



Research on a dielectric breakdown probe for measuring the density of a flowing gas
by Paul Matthew Jurenka

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:

The use of a diagnostic probe to measure the pitot density of supersonic flow was investigated for this research. The breakdown probe operates on the well known Paschen similarity principle which states that the dielectric breakdown voltage of a gas is a function of gas density only. The effects of ionization enhancement mechanisms such as radioactivity and ultraviolet illumination on the electrodes of the breakdown gap have been investigated. The use of ultraviolet illumination greatly improves the operation of the probe. The tests using radioactivity as an ionization enhancement mechanism were inconclusive because of the relative weak strength of the radioactive source used. The Paschen theory predicts that the breakdown voltage is a function of density only and not pressure and temperature acting alone. This was proven to be the case by breakdown probe experimentation. The relations between the stream density and pitot density in supersonic flow have been resolved for different flow conditions. One relation states that the free stream density can be directly found from a measurement of the pitot density provided that the Mach number is sufficiently high. A probe tested in a supersonic flow field measured the mean pitot density reasonably well when compared with other pitot density measuring instruments. In the worst case the probe was off 30% but in the best case the probe was almost exact in measuring the pitot density. An investigation was made into using a breakdown probe for measuring turbulent density fluctuations. Only rough trends in density fluctuations were measured in supersonic flow because the instrumentation used for the fluctuation measurements proved to be unreliable.

**RESEARCH ON A DIELECTRIC BREAKDOWN PROBE FOR
MEASURING THE DENSITY OF A FLOWING GAS**

by

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**A thesis submitted in partial fulfillment
of the requirements for the degree**

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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NOMENCLATURE

Symbol	Description
ASR	Automatic single ramp
BP	Breakdown probe
C	Celsius
CDAS	Computerized data acquisition system
d	Electrode separation distance
dc	Direct current
F	Fahrenheit
i	Current
M	Mach number
MSU	Montana State University
mil	0.001 inch
N	Total number of ramp pulses
P	Pressure
R	Gas constant
S	Sensitivity coefficient for a breakdown probe
SWT	Supersonic Wind Tunnel
T	Temperature
UV	Ultraviolet
u	Streamwise velocity component
V	Voltage
γ	Specific heat ratio

NOMENCLATURE—Continued

Γ	Electron emitted per incident position ion
τ	Voltage ramp pulse duration
ρ	Gas density
μCi	Microcurries
$\partial()$	Partial derivative of quantity
$d()$	Small, time-dependent fluctuation of the quantity
$()'$	R.M.S. value of a property
$()_b$	Condition at breakdown
$()_o$	Flow stagnation property
$()_p$	Probe pitot quantities
$()_2$	Condition after a normal shock

ABSTRACT

The use of a diagnostic probe to measure the pitot density of supersonic flow was investigated for this research. The breakdown probe operates on the well known Paschen similarity principle which states that the dielectric breakdown voltage of a gas is a function of gas density only. The effects of ionization enhancement mechanisms such as radioactivity and ultraviolet illumination on the electrodes of the breakdown gap have been investigated. The use of ultraviolet illumination greatly improves the operation of the probe. The tests using radioactivity as an ionization enhancement mechanism were inconclusive because of the relative weak strength of the radioactive source used. The Paschen theory predicts that the breakdown voltage is a function of density only and not pressure and temperature acting alone. This was proven to be the case by breakdown probe experimentation. The relations between the stream density and pitot density in supersonic flow have been resolved for different flow conditions. One relation states that the free stream density can be directly found from a measurement of the pitot density provided that the Mach number is sufficiently high. A probe tested in a supersonic flow field measured the mean pitot density reasonably well when compared with other pitot density measuring instruments. In the worst case the probe was off 30% but in the best case the probe was almost exact in measuring the pitot density. An investigation was made into using a breakdown probe for measuring turbulent density fluctuations. Only rough trends in density fluctuations were measured in supersonic flow because the instrumentation used for the fluctuation measurements proved to be unreliable.

CHAPTER 1

INTRODUCTION

In the area of supersonic and hypersonic research there is a definite need to measure flow variables such as density, pressure, temperature, and velocity at various points in a flow. Normally, a measurement of three variables combined with the equation of state, isentropic relations, and normal shock theory will define the flow. The standard practice is to use a pitot tube to measure pitot pressure, a pitot temperature thermocouple to measure total temperature, and a static pressure sensor. A pitot density measurement combined with any two of the three measurements mentioned above would give the local flow variables. One advantage of using the pitot density measurement is that it becomes sensitive to the stream density only as the Mach number tends to infinity, as shown in Chapter 3. Thus one of the flow variables can be measured directly at high hypersonic Mach numbers with a pitot density measuring device. This research is aimed at developing a density measuring instrument called a "breakdown probe".

To the best knowledge of this author there has not been a "pitot" density measurement technique yet reported. Previous attempts at using electrical discharges to measure flow properties have included investigations by Lindvall [1] and Werner [2]. Both researchers studied the effects of using a "glow discharge" to measure pressure and velocity in subsonic flow. Other density measurement techniques include the use of optics to measure averaged density gradients.

The underlying operating principle of the breakdown probe is the well known phenomenon that the dielectric breakdown strength of a gas between two electrodes is a unique function of the gas density and the applied voltage on the electrodes. The breakdown voltage versus density characteristic of an electrode gap is characterized by the Paschen similarity principle which will be explained at the beginning of Chapter 2.

Basically, the breakdown probe and driving circuit operate as follows. First, the applied voltage difference of two closely spaced electrodes is steadily increased. The voltage difference will reach a point where a spark will jump the electrode gap as the gas is transformed from an insulator to a conductor (condition of "breakdown" explained in Chapter 2). Once breakdown has occurred, the circuit is interrupted and the breakdown voltage is recorded. The voltage necessary to initiate the spark is a unique function of the gas density for a given electrode configuration, driving circuit, and gas.

The breakdown probe is calibrated in a static environment of known gas density to determine its breakdown voltage versus density characteristic. With the characteristic known the probe can be used to measure the pitot density in a flowing gas. Since the electrodes of the probe will be located at the stagnation point on the probe tip where the fluid comes to a stop, the breakdown voltage versus pitot density characteristic is identical to the characteristic obtained in a static calibration. A measurement of the breakdown voltage in a flowing gas will therefore directly give the pitot density.

From the pitot density other flow variables such as stream density can be calculated from compressible flow theory. For instance, as stated earlier at hypersonic Mach numbers the pitot density is a known function of the stream density

only. From a measurement of the pitot density the stream density can be closely estimated even at lower Mach numbers.

The goal of this research is to prove that a breakdown probe can be used to measure the density of a moving air stream. Several tests were devised to prove the utility of the probe under different operating conditions. The reliability and repeatability of the probe to measure density will be demonstrated. A more thorough discussion of the research goals will be given in Chapter 4.

CHAPTER 2

DIELECTRIC BREAKDOWN PRINCIPLE REVIEW

Introduction

The theory of dielectric breakdown of a gas is discussed in considerable detail by Cobine [3] and Flugge [4]. For brevity only the theory directly related to this research topic will be discussed.

To understand the dc breakdown of a gas, consider a gap formed in a gas by two parallel plane electrodes. An applied voltage across the electrodes will create a voltage gradient in the gas and initiate the breakdown process. The gas usually acts as an electrical insulator but can begin conducting electricity beyond a sufficient voltage potential. An observation of the voltage-current characteristic of a dc discharge along with an explanation of the electron-ion collision phenomena is needed to understand the complex events leading to the breakdown of a gas.

Primary Electrons

The breakdown events are initiated by a free electron (primary electron) that is released into the gas. The origin of these primary electrons is both natural (ambient electrons, cosmic rays, etc.) or artificial (impressed electron generation e.g. from photo-irradiation of the electrodes or the gas with ultraviolet light, X rays, radioactivity, etc.). When an electric field is applied on the electrodes the primary electrons are accelerated in the direction of the anode. The electrons eventually gain kinetic energy until they impact gas atoms with sufficient energy to produce ionization. From ionization additional free electrons and positive charged ions are

produced. The positive charged ions are accelerated by the electric field towards the cathode. This motion is opposite that of the electron and the combined drift of the electrons and the ions leads to a small net current across the gap. The voltage-current characteristic of this "dark" discharge is shown in Figure 1 in the region between points A and B.

As shown in Figure 1, at low voltages the multiplication of electrons by ionization is insufficient to lead to a self-sustaining discharge (an arc). The current can only be increased by increasing the electrode voltage as shown in the region from point A to B.

