire to ambient gas, (W)
R	Hot wire resistance, (ohms)
R	Universal gas constant, 8.314 (j/gm-mole °K)
r	Local resistivity of hot wire material (ohms/cm)
t	Time (seconds)
t_w	Local wire temperature, (°C)
T	Temperature, (°K)

NOMENCLATURE (Concl'd)

Symbols

T_a	Ambient gas temperature, (°K)
T_f	Final hot wire temperature, (°K)
$T_{w,\infty}$	Term having units of temperature, $\left(\frac{\eta_1}{\eta}\right)^2$, (°K)
X	Distance along hot wire measured from center of wire, (cm)
α	Thermal coefficient of resistance of hot wire material, (1/°K)
λ	Mean free path between gas molecules, (cm)
η	Constant in equation (9), (cm^{-1})
η_1	Constant in equation (9), ($^\circ\mathrm{K}^{1/2}/\mathrm{cm}$)
σ	Hot wire resistivity at 273°K, (ohm - cm)
ζ	Density of hot wire material, ($\mathrm{gm/cm}^3$)
τ	Hot wire time constant, (seconds)

I. INTRODUCTION

A very small pressure transducer is required to measure transient pressures in the range from 0.02 to 0.08 psia (5 mm Hg to 0.5 mm Hg) in a hypersonic wind tunnel. The pressure fluctuations are of the order of 10 cycles or less, so that high frequencies are not important. The transducers employed for transient pressure measurements are: microphones, crystals, and strain gage diaphragm pressure cells. The microphone and crystal pressure pickups measure only the transient change in pressure. Presently available microphones and crystal pickups do not extend down to the required low frequencies. Although it is possible that further development could produce a crystal with both the low frequency and low pressure measuring ability, such a device was not felt to be forthcoming in the time required. The strain gage diaphragm pressure cell is capable of measuring pressure and frequencies at the levels required, but the instrument is approximately 4 inches in diameter and weighs more than the complete model in which it would be mounted. Thus, it appears that a new approach to the present transient pressure measurement must be considered.

The variation in molecular conduction of heat from a wire at low pressures has been employed as a pressure measuring device for the past 75 years. The Pirani or hot-wire manometer is the name associated with this instrument. The instrument belongs to the resistance-temperature transducer family, wherein a change in the sensing element temperature results in a change in the element's resistance. The characteristic of interest for the present application is that the sensing element has a reasonably fast response to changes in temperature. The response of the basic element can be greatly improved by electronic circuits, so that high frequency transient measurements are possible. The size of the sensing element is of the order of 0.0001 inch in diameter. Thus, the pressure measuring gage can be made very small with very little mass to affect dynamic movement of the test model.

II. THEORETICAL BACKGROUND

A. THE RESISTANCE-TEMPERATURE TRANSDUCER

The variation of the electrical resistance of materials with temperature is a well known phenomenon. All materials, including electrical insulators, demonstrate the effect. Figure 1 shows the variation of electrical resistivity with temperature for three types of material: metallic conductors, semiconductors (thermistors), and insulators. There is no sharp division between the different types of conductors and it is possible to find a material that will have any particular value of resistivity at a given temperature, over the range covered in figure 1.

The selection of a resistance-temperature material for use as a transducer depends on several factors. Certainly, from a sensitivity standpoint it is desirable to have as great a variation in resistivity with temperature as possible. This explains the interest in using thermistors as sensors of temperature, since they have a large change in resistivity compared to platinum. The other important aspect of selecting a material will have to do with its transient characteristics.

The single characteristic of major interest for the resistance-temperature element is its transient response. While all transducers respond to some extent to transient changes, few have been developed that approach the speed of the electronic-operated, resistance-temperature transducer. The response of a hot wire to changes in surrounding gas properties can be computed theoretically. Dryden and Kuethe[1] give the solution for the limiting case where the wire is in continuum gas flow. Baldwin and Sandborn[2] give the solution for the other limiting case where the wire is in a vacuum and heat from the wire is lost by conduction to the wire supports. Figure 2 shows typical frequency response curves for a 0.0002-inch-diameter tungsten wire in atmospheric air and in a vacuum. These curves are for the basic sensing element without electronic improvement. At approximately 20 cps the wire in the vacuum is at 63 percent of its steady state value. In air the usable frequency response of the wire extends to approximately 100 cps.

For the hot-wire, resistance-temperature element operating in a continuum gas, the response of the element is described by a "first order" system. In the general area of servomechanisms a first order system is by definition, one whose response is given by the first order differential equation,

$$\tau \frac{dT}{dt} + T = T_f \quad . \tag{1}$$

In other words, if the sensing element responds to a sinusoidal temperature (forcing function), then the actual time rate of change of the element temperature

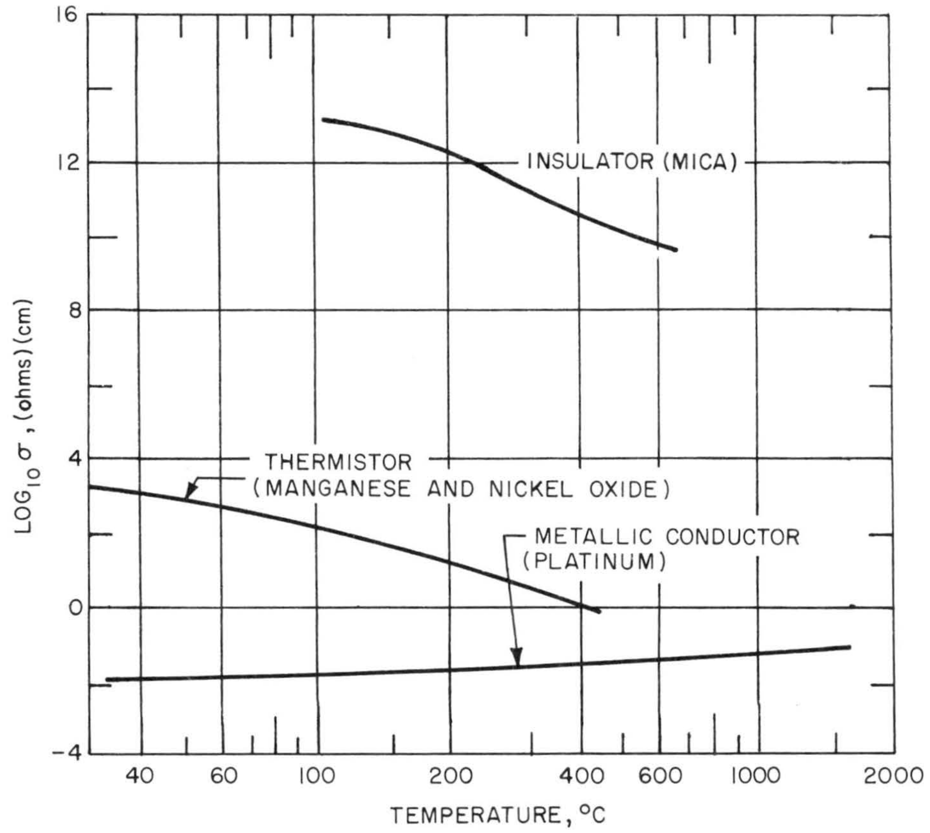

Figure 1 VARIATION OF ELECTRICAL RESISTITY WITH TEMPERATURE
OF THE BASIC TYPES OF CONDUCTORS
63-5535

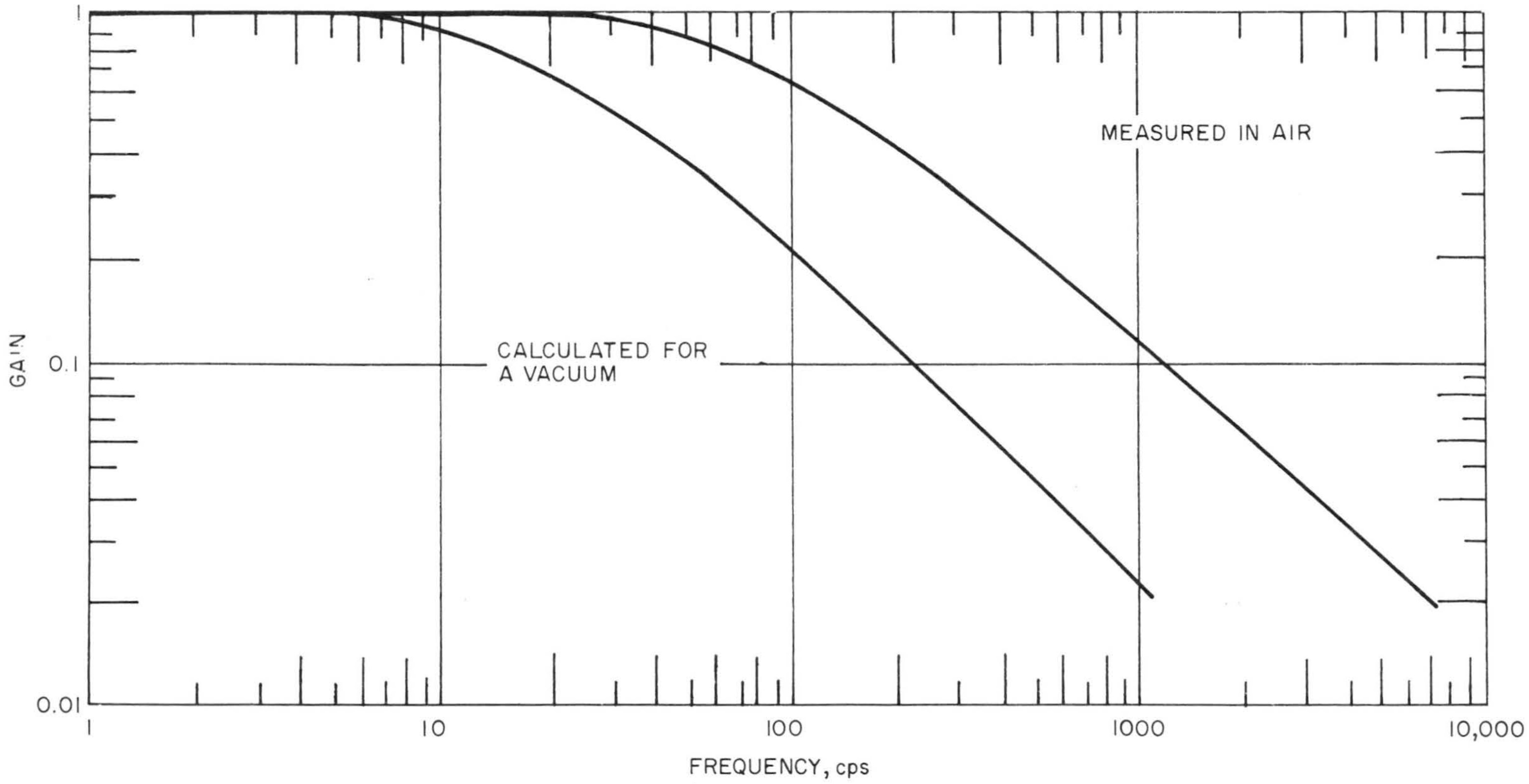

Figure 2 TYPICAL FREQUENCY RESPONSE CURVES FOR A
0.0002-INCH-DIAMETER TUNGSTEN HOT WIRE
63-5536

dT/dt is proportional to the difference in temperature of the element and the gas flow ($T_f - T$). The constant of proportionality τ is the "time constant" of the element. The response characteristics of a first order system can be adequately described by the single time constant τ.

For the hot-wire, resistance-temperature element operating in a vacuum with conduction to the wire supports, the response of the element is not of first order. However, as demonstrated in reference 2, errors of less than 3 percent are made for normal wire operation if the first order terms are employed. For practical applications the wire with conduction only is also treated as a first order system. The general time constant (which physically represents the time required for the hot-wire to reach 63 percent of a step change in conditions) for continuum and vacuum conditions is given by the relation

$$\tau = \frac{1}{\frac{k}{\rho c}\left(\frac{\pi}{l}\right)^2 + \frac{4}{D^2}\,\frac{hD}{\rho c} - \frac{\sigma a}{\rho c}\left(\frac{4}{\pi D^2}\right)^2 I^2} \,. \qquad (2)$$

This relation is approximate in that the general solution cannot be described by a single time constant. The term $(k/\rho c)(\pi^2/l^2)$ corresponds to the conduction part of the time constant and is exact for the limiting value of the vacuum case of a zero size step in conditions. The term $(4/D^2)(hD/\rho c)$ represents the convection part of the time constant. The last term is associated with the electrical heating of the wire. Equation (2) has at present only been checked at its end points of pure conduction and pure convection. For the vacuum case of conduction, the check[2] is good as long as radiation heat loss is negligible. The radiation acts in such a way as to improve the rise time (lower the time constant) for an increasing temperature step.

B. THE HOT-WIRE MANOMETER

In the present application of the resistance-temperature transducer it is operated as a sensor of heat transfer, rather than temperature change. For heat transfer measurements, Joulean heating is employed to heat the sensing element. The temperature of the sensing element can be controlled by the amount of electrical power (Joulean heating) put into the element. The amount of electrical power required to maintain the element at a fixed temperature is a measure of the heat transfer from the element. The steady state energy balance for an element of wire losing heat to the surrounding gas and to the wire supports may be written as

$$q_j = q_g + q_c \,. \qquad (3)$$

The quantity q_j is the rate of production of Joulean heat due to the current I. It is a function of the local resistivity along the wire, which is temperature dependent.

$$q_j = I^2 r \; . \tag{4}$$

$$r = \frac{4\sigma}{\pi D^2}\left[1 + \alpha(t_w - 273)\right] \; .$$

The quantity q_c is the heat loss rate by conduction along the wire to the cooled supports

$$q_c = -\frac{\pi k D^2}{4}\,\frac{d^2 t_w}{dx^2} \; . \tag{5}$$

The heat loss through the ambient gas, q_g, must be obtained from a molecular conduction analysis. It is obvious that the heat conduction away from the sensing element will be a function of the number of molecules available to transport the heat away from the surface. Theoretically, the classical work of Knudsen done in 1911, shows that the heat transfer from a body to a rarified gas is a fundamental function of the mean free path between the molecules and of the accommodation coefficient. The accommodation coefficient, a, (where $a \leq 1$) is necessary to express the imperfect exchange of energy between the element surface and the molecules. The accommodation coefficient is roughly a constant for a given element surface and gas, so it represents a constant of proportionality in the heat transfer relation. The nondimensional parameter of importance in expressing the heat transfer is the Knudsen number, which is the ratio of the mean free path to the hot wire diameter (or a characteristic length associated with the sensing element geometry). The range of operation of the hot-wire manometer depends on the size of the wire. For pressures approaching atmospheric pressures a small diameter wire is required, and at very low pressures a large diameter wire is more sensitive.