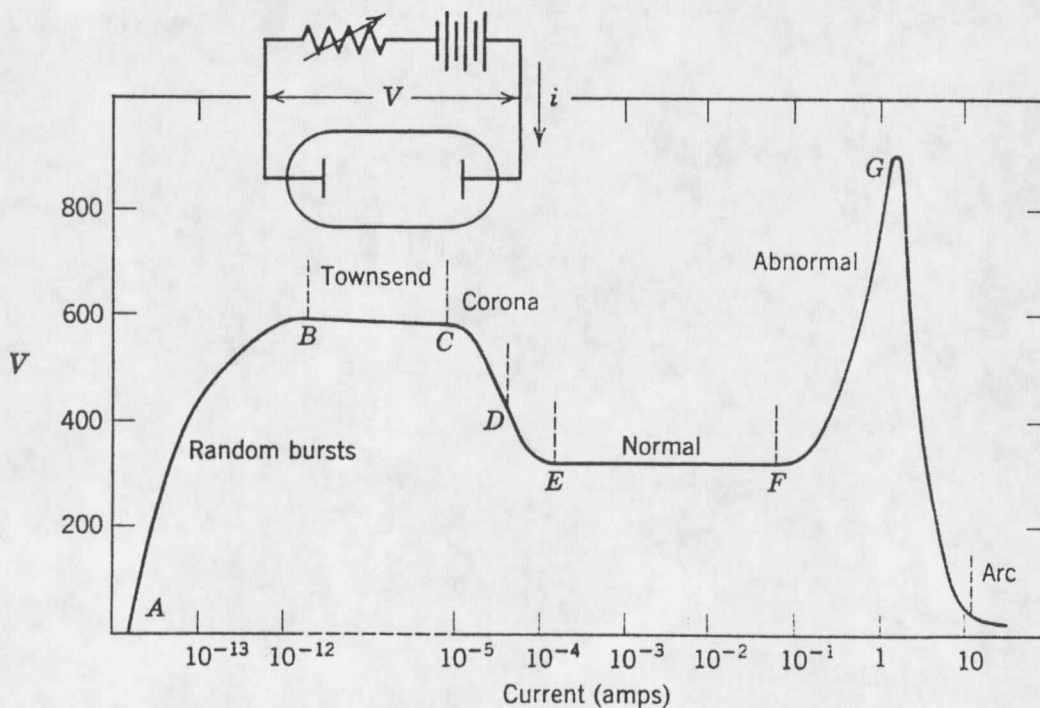


Figure 1. Voltage-Current Characteristics of a dc Discharge.
(Reproduced from [5].)

Secondary Electrons

A positive ion that impacts the cathode will knock loose electrons from the cathode which try to neutralize the positive charge of the ion. Several more electrons than the one necessary to neutralize the ions charge may be released. The excess electrons (secondary electrons) are now free to participate in the ionization process. The collision process then continues with multiple electrons and ions.

The ratio (Γ ratio) of the production of secondary electrons per ion pair formed in the gas is an important determining factor in the formation of an arc. To maintain the current in breakdown, a sufficient number of secondary electrons must be formed to replace the initial primary electrons. If the electrode voltage is large enough every primary electron will be replaced by a secondary electron which leads to an avalanche of electrons across the gap. An arc extends across the electrodes with the corresponding drop in voltage and with a significant increase in current (Past point G in Figure 1).

Breakdown Characteristic

The breakdown voltage, V_b (Point G in Figure 1), is a unique function of gas pressure, P , and electrode separation, d , which is known as Paschen's similarity principle [6]. The constants A and B are different for each gas (for air, $A = 14.6$ [1/cm mm Hg] and $B = 365$ [volts/cm mm Hg]).

$$V_b = \frac{BPd}{\ln \left[\frac{APd}{\ln(1/\Gamma)} \right]} \quad (1)$$

The usual practice in the gas discharge literature of referring to V_b as dependent on the gas pressure can be misleading when the density should be correctly mentioned as the cause. (The "pressure" nomenclature originated in the discovery

that avalanche ionization, i.e. Townsend's "first" coefficient depends on the pressure.) The breakdown voltage is a function of the number of collisions between electrons and gas atoms while the electrons are being accelerated in the electric field. Closer spaced gas atoms result in more collisions. While the product of pressure and gap separation distance does represent the number of atoms in the space between electrodes, it does not take into account the temperature of the gas. Thus the gas density is a better representation of the number of gas atoms in the path of an electron. In this context, the attainment of ionizing energies and hence of voltage breakdown, is controlled only by the interelectrode voltage and the gas density.

A typical breakdown voltage versus density characteristic (data points generated from this research) is shown in Figure 2. Experiment and semi-empirical theory show that V_b initially decreases as density increases, reaches a minimum and then increases as density continues increasing. Typical minimum V_b are of order 100-600 volts (about 350 volts for air). According to Brown [7], the shape of the V_b versus ρ characteristic is controlled by the response of the Γ ratio to different pressures. At low pressure, the controlling Γ process is electron emission by positive ions striking the cathode. At high pressures the controlling process is photoelectric emission of electrons from the cathode. The minimum in the characteristic curve is the result of the two competing Γ factors at different pressures and will occur at about the pressure where the mean free path of an electron is equal to the electrode spacing. To the left of the minimum the necessary breakdown voltage increases since the electrons can traverse the gap with less and less chance of producing an ionizing collision as the pressure decreases. The slower increase to the right of the minimum is caused by the electrons obtaining less and less energy between collisions as the pressure increases.

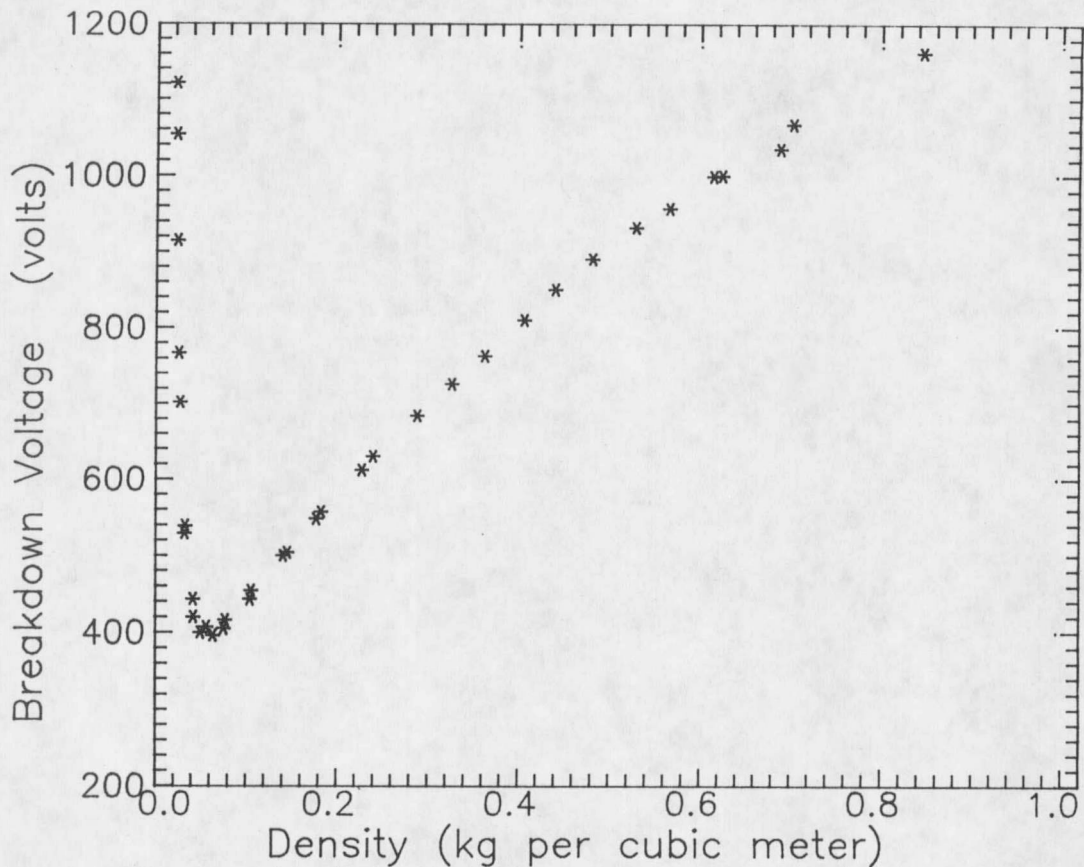


Figure 2. Typical Paschen Characteristic Curve.
(Data points taken from this research.)

The numerical dependence of V_b on density depends greatly on both controllable and uncontrollable factors. Controllable factors include the electrode shape, arrangement, and material, along with the driving electrical circuit. Uncontrollable factors include the surface condition of the electrodes (dust, oxidation, etc.) along with the presence of ionizing agents (X rays, light rays, etc.) and the gas impurities (trace contaminants, water vapor, etc.). Because of the above reasons it is necessary to limit the scope of the research to the use of a single electrode geometry in a single gas.

CHAPTER 3

DENSITY MEASUREMENTS IN COMPRESSIBLE FLOW

It is desired to find the stream density in supersonic flow by measuring the probe stagnation density (pitot density). When a probe is placed in a supersonic flow a bow shock will form in front of the probe tip. The equations that relate the stream density to the pitot density through the shock wave will now be presented.

Definitions

In the following discussion (refer to Figure 3) the probe pitot quantities will be denoted by the subscript " p ", the flow conditions after the normal shock by the subscript " 2 ", and the free stream quantities will be unsubscripted. Small, time dependent fluctuations of the quantities from the steady-state (ρ , u , T , etc.) will be represented by the differential sign $d\rho$, du , dT , etc.