From kinetic theory the mean free path between molecules is inversely proportional to the gas density.

$$\lambda = \frac{7.746 \times 10^{-9}}{\rho(\mathrm{gm/cm^3})} = \frac{1.502 \times 10^{-8}}{\rho(\mathrm{slugs/ft^3})} \; . \tag{6}$$

Thus, the heat transfer is directly a function of the gas density. The heat transfer coefficient from the wire can be expressed in terms of the gas density, or more usefully, in terms of gas pressure and temperature,[2]

$$h = \left(\frac{3a}{2}\right)\sqrt{\frac{2R}{\pi M_a T_a}}\;\frac{P}{0.987 \times 10^{-5}} \; , \tag{7}$$

where the pressure is in atmospheres and the factor 0.987×10^{-5} is a conversion factor from atmospheres to newtons per square meter. The quantity q_g is given by

$$q_g = h\pi D\,(T_w - T_a) \quad . \tag{8}$$

Equation (3) is a differential equation of the form

$$\frac{d^{2}T_w}{dx^2} - \eta^2\, t_w = -\eta_1^2 \quad , \tag{9}$$

where

$$\eta^2 = \left(\frac{4h}{k} - \frac{16 I^2 \sigma a}{\pi^2 k\, D^4}\right) \quad \text{and} \quad \eta_1^2 = \left[\frac{4 I^2 \sigma}{\pi^2 k\, D^4}\,(1 - 273a) + \frac{4h\,T_a}{k}\right] .$$

This equation is common in heat transfer problems. The solution for the wire temperature t_w is

$$t_w - T_s = (T_{w,\infty} - T_s)\left(1 - \frac{\cosh \eta x}{\cosh \frac{\eta l}{2}}\right) \quad , \tag{10}$$

where T_s is the wire support temperature and $T_{w,\infty}$, is a term having units of temperature $[T_{w,\infty} \equiv (\eta_1/\eta)^2]$. The length average temperature of the wire is given by integration of equation (10) over the length l.

$$T_w - T_s = (T_{w,\infty} - T_s)\left(1 - \frac{\tanh \frac{\eta l}{2}}{\frac{\eta l}{2}}\right) \quad . \tag{11}$$

For the wire to be effective as a manometer it is evident that the heat loss to the gas is much greater than the heat loss by conduction to the wire supports. From the foregoing analysis the ratio of total heat loss by molecular conduction to total heat loss by conduction is

$$\frac{Q_g}{Q_c} = \left(\frac{hD}{k}\right)\left(\frac{l}{D}\right)^2 \left(\frac{T_w - T_s}{T_{w,\infty} - T_s}\right)\left(\frac{1}{\frac{\eta l}{2}\,\tanh\frac{\eta l}{2}}\right) \quad . \tag{12}$$

Figure 3 is a plot of $\frac{Q_g}{Q_c}$ versus pressure for a 0.0002-inch-diameter tungsten wire and a 0.00025-inch-diameter 80 percent platinum - 20 percent iridium wire. Figure 3 shows that long wires are required to reduce conduction losses in the range of 10^{-4} atmospheres.

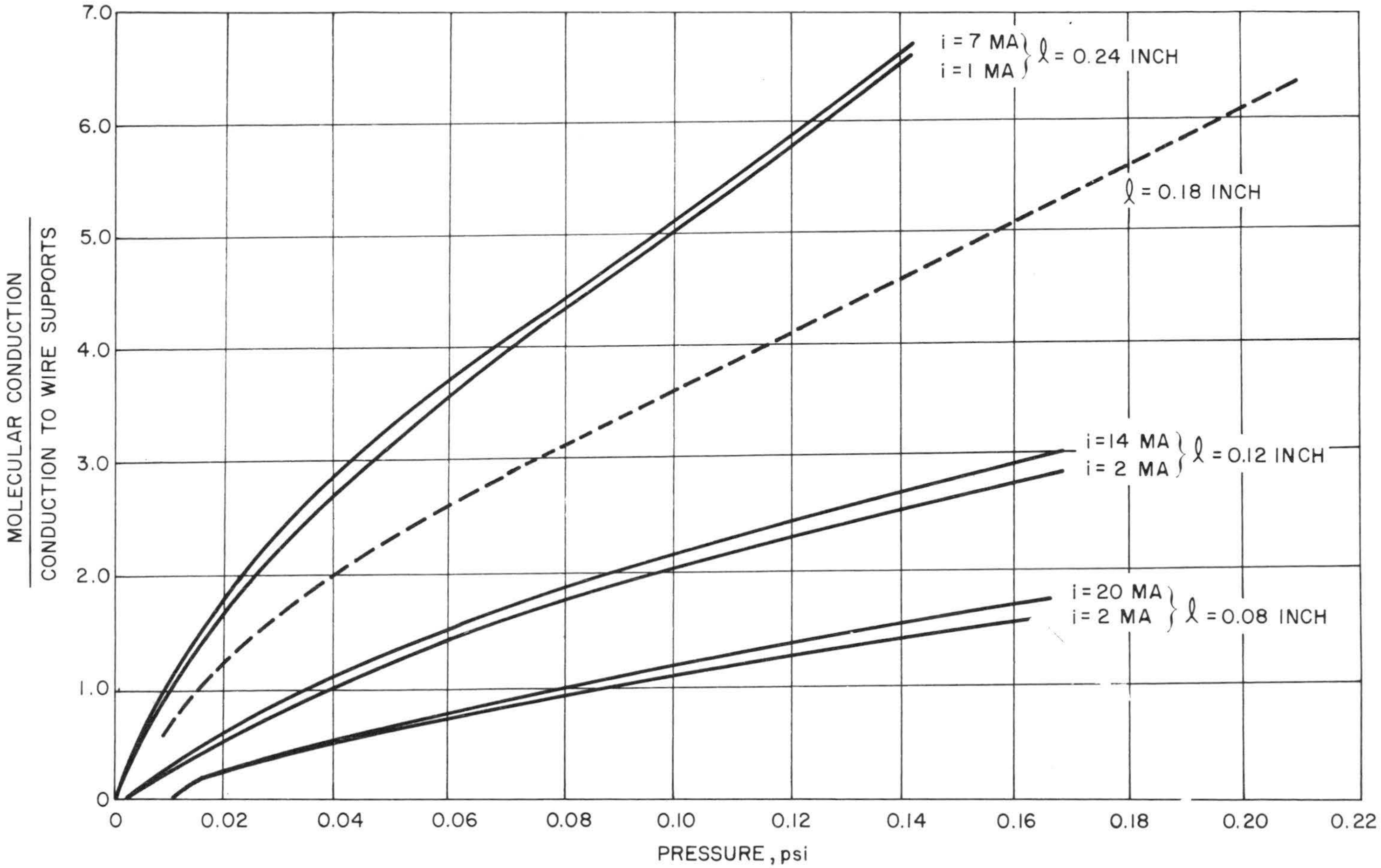

Figure 3 RATIO OF MOLECULAR CONDUCTION IN AIR TO MOLECULAR CONDUCTION TO HOT WIRE SUPPORTS FOR FINITE LENGTH HOT WIRE MANOMETERS

63-5537

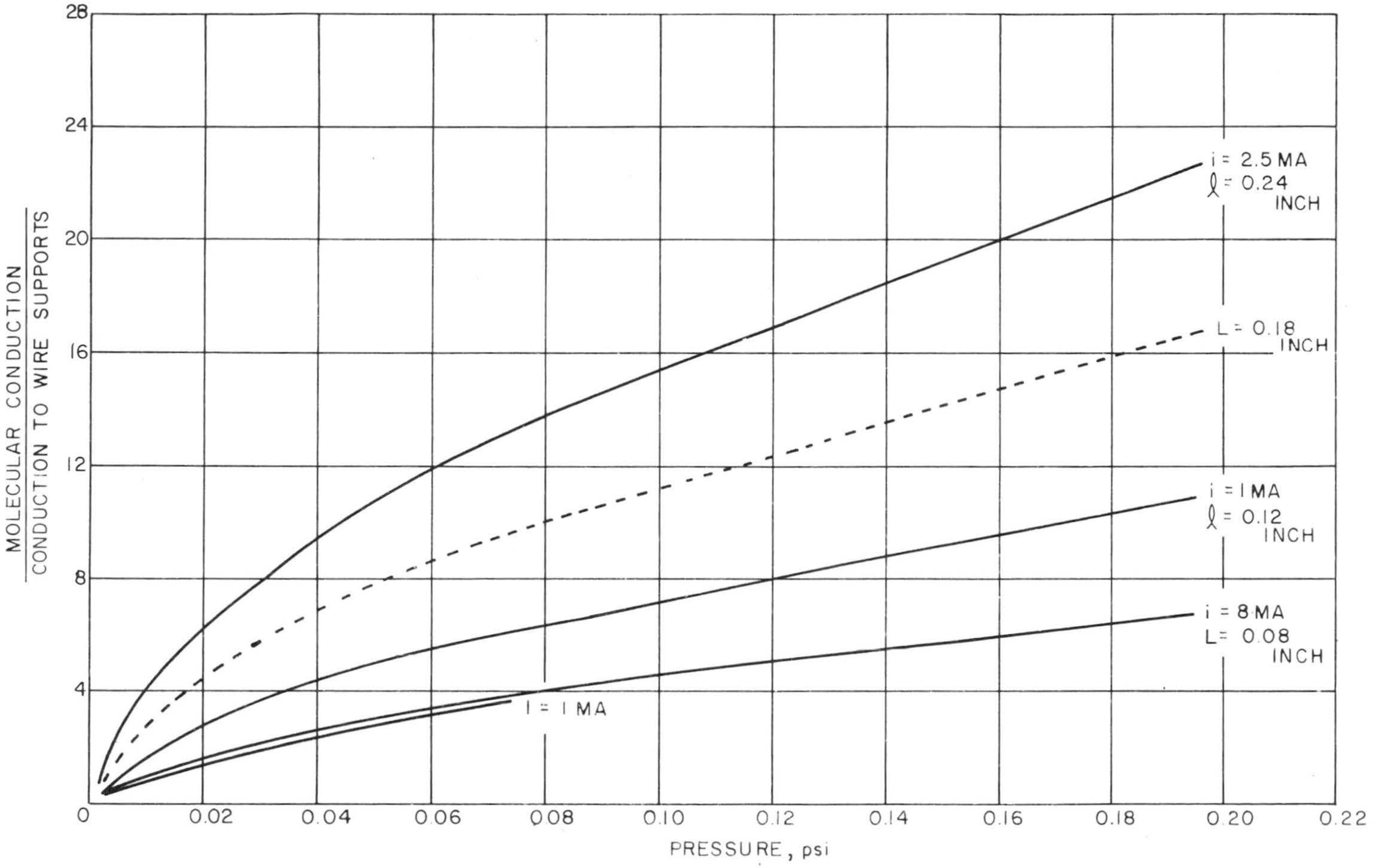

Figure 3 Concluded
63-5538

III. PRACTICAL APPLICATION

A. HOT WIRE SIZE

The basic requirement of the sensing element is that its diameter be comparable with the mean free path between the gas molecules. Figure 4 is a plot of the mean free path length versus gas pressure for different values of gas temperature (equation 6). For the wind tunnel application the pressure range is expected to be between 0.02 and 0.08 psia. At room temperature (297°K) this range of pressure gives mean free paths between 4×10^{-3} and 1×10^{-3}cm. It is found experimentally[3] that the wire diameter should be approximately one-fifth of a mean free path for true free molecule heat transfer. This then suggests that a wire of the order of 2×10^{-4} cm in diameter is desired for the present measurement.

Wires of the order of 10^{-4} cm in diameter are in common use with hot wire anemometers. Two wires, one of tungsten, 5.1×10^{-4} cm in diameter, and the other of 80 percent platinum - 20 percent iridium, 6.3×10^{-4} cm in diameter, were directly available in the laboratory. These two wires, although slightly larger in diameter than indicated above, were evaluated for the present application. In the preceding section it was shown that the basic considerations to be made in selecting the wire sensing element are: 1) the change in resistance with temperature, 2) the conduction loss to the wire supports, and 3) the time constant of the wire. These considerations are somewhat in conflict and compromises are necessary.

Figure 5 compares the variation of the resistance with temperature for the two wire materials considered. The percentage change in resistance for tungsten is greater by a factor of 5 compared to the platinum-iridium, however the resistivity of platinum-iridium is much greater than that of tungsten. This results in a comparable change ΔR in resistance with temperature for the two materials (note that had the platinum-iridium wire diameter been the same as the tungsten the curves of figure 5b would have been even closer together). The output of the instrument is related directly to the change in voltage due to the change in resistance, ΔR, so the two wire materials are comparable in sensitivity, with tungsten being slightly the better of the two. Figure 3 shows that from a conduction loss standpoint the platinum-iridium wire is better than tungsten by a factor of roughly 3.

B. CALIBRATION

The heat transfer from a wire to the surrounding gas is given by equation (7). However, in practice it will be found best to calibrate a wire directly. The uncertainty in accommodation coefficient, wire diameter, and wire physical properties make theoretical calculations difficult. For practical measurements the hot wire may be operated either in a constant current or a constant resistance circuit. For constant current operation the wire is placed across