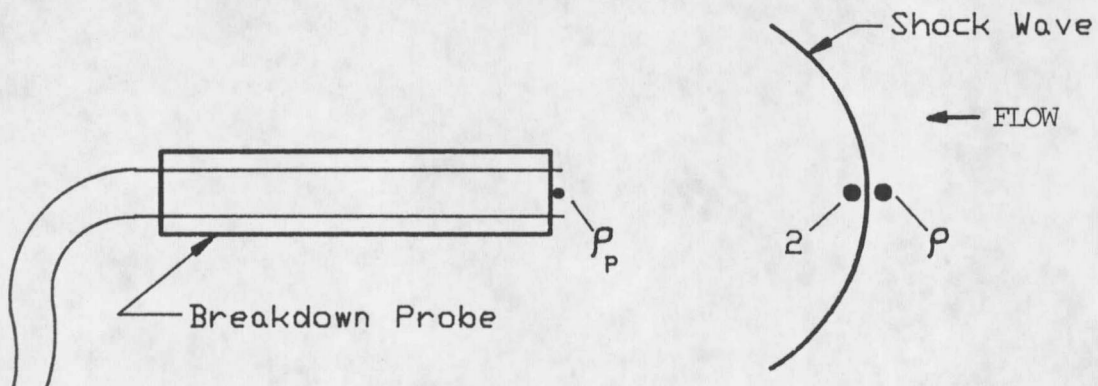


Figure 3. Nomenclature Used to Define Variables.

Pitot Density Relation

The ratio between the probe pitot density and the free stream density can be derived starting with Rayleigh's supersonic pitot formula. Rayleigh's pitot formula [8] relates the probe pressure and free stream pressure as a function of Mach number.

$$\frac{P}{P_p} = \frac{\left[\frac{2\gamma M^2}{\gamma+1} - \frac{\gamma-1}{\gamma+1} \right]^{\frac{1}{\gamma-1}}}{\left[\frac{(\gamma+1)M^2}{2} \right]^{\frac{\gamma}{\gamma-1}}} \quad (2)$$

From the ideal gas law, the free stream density is given by

$$\rho = \frac{P}{RT} \quad (3)$$

where similarly the probe stagnation density is

$$\rho_p = \frac{P_p}{RT_p} \quad (4)$$

Combining equations (3) and (4) gives the pitot density relation:

$$\frac{\rho_p}{\rho} = \frac{\left[\frac{P_p}{RT_p} \right]}{\left[\frac{P}{RT} \right]} = \left[\frac{P_p}{P} \right] \left[\frac{T}{T_p} \right] \quad (5)$$

For adiabatic flow the total temperature T_o must be constant throughout the flow. The relation between the free stream temperature and the pitot temperature is then given by:

$$\frac{T}{T_p} = \frac{1}{1 + \frac{(\gamma-1)M^2}{2}} \quad (6)$$

The pitot density relation (7) is found by substituting equations (2) and (6) into (5) and simplifying the like terms.

$$\frac{\rho_p}{\rho} = \left[\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)} \right]^{\frac{1}{\gamma-1}} \left[\frac{(\gamma+1)M^2}{(\gamma-1)M^2 + 2} \right] \quad (7)$$

For brevity the pitot density relation will be defined by the function $F(M)$. The pitot density relation for air is plotted in Figure 4.

$$F(M) \equiv \frac{\rho_p}{\rho} \quad (8)$$

High Mach Number Relation

The stream density can be found directly from the pitot density provided that the Mach number is sufficiently high. This is shown by examining the pitot density relation as the Mach number approaches infinity.

$$\lim_{M \rightarrow \infty} \frac{\rho_p}{\rho} = \left[\frac{(\gamma + 1)^2}{4\gamma} \right]^{\frac{1}{\gamma-1}} \left[\frac{\gamma + 1}{\gamma - 1} \right] \quad (9)$$

For air, $\gamma = 1.4$, the high Mach number pitot-density relation becomes

$$\frac{\rho_p}{\rho} = 6.438 \quad (10)$$

As shown in the plot of the pitot density relation (Figure 4), the pitot density relation approaches the asymptotic value of 6.438 even at relatively lower Mach numbers. For example, even if it is assumed that equation (10) holds for lower Mach numbers at Mach 7 the error is less than 10%, at Mach 10 the error is less than 5%.

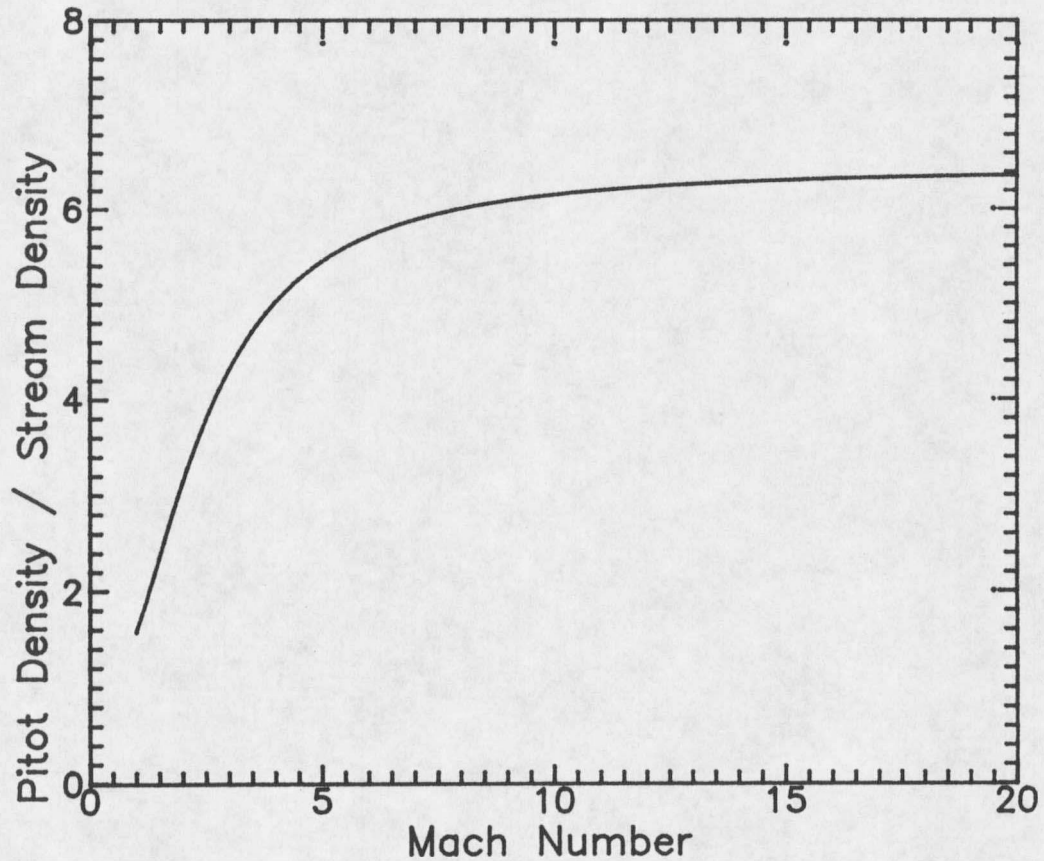


Figure 4. Pitot Density Relation For Air ($\gamma = 1.4$).

Density Fluctuation Measurement

General Case

Quantitative stream fluctuation data can be found from a measurement of the mean (ρ_p) and fluctuating pitot density ($d\rho_p$). The equations relating $d\rho_p$ to other fluctuations (dp , du , dT) are derived by differentiating the pitot density relation (8).

$$\frac{d\rho_p}{\rho_p} = \frac{d\rho}{\rho} + \frac{dF}{F} \quad (11)$$

The $F(M)$ functional derivative term can be expressed as

$$\frac{dF}{F} = \left[\frac{M^2}{F} \frac{\partial F}{\partial M^2} \right] \left[\frac{dM^2}{M^2} \right] \quad (12)$$

The first product term in brackets in equation (12) will be defined as the function $G(M)$.

$$G(M) \equiv \frac{M^2}{F} \frac{\partial F}{\partial M^2} \quad (13)$$

By evaluating the derivative of $F(M)$ with respect to M^2 and substituting into (13), the function $G(M)$ is

$$G(M) \equiv \frac{(3\gamma + 1)M^2 - 2\gamma}{2\gamma(\gamma - 1)M^4 + (6\gamma - \gamma^2 - 1)M^2 - 2(\gamma - 1)} \quad (14)$$

From the definition of Mach number

$$M^2 = \frac{u^2}{\gamma RT} \quad (15)$$

The Mach number derivative term in equation (12) is given by

$$\frac{dM^2}{M^2} = \frac{2dM}{M} = 2 \left[\frac{du}{u} - \frac{dT}{2T} \right] \quad (16)$$

By differentiating the equation of state (3) the relation between dP , $d\rho$, and dT is

$$\frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dT}{T} \quad (17)$$

By combining equations (11), (12), (13), (16), and (17), the general case for the normalized pitot density fluctuation becomes

$$\frac{d\rho_p}{\rho_p} = 2G \frac{du}{u} - G \frac{dP}{P} + (1 + G) \frac{d\rho}{\rho} \quad (18)$$

Thus the pitot density fluctuation depends on the velocity, pressure, and density fluctuations. The "sensitivity coefficients" $2G$, G , and $(1 + G)$ for air are tabulated

in Table 1 and plotted as a function of Mach number in Figure 5. The sensitivity to the stream density fluctuations is the highest because G is always less than 0.53 (Table 1 or Figure 5). The sensitivity to pressure fluctuations is always the lowest because the normalized pressure fluctuation is multiplied by the function $G(M)$ alone. Referring to Figure 5, note that the normalized pitot density fluctuation is only sensitive to the stream density fluctuation as the Mach number becomes sufficiently high. For the general case of the pitot density fluctuation (18), a $d\rho_p/\rho_p$ measurement producing r.m.s. data only depends on six unknowns. The six unknowns come from taking the r.m.s. of equation (18). First equation (18) is squared which results in six terms (u^2 , P^2 , ρ^2 , uP , $u\rho$, $P\rho$) each with a leading coefficient. The six unknowns are the r.m.s. of the six terms listed above. For this measurement to be useful either the Mach number must be high or assumptions must be made about the flow conditions to reduce the number of unknowns. These special cases of the flow conditions will be discussed later.