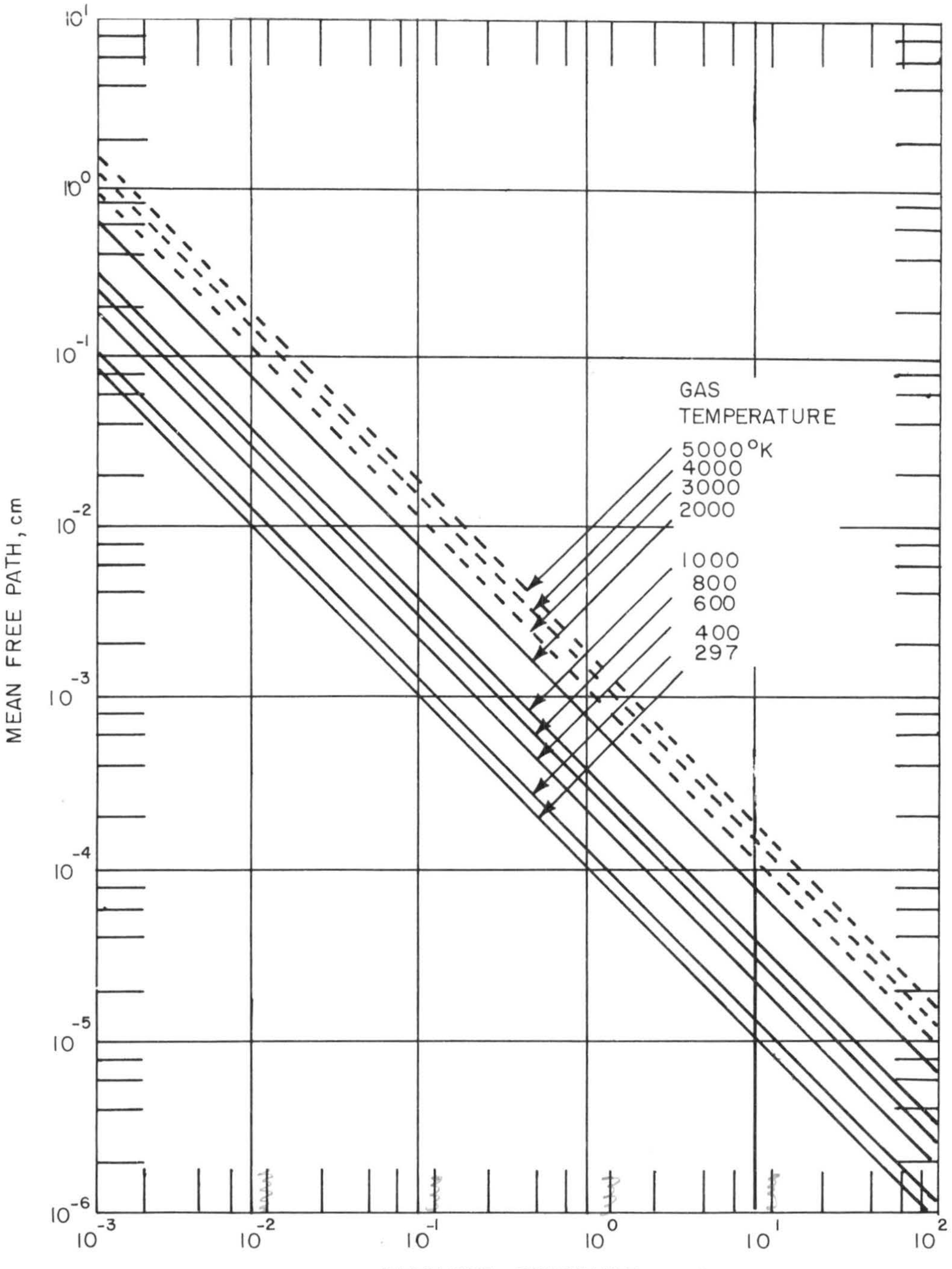

Figure 4 MEAN FREE PATH BETWEEN MOLECULES IN AIR (IDEAL GAS, $Z=1$)
63-5539

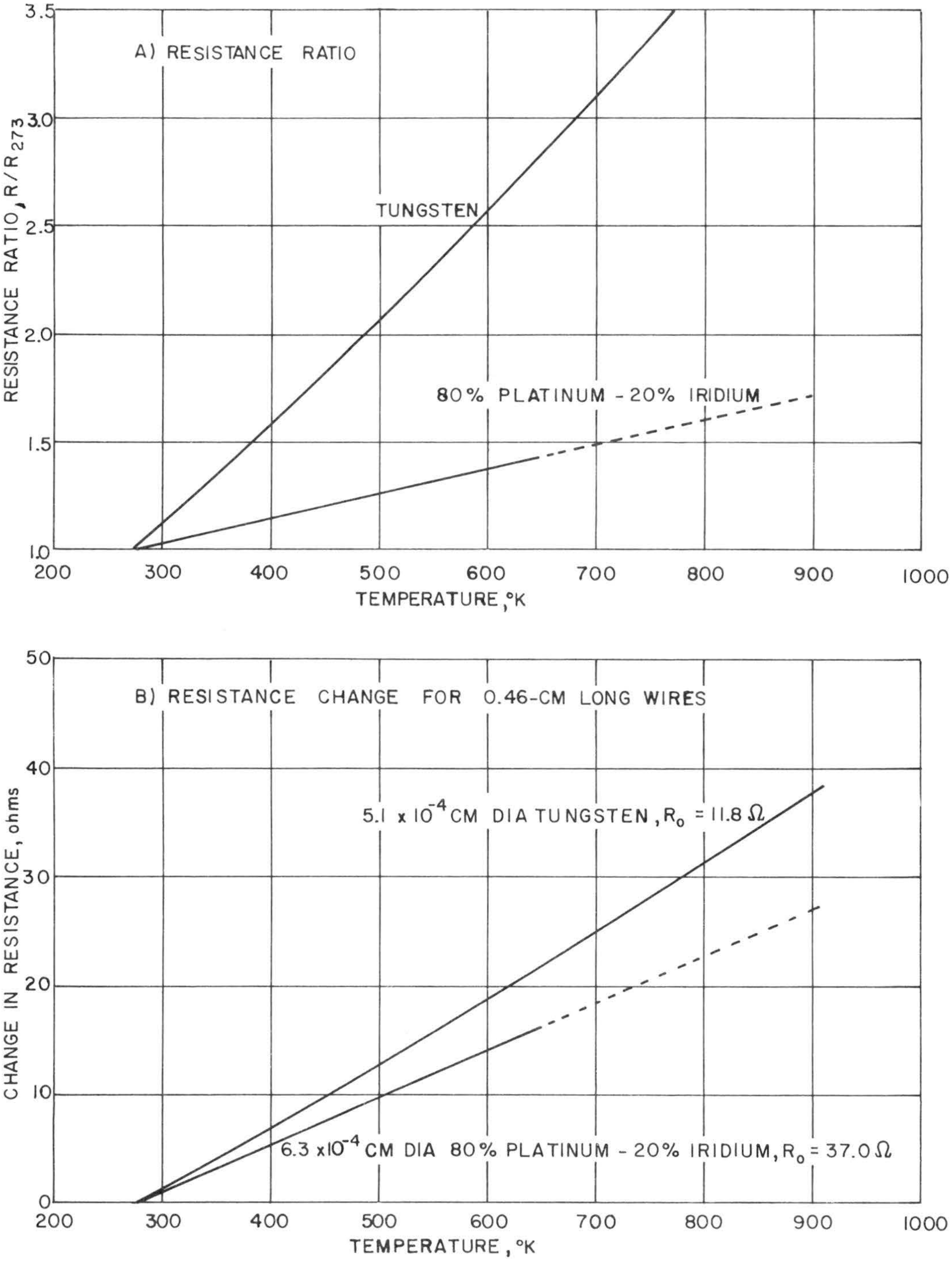

Figure 5 HOT WIRE RESISTANCE VARIATION WITH TEMPERATURE
63-5540

a constant current source of very high impedance. The voltage drop measured directly across the wire is then related directly to the wire resistance. With the current held constant the heat loss from the wire varies as the wire resistance. The second method varies the current through the wire, so that the resistance of the wire remains fixed. Constant resistance operation is obtained by operating the hot wire at one arm of a Wheatstone bridge. A measure of the voltage drop across the wire is an indication of the heat loss from the wire. Figure 6 shows typical calibration curves for the two wire materials. Both the constant current and the constant resistance curves are shown on the plots. The curves show that the wire sensitivity increases with either increased current or resistance. The greatest sensitivity is obtained by operating the wires at constant mean resistance.