Table 1. Sensitivity Coefficients for the Pitot Density Fluctuation for Air ($\gamma = 1.4$).

M	$F(M)$	$G(M)$	$2G(M)$	$1 + G(M)$
1.0	1.577	0.4167	0.8333	1.4167
1.2	1.869	0.5011	1.0021	1.5011
1.4	2.191	0.5219	1.0437	1.5219
1.6	2.517	0.5136	1.0272	1.5136
1.8	2.834	0.4915	0.9830	1.4915
2.0	3.134	0.4630	0.9259	1.4629
2.2	3.412	0.4320	0.8641	1.4320
2.4	3.669	0.4011	0.8022	1.4011
2.6	3.903	0.3711	0.7423	1.3711
2.8	4.115	0.3430	0.6860	1.3430
3.0	4.307	0.3168	0.6336	1.3168
3.2	4.480	0.2927	0.5854	1.2927
3.4	4.635	0.2706	0.5413	1.2706
3.6	4.776	0.2505	0.5010	1.2505
3.8	4.902	0.2322	0.4644	1.2322
4.0	5.016	0.2155	0.4311	1.2155
4.2	5.119	0.2004	0.4008	1.2004
4.4	5.212	0.1866	0.3733	1.1866
4.6	5.296	0.1741	0.3482	1.1741
4.8	5.372	0.1627	0.3254	1.1627
5.0	5.442	0.1522	0.3045	1.1522
6.0	5.709	0.1119	0.2239	1.1119
7.0	5.884	0.0852	0.1705	1.0852
8.0	6.004	0.0668	0.1337	1.0668
9.0	6.090	0.0537	0.1074	1.0537
10.0	6.153	0.0440	0.0880	1.0440
11.0	6.200	0.0367	0.0734	1.0367
12.0	6.237	0.0310	0.0621	1.0310
13.0	6.266	0.0266	0.0532	1.0266
14.0	6.289	0.0230	0.0461	1.0230
15.0	6.307	0.0201	0.0403	1.0201
16.0	6.323	0.0177	0.0355	1.0177
17.0	6.336	0.0157	0.0315	1.0157
18.0	6.346	0.0140	0.0281	1.0140
19.0	6.356	0.0126	0.0253	1.0126
20.0	6.363	0.0115	0.0231	1.0115

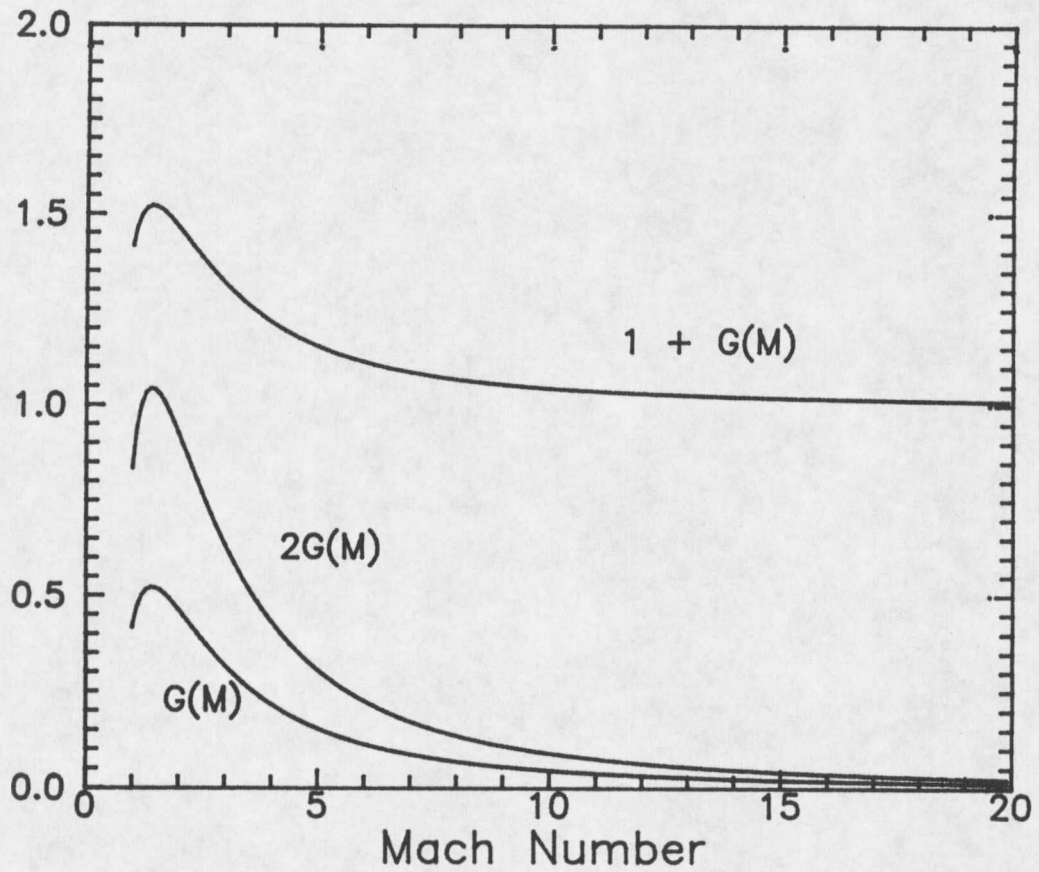


Figure 5. Sensitivity Coefficients for the Pitot Density Fluctuation for Air ($\gamma = 1.4$).

Fluctuations at High Mach Numbers

By examining the function $G(M)$ at large Mach numbers

$$\lim_{M \rightarrow \infty} G(M) = \lim_{M \rightarrow \infty} \frac{3\gamma + 1}{2\gamma(\gamma - 1)M^2} = 0 \quad (19)$$

it follows that

$$\lim_{M \rightarrow \infty} \frac{d\rho_p}{\rho_p} = \frac{d\rho}{\rho} \quad (20)$$

so that the normalized pitot density fluctuation is equal to the normalized stream density fluctuation. This result also applies to r.m.s. quantities and is independent

of the fluctuation magnitude. It is not restricted to the small fluctuation case. Therefore the stream density fluctuation can be directly found from the pitot density fluctuation at large Mach numbers.

Fluctuations at Other Mach Numbers: Special Cases

The general pitot density fluctuation (18) is difficult to use for lower Mach numbers because of the influence of the du/u and dP/P terms. It is desired to make simplifying assumptions for lower Mach numbers in order to reduce the number of unknowns. The author would like to acknowledge Dr. Demetriades for bringing out the ideas on the different flow conditions presented in the following special cases.

Case 1: Constant Total Temperature T_o . For small isentropic fluctuations in adiabatic flows it is generally true that $dT_o = 0$. Then by reducing the energy equation, the normalized temperature fluctuation becomes

$$\frac{dT}{T} = -(\gamma - 1)M^2 \frac{du}{u} \quad (21)$$

combined with equation (16) gives

$$\frac{dM}{M} = \left[1 + \frac{(\gamma - 1)M^2}{2} \right] \frac{du}{u} = - \left[\frac{1}{2} + \frac{1}{(\gamma - 1)M^2} \right] \frac{dT}{T} \quad (22)$$

These results combined with the general equation (18) and the equation of state (17) give the normalized pitot density fluctuation as a function of the temperature fluctuation (23) and the velocity fluctuation (24).

$$\frac{d\rho_p}{\rho_p} = \frac{d\rho}{\rho} - G \left[1 + \frac{2}{(\gamma - 1)M^2} \right] \frac{dT}{T} \quad (23)$$

or

$$\frac{d\rho_p}{\rho_p} = \frac{d\rho}{\rho} + G [(\gamma - 1)M^2 + 2] \frac{du}{u} \quad (24)$$

With the assumption of constant total temperature T_o , the fluctuations in ρ_p therefore depend on only two fluctuations (as opposed to three for the general case). Also note that if only the r.m.s. pitot density is measured the unknowns are reduced from 6 in the general case to 3 in the constant total temperature case. The three unknowns come out of taking the r.m.s. of equation (23) or (24) in a similar manner as described earlier for the general equation.

Equation (24) raises a conceptual problem in that the first term in its brackets is finite for infinite Mach numbers:

$$\lim_{M \rightarrow \infty} G(M)(\gamma - 1)M^2 = \frac{(3\gamma + 1)(\gamma - 1)}{2\gamma(\gamma - 1)} = \frac{3\gamma + 1}{2\gamma} \quad (25)$$

For air ($\gamma = 1.4$) the high Mach number pitot density relation becomes

$$\lim_{M \rightarrow \infty} \frac{d\rho_p}{\rho_p} = \frac{d\rho}{\rho} + 1.857 \frac{du}{u} \quad (26)$$

which at first seems to contradict equation (20). This apparent contradiction is resolved by considering that this analysis is linearized, i.e. the fluctuations variables are very small.

$$\frac{d\rho_p}{\rho_p}, \quad \frac{du}{u}, \quad \frac{dT}{T}, \quad \frac{d\rho}{\rho} \ll 1 \quad (27)$$

But if dT/T fulfills this condition at large Mach numbers, then according to the energy equation (21) the velocity fluctuation du/u must be of order $1/M^2$. With the velocity fluctuation tending to zero at large Mach numbers, equations (26) and (20) are brought into agreement. (The available data show that at hypersonic speeds the velocity fluctuation du/u is greatly decreased in boundary layers [9].)

Case 2: Weak or Zero Pressure Fluctuations. For Mach numbers lower than about 3, it is generally assumed that within shear turbulence (e.g. in a boundary

layer) the pressure fluctuations are much less ($dP = 0$) than the velocity fluctuations and the density fluctuations ($dP \ll du, d\rho$) [10]. In this case the general equation (18) can be approximated by

$$\frac{d\rho_p}{\rho} = 2G \frac{du}{u} + (1 + G) \frac{d\rho}{\rho} \quad (28)$$

Case 3: Combination of $dT_o = 0$ and $dP = 0$. Analytical arguments and experimental data together support the view that in adiabatic flows up to Mach 3 or so dT_o and dP are so small compared to other fluctuations in shear flows in which case $dT_o = dP = 0$ is a safe assumption [10]. In such flows the argument about small fluctuations in Case 1 above ($dT_o = 0$) is no longer valid. For lower Mach numbers the assumption that $dT_o = 0$ and $dP = 0$ can be used to simplify the general fluctuation equation. From the equation of state (17) and the assumption that $dP = 0$:

$$\frac{d\rho}{\rho} = -\frac{dT}{T} \quad (29)$$

With $dT_o = 0$ the energy equation is given by equation (21) and this combined with equation (29) gives the following relations among the velocity, temperature, and density fluctuation.

$$\frac{du}{u} = \frac{-1}{(\gamma - 1)M^2} \frac{dT}{T} = \frac{1}{(\gamma - 1)M^2} \frac{d\rho}{\rho} \quad (30)$$

Substituting equation (30) and the assumption that $dP = 0$ into the general equation (18) gives the simplified pitot density relation for the range $1 < M < 3$:

$$\frac{d\rho_p}{\rho_p} = (1 + H(M)) \frac{d\rho}{\rho} \quad (31)$$

The function $H(M)$ is

$$H(M) = G \left[\frac{2}{(\gamma - 1)M^2} + 1 \right] \quad (32)$$

and is tabulated in Table 2 and plotted in Figure 6. In this case a measurement of $d\rho_p/\rho_p$ will give $d\rho/\rho$ within a known factor depending on the Mach number M . If M is very large the factor is unity which is consistent with equation (20) (see Table 2).

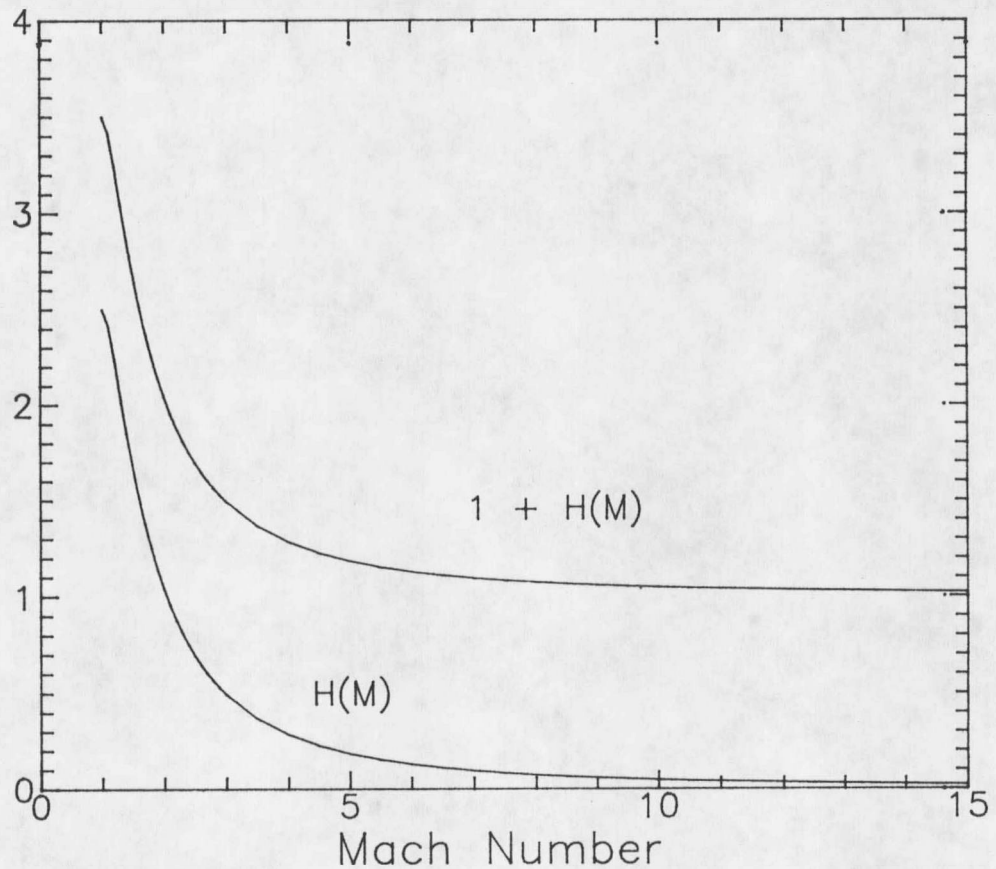


Figure 6. Sensitivity Coefficients for Case Where $dT_o = 0$ and $dP = 0$ (Air: $\gamma = 1.4$).

Table 2. Sensitivity Coefficients for Case Where $dT_o = 0$ and $dP = 0$
(Air: $\gamma = 1.4$).

M	$F(M)$	$G(M)$	$H(M)$	$1 + H(M)$
1.0	1.5774	0.4167	2.5000	3.5000
1.2	1.8692	0.5011	2.2409	3.2409
1.4	2.1905	0.5218	1.8531	2.8531
1.6	2.5165	0.5136	1.5168	2.5168
1.8	2.8334	0.4915	1.2499	2.2499
2.0	3.1336	0.4630	1.0417	2.0417
2.2	3.4128	0.4321	0.8785	1.8785
2.4	3.6696	0.4011	0.7493	1.7493
2.6	3.9036	0.3712	0.6458	1.6458
2.8	4.1158	0.3430	0.5618	1.5618
3.0	4.3075	0.3168	0.4928	1.4928
3.5	4.7078	0.2604	0.3666	1.3666
4.0	5.0162	0.2156	0.2829	1.2829
4.5	5.2552	0.1803	0.2248	1.2248
5.0	5.4422	0.1523	0.1828	1.1828
5.5	5.5904	0.1300	0.1515	1.1515
6.0	5.7092	0.1120	0.1275	1.1275
6.5	5.8055	0.0973	0.1089	1.1089
7.0	5.8845	0.0853	0.0940	1.0940
7.5	5.9500	0.0753	0.0820	1.0820
8.0	6.0047	0.0669	0.0721	1.0721
8.5	6.0510	0.0598	0.0639	1.0639
9.0	6.0903	0.0537	0.0570	1.0570
9.5	6.1241	0.0485	0.0512	1.0512
10.0	6.1532	0.0440	0.0462	1.0462
11.0	6.2006	0.0367	0.0382	1.0382
12.0	6.2372	0.0311	0.0322	1.0322
13.0	6.2660	0.0266	0.0274	1.0274
14.0	6.2891	0.0231	0.0236	1.0236
15.0	6.3079	0.0202	0.0206	1.0206
16.0	6.3233	0.0178	0.0181	1.0181
17.0	6.3361	0.0158	0.0160	1.0160
18.0	6.3470	0.0141	0.0143	1.0143
19.0	6.3561	0.0127	0.0128	1.0128
20.0	6.3640	0.0115	0.0116	1.0116

Case 4: Assumptions For Intermediate Mach Numbers. Useful results from the general equation (18) can also be obtained by a second look at the discussion of the general pitot density fluctuation development. The consensus of data show that in this range the velocity fluctuations (vorticity mode) decline [9] while the pressure fluctuations become more prominent. Thus the first term in (18) is minor because du/u is small, while the second is also minor because G is small. The normalized pitot density relation then becomes

$$\frac{d\rho_p}{\rho_p} = (1 + G) \frac{d\rho}{\rho} \quad (33)$$

Conclusions

Besides the exact correspondence between $d\rho_p/\rho_p$ and $d\rho/\rho$ at very high M , the two most reasonable approximations put forth here are the case (Case 3) of isothermal, isobaric flow ($dT_o = dP = 0$) at low M and the case (Case 4) of vanishing velocity fluctuations at high M . In the Mach number range $1 < M < 3$ equation (31) is utilized, equation (33) applies over the range $3 < M < 10$ and the exact relation (20) is valid for higher Mach numbers. In all three cases the two types of density fluctuations $d\rho_p/\rho_p$ and $d\rho/\rho$ are proportional to each other, with a proportionality factor plotted in Figure 7. Note that even for Mach numbers as low as 3 the difference between equations (31) and (33) is only 11%.