The maximum operational temperature of tungsten is restricted to less than 600°K because of oxidation. The oxidation changes the resistance of the wire, so that the calibration changes with time. At the high temperatures some heat loss due to radiation will occur. As long as operation and calibration conditions are similar, the end loss and radiation errors are accounted for by the calibration.

C. TIME CONSTANT

The important aspect of the present instrument is its ability to follow transient changes in pressure. The time constant of the hot wire is given by equation (2). The dimensional terms in equation (2) are listed below for the two wire materials.

	Tungsten	80 Percent Platinum 20 Percent Iridium
$\frac{k}{\rho c}$ (cm^2/sec)	0.642	0.0881
$\frac{4}{\rho c}$ (cm^3 °K/watt-sec)	1.60	1.38
$\frac{\sigma a}{\rho c}$ (ohm-cm^4/watt-sec)	1.12×10^{-8}	9.63×10^{-9}

For identical wire lengths, tungsten will have a support conduction time constant almost an order of magnitude faster than platinum-iridium. This of course was already reflected in the greater conduction losses shown for tungsten in figure 3. The pure support conduction time constant of tungsten is 33 msec compared to 226 msec for platinum-iridium (where both are based on a wire length of 0.46 cm and a zero current step). For the range of pressures of interest in the present application the molecular conduction term $\frac{4h}{\rho c D}$ will be the major determinate of the time constant. The current term, $\frac{\sigma \alpha}{\rho c} \left(\frac{4}{\pi D^2} \right)^2 I^2$, for the present operating conditions is roughly equal to or less than the support conduction term.

The frequency response of the platinum-iridium wire was experimentally determined by measuring the increase in wire resistance due to a step increase in heating current. A fast acting switch (less than 10 μsec) was used to impose the step increase in current on the circuit. Typical traces are shown in figure 7. The measured time constants, defined as the time to reach 63 percent of the final voltage level, are plotted on figure 8. The data at very low pressures apparently shows considerable effect of radiation heat loss. The radiation acts in such a way as to reduce the time constant, however it also causes a departure from the first order response curve. The current step used for the measurements was 10 ma, so that the temperature of the wire was increasing as the pressure decreased. A similar effect of radiation reducing the time constant was reported in reference 2.

A limited amount of data for the tungsten wire is shown as the dashed curve on figure 8. Over the range from 0.02 to 0.08 psia, the frequency response (to a sine wave) of the tungsten wire is 20 to 30 cps and the platinum-iridium wire is 7 to 14 cps.

D. FREQUENCY RESPONSE IMPROVEMENT

The tungsten wire by itself is capable of following the expected pressure fluctuations encountered on the wind tunnel model. However, by employing electronic improvement the frequency response of either the tungsten or the platinum-iridium wire can be greatly increased. Amplifiers are available to maintain the wire at constant resistance in a Wheatstone bridge, and by a feedback servo control the frequency response can be increased by as much as a factor of 500. A typical calibration curve of output voltage versus pressure for the amplifier operating the platinum-iridium wire is shown in figure 9. Figure 10 is a photograph of a small "amplifier" which has been employed to improve the present wire's response to values greater than 300 cps.