This analysis is valid for small (linearized) fluctuations, and offers no suggestions for the utility of the pitot density fluctuation measurement at low supersonic speeds for cases when dT_o and dP are large.

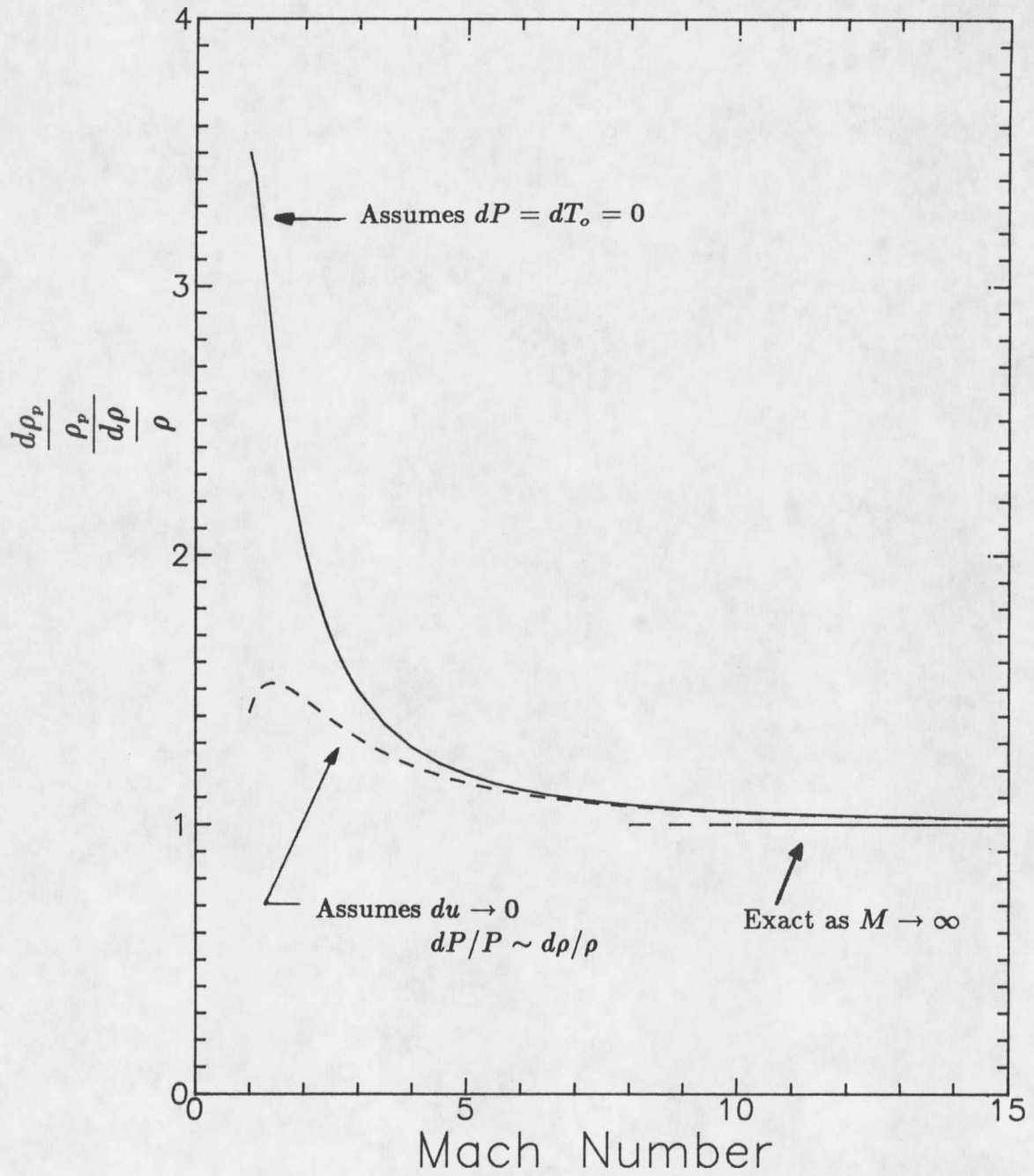


Figure 7. Proportionality Factor for the Density Fluctuation.

Relation Between Density and Breakdown Voltage Fluctuations

Now that the relations between the stream density fluctuations and the pitot density fluctuations have been resolved, the breakdown voltage fluctuations must be related to stream fluctuations. It is necessary to calculate the stream fluctuation from the breakdown voltage fluctuations to obtain turbulent flow information.

Consider stream density fluctuations ρ' where the prime superscript denotes r.m.s. fluctuations. The stream fluctuations will produce pitot density fluctuations at the tip of the breakdown probe. Equations (20), (31), and (33) describe the relationship for the respective Mach number range.

A fluctuation in the pitot density will in turn be measured by a fluctuation in the breakdown voltage V_b' . The relationship between pitot density and breakdown voltage is given by the Paschen characteristic ($V_b = V_b(\rho_p)$).

For small fluctuations the connection between ρ' and V_b can be found by differentiating the Paschen characteristic.

$$\frac{V_b'}{V_b} = \left[\frac{\rho_p}{V_b} \frac{\partial V_b}{\partial \rho_p} \right] \frac{\rho_p'}{\rho_p} \quad (34)$$

The product in brackets will be called the "sensitivity coefficient", S , for a breakdown probe.

$$S = \frac{\rho_p}{V_b} \frac{\partial V_b}{\partial \rho_p} \quad (35)$$

The pitot density fluctuation is then:

$$\frac{\rho_p'}{\rho_p} = \frac{1}{S} \frac{V_b'}{V_b} \quad (36)$$

Thus the relation between the r.m.s. breakdown voltage fluctuations and the r.m.s. pitot density fluctuations can be determined.

CHAPTER 4

EXPERIMENTAL APPARATUS

Breakdown Probe Design

Three different basic designs of breakdown probes were tested during this research, each with a slightly different electrode geometry. The three probe designs are the small wire probes, the radioactively enhanced probe, and the fiber-optic breakdown probe. (Other probes of various designs were built and tested but their performance was unsatisfactory. These probes are described in Appendix A.)

Probe Design Considerations

One design criterion for all of the probes built is that they must be suitable for use in the wind tunnel. The probe tip must be of small diameter to make near point measurements in a flow. The smaller the tip diameter the greater the spatial resolution. The small tip must be supported by a probe body that facilitates easy mounting in the tunnel. This means the probe body should be less than 1/4 inch diameter and 2 to 3 inches in length. All connections for the probe (lead wires, optical fibers, etc.) must be solidly anchored in the probe body to withstand light "misuse" during normal handling and tunnel operation. Another design consideration which dictates the right use of probe materials is maximum operating temperature. In all probes it is important to ensure that the breakdown occurs at the probe tip stagnation point. The electrodes must also be well insulated electrically to avoid arcing at locations other than at the probe tip.

Small Wire Probe

These probes are constructed from twin bore, Pyrex or quartz glass tubing which has been drawn down to a fine tip. The wires used to make the electrodes varied from 1/2 mil to 5 mil diameter and were either tungsten or platinum. The dimensions of the small wire probes are given on the drawing in Figure 8. See Figure 9 for a picture of a typical probe. The electrode wires at the tip are sealed in the glass bores with Pyroceram glass. The glass tip and electrodes are sanded flush with 600 grit sandpaper and polished smooth with a polishing wheel. The lead wires exiting the rear of the probe are anchored in place with Pyroceram.

The geometry of this probe leads to another factor that may give a more consistent breakdown. According to Maxstadt [11], it is observed that simply placing an insulator in the space of a breakdown gap will considerably lower the breakdown strength of the air. The reason for this is that the surface of the insulator is very irregular and may hold pockets of water or water vapor. These pockets act as an "electrolyte" and reduce the surface breakdown strength of the air at the insulator surface. The breakdown then follows a path of lower resistance. The insulation that separates the two wires at the tip may give the breakdown gap this effect.

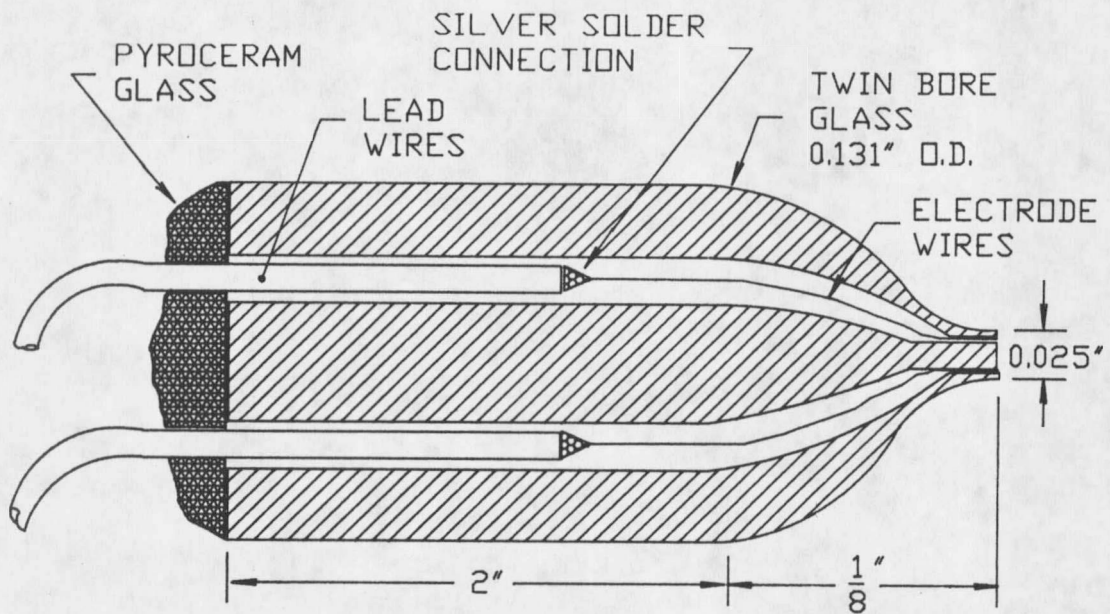


Figure 8. Dimensions of Small Wire Probe.

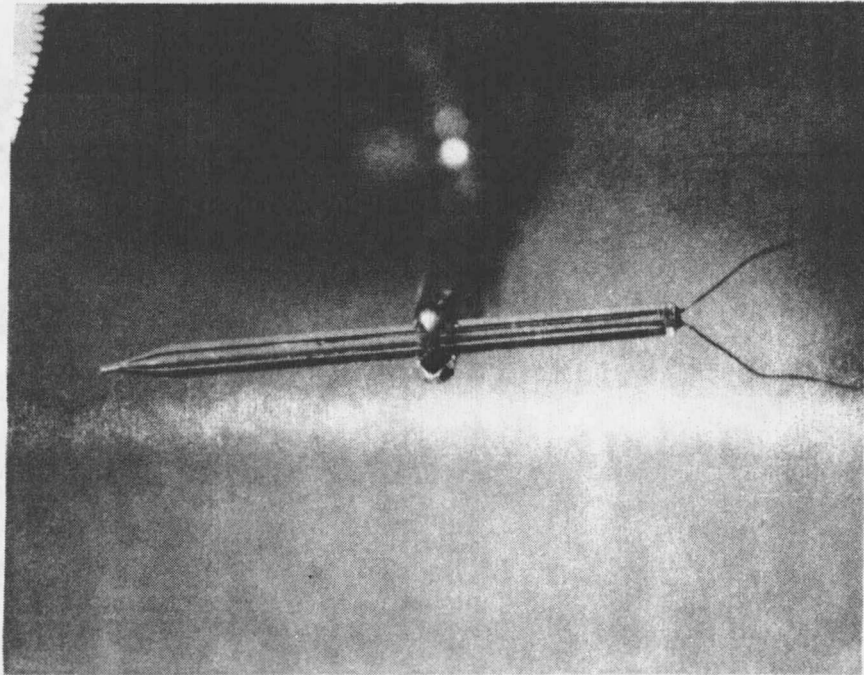


Figure 9. Small Wire Probe.

Radioactively Enhanced Probes

Two separate breakdown gaps were constructed that incorporated radioactivity. The first used an alpha ray source, the radioisotope Lead 210 for the radioactive source. The Lead 210 source (activity $0.1 \mu Ci$) was supplied by the manufacturer, The Nucleus Inc., as the source electroplated on the "eye" end of an ordinary sewing needle. A breakdown gap was constructed with this needle using a 6.5 mil nichrome wire as the second electrode. The axis of the needle is aligned with the axis of the wire, with the eye end of the needle facing the flat end of the wire. The ends of the needle and wire are separated by a gap of approximately 10 mils.

The second radioactive enhanced breakdown gap is a probe (called Probe BP7) assembled as shown in Figure 10. It is similar to the small wire probes discussed in the previous section only Alumina instead of glass is used for the probe body. Once the construction of the probe was completed the electrode tip was dipped in a radionuclide Carbon 14 (activity $0.1 \mu Ci$) solution for approximately 5 seconds, the idea being that some of the radioactivity from the solution would remain on the probe tip after the water carrier evaporated.

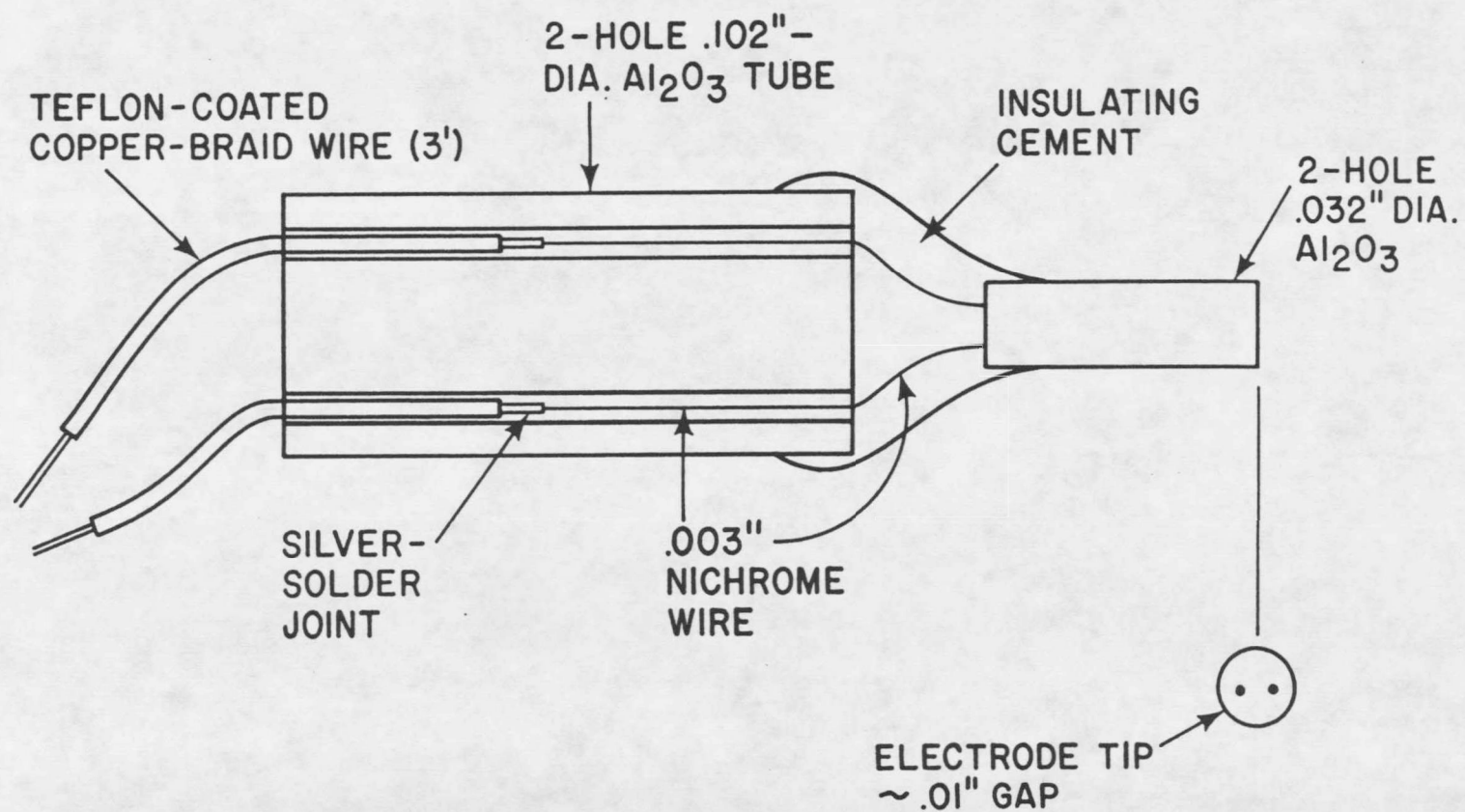


Figure 10. Radioactive Probe BP7.