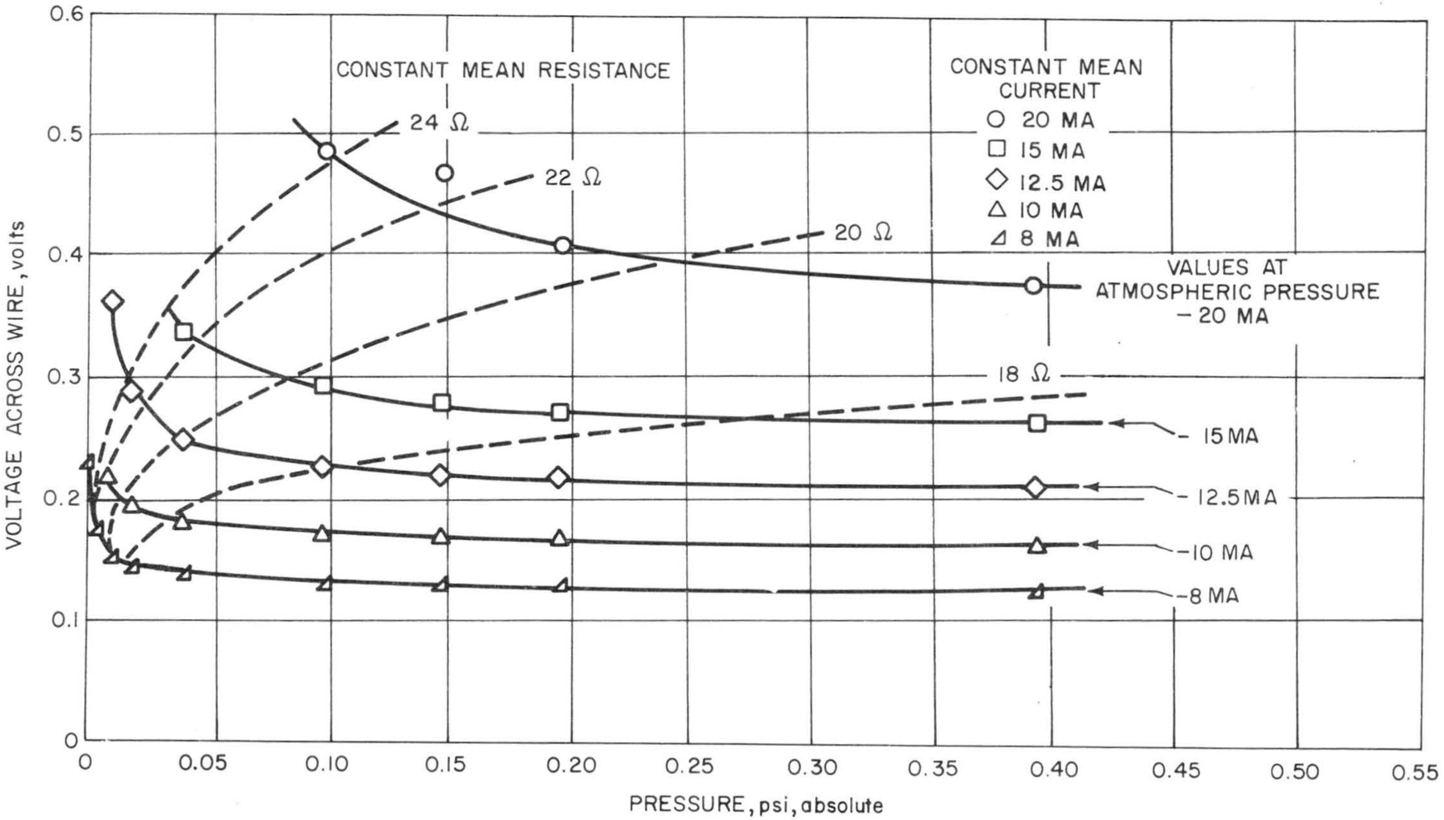

Figure 6 CALIBRATION OF A 0.0002-INCH DIAMETER BY 0.175-INCH-LONG TUNGSTEN WIRE AS A FUNCTION OF PRESSURE
63-5541

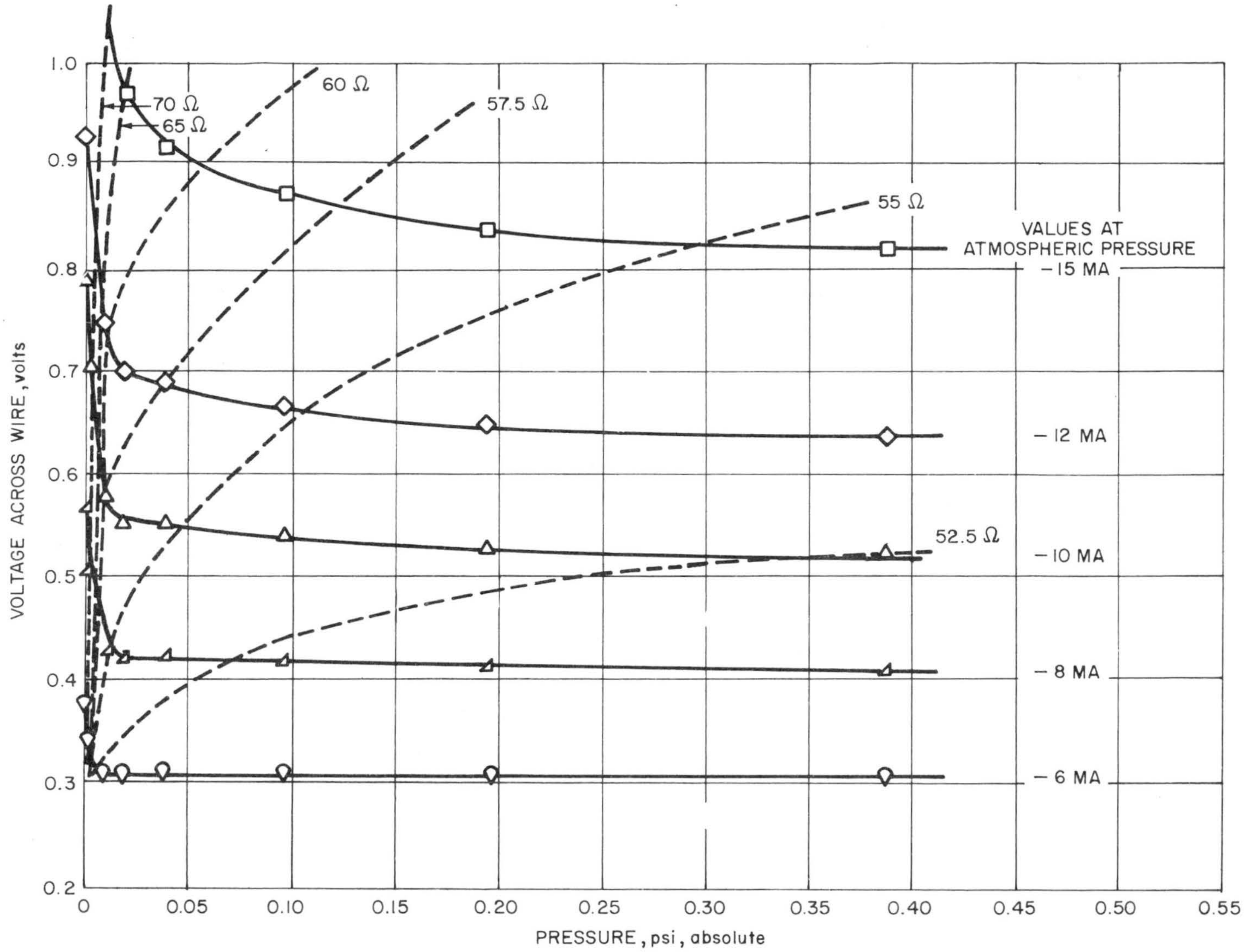

Figure 6 Concluded
63-5542

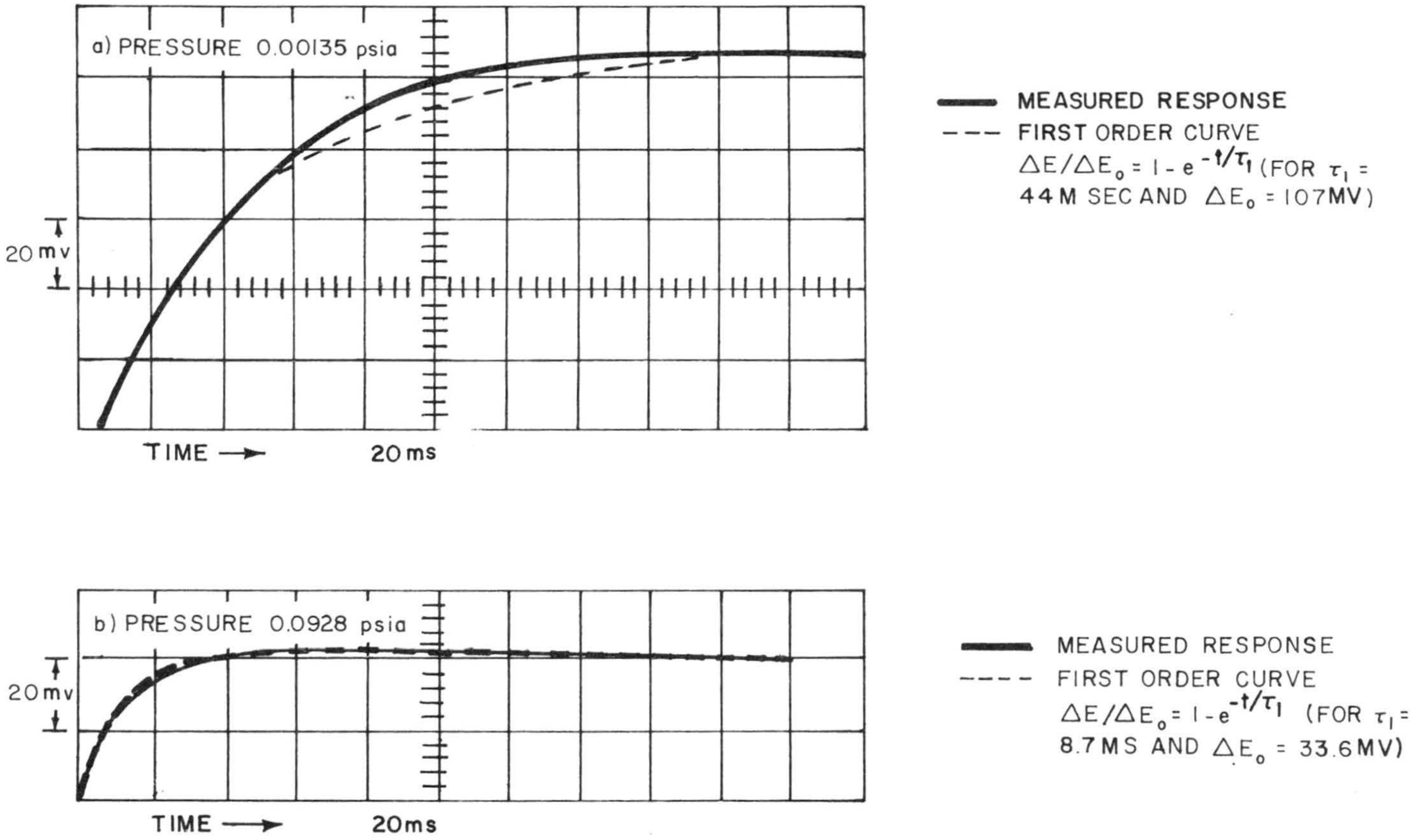

Figure 7 TYPICAL MEASURED WIRE RESPONSE TO A 10 MA STEP CHANGE IN HEATING CURRENT 0.00025-INCH DIAMETER BY 0.18-INCH-LONG PLATINUM - IRIDIUM WIRE
63-5543

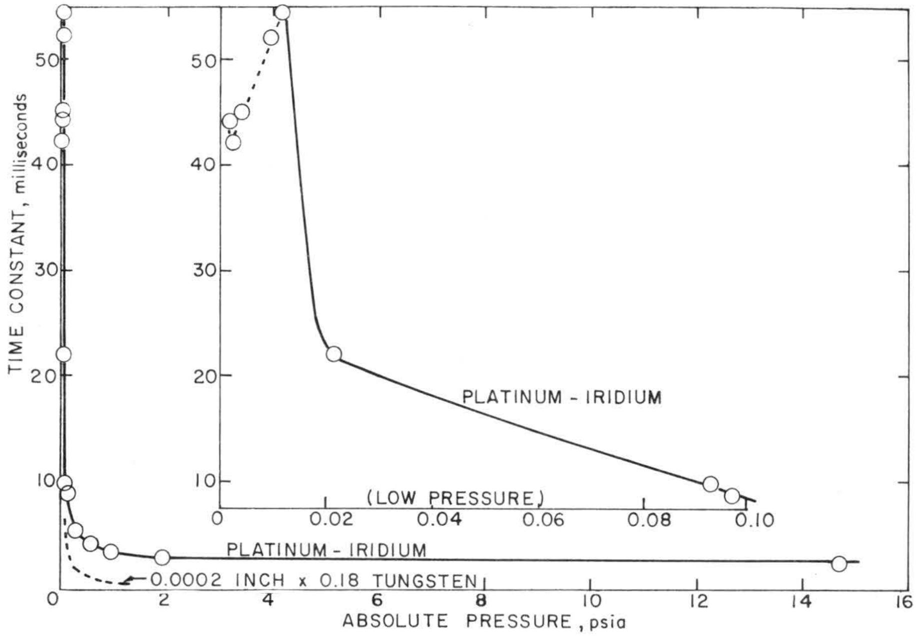

Figure 8 MEASURED TIME CONSTANT OF A 0.00025-INCH DIAMETER PLATINUM-IRIDIUM WIRE 0.18-INCH LONG
63-5544

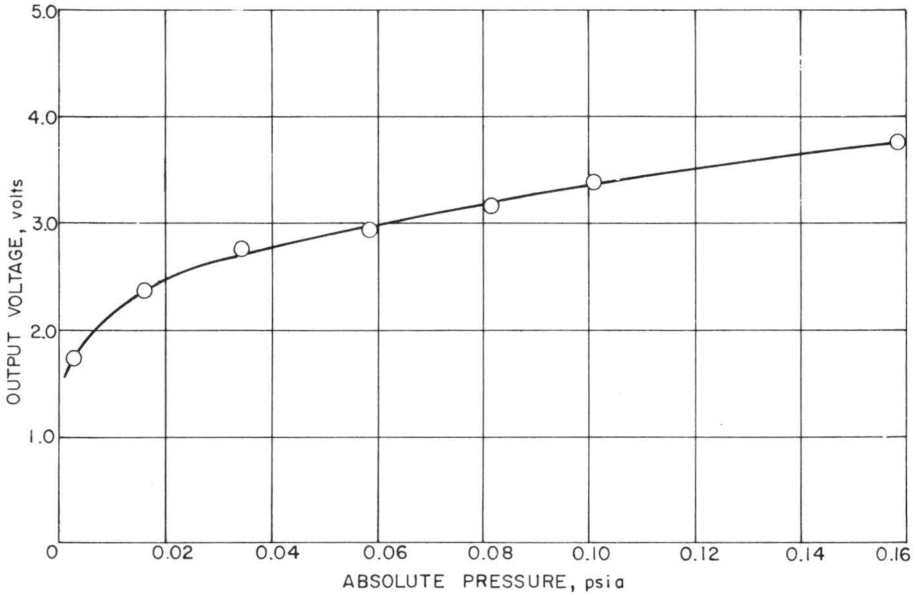

Figure 9 TYPICAL BRIDGE OUTPUT VOLTAGE CALIBRATION OF THE 0.00025-INCH-DIAMETER BY 0.18-INCH-LONG PLATINUM-IRIDIUM WIRE
63-5544

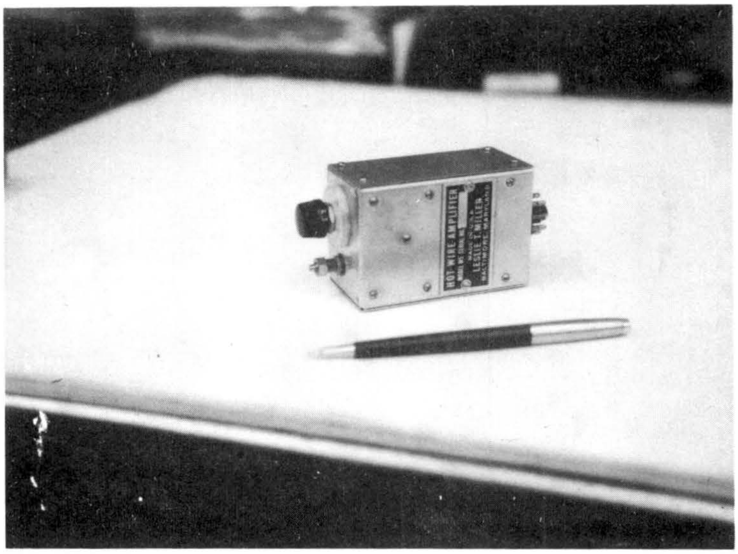

Figure 10 CONSTANT TEMPERATURE HOT WIRE AMPLIFIER

IV. PHYSICAL DESIGN

An instrument to meet the present wind tunnel requirements seems feasible using the equipment described above. The platinum-iridium wire is suggested for several reasons:

1) It has a better molecular to wire support conduction ratio.

2) It can be operated at higher temperatures without oxidation.

3) The lead resistance for the particular application will be quite high, so the higher the sensing element resistance, the less lead error correction effect.

The hot-wire amplifier would be employed to ensure that the frequency response of the sensing element is well above the expected time variation in the pressure.

One problem that has not been considered is the effect of changing gas temperature on the hot-wire pressure calibration. The calibrations shown in figures 6 and 10 were made at a constant value of gas temperature, however this will not be the case for the wind tunnel tests. The instrument is basically a sensor of gas density rather than pressure, so a pressure calibration is not valid if the gas temperature changes. The problem can be further complicated by the end loss and radiation errors changing with gas temperature. The practical solution is to measure the gas temperature at the same time the heat transfer is measured. The vacuum gage should be calibrated at several temperatures (covering the temperature range of operation), so that end loss and radiation effects are, so to speak, calibrated out of the instrument.

The present experiments were made with a wire 0.46 cm long. This length appears adequate for the final instrument, however it should be apparent that a longer wire is desirable to reduce the end losses. The measurement of temperature would be made with a wire identical to the pressure sensing wire, only operated as a resistance thermometer.

The time response of the cavity in which the hot wire is operated may pose a limit to the instrument frequency response. In the foregoing analysis it was assumed that the time to fill the cavity is short compared to the wire time constant. The cavity can be made rectangular of roughly 0.7 by 0.25 cm dimensions. To decrease the fill time, a slit rather than the usual "static tap" hole might be employed over the 0.7 cm length of the cavity.

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