Ultraviolet Enhanced Breakdown Probe

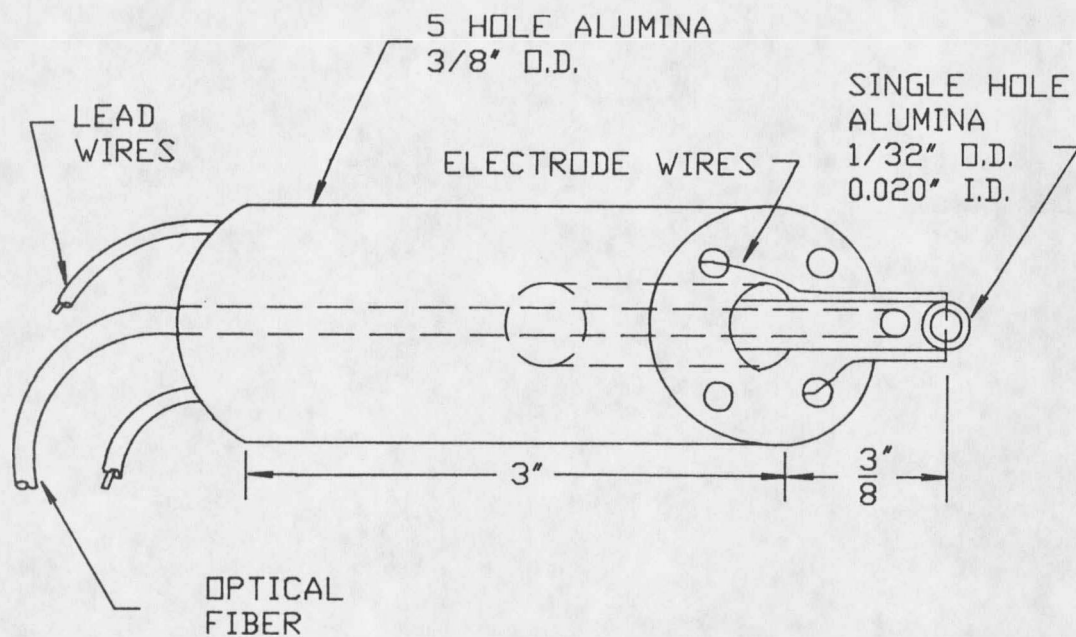
Several probes were built that incorporated a single optical fiber to illuminate the electrode tip with ultraviolet light (see Figure 11 for probe dimensions). Platinum was used for the electrode metal because of its resistance to corrosion. Probes with platinum wires of 5 mil and 1 mil diameter were built and tested. The ends of the wire were bent around the end of the single hole alumina so they faced each other. The optical fiber at the probe tip is sufficiently close to the electrodes to illuminate both electrodes. The optical fiber used was a PCS (plastic clad silica) with a fused quartz core. The probe geometry is such that it is small enough to be suitable for wind tunnel use.

Ultraviolet Light Source System

Mercury Arc Lamp

A 200 watt, high pressure, mercury arc lamp provides high spectral radiance in the medium and long wave ultraviolet (UV) region along with a high luminance in the visible range. The arc lamp is model HBO 200W/2 and is made by Gates Manufacturing. The lamp is powered by a Gates regulated power supply (model DCR-200M). (See Appendix B for operating instructions of arc lamp and power supply.)

In order to protect the user from the UV radiation the lamp must be placed in an enclosure (lamp house). The arc lamp, arc lamp holder, power supply, and lamp house are all shown in Figures 12 and 13. The lamp house is also connected to a small air blower to cool the arc lamp during operation.



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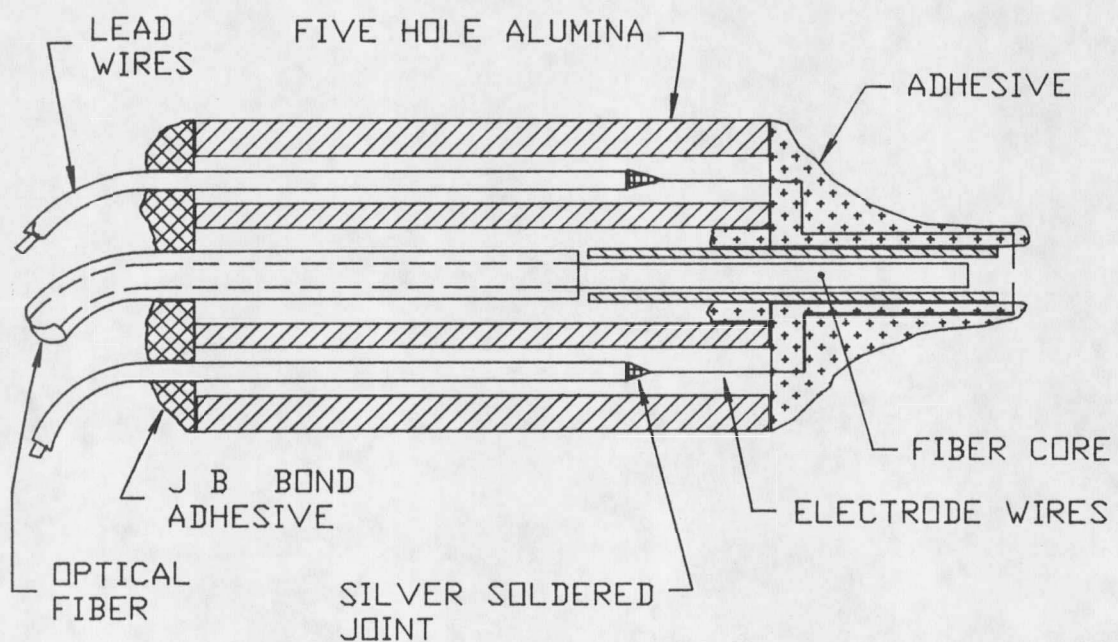


Figure 11. Ultraviolet Enhanced Breakdown Probe (Optical Probe).

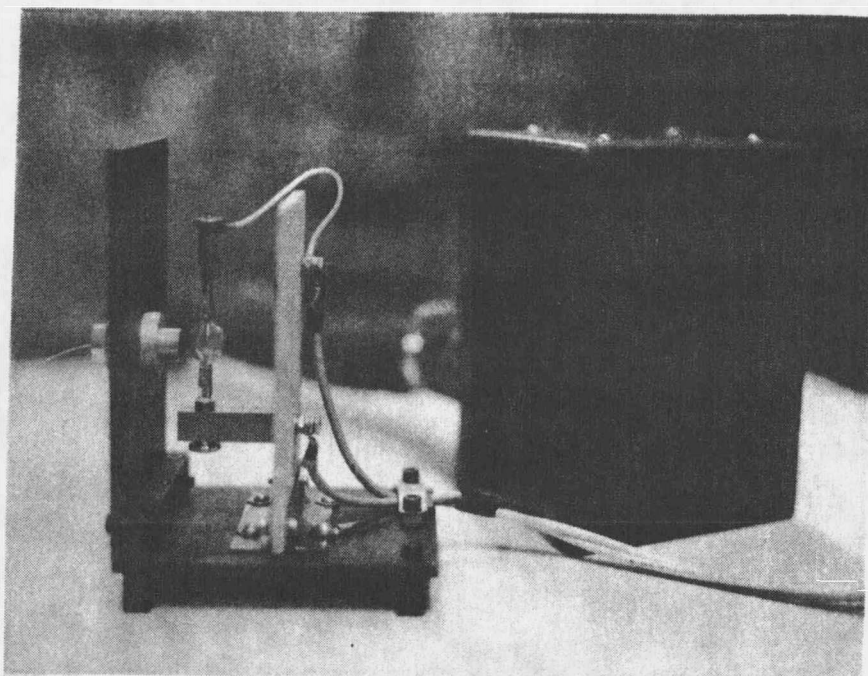


Figure 12. Mercury Arc Lamp and Holder.

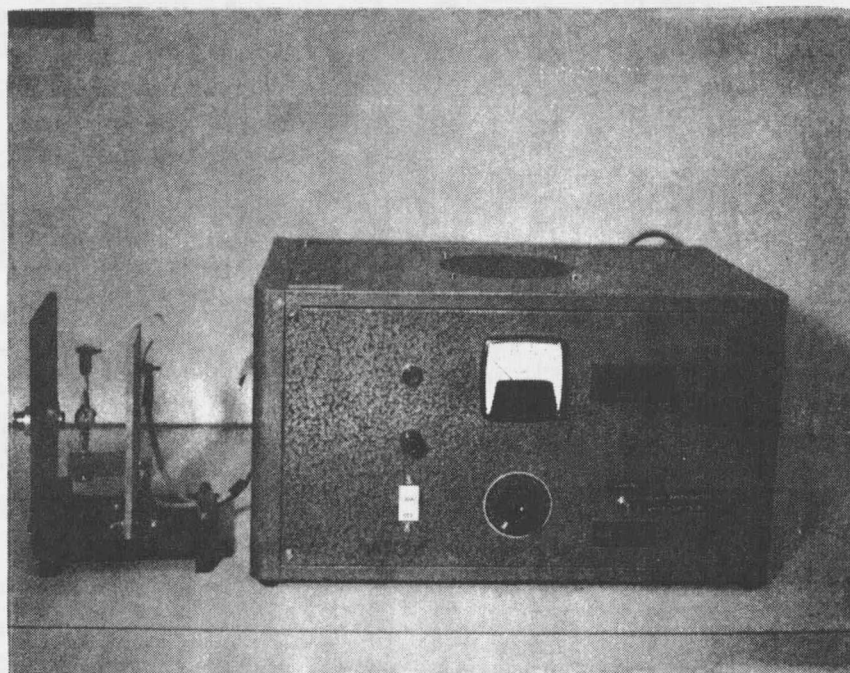


Figure 13. Arc Lamp and Power Supply.

Collimating Probe

The lamp house provides for mounting a fiber optic focusing assembly called a collimating probe. The dimensions of the collimating probe are shown in Figure 14 and the collimator can be seen in the left side of the picture (Figure 12) facing the arc lamp bulb. Its purpose is to focus the light from the mercury arc lamp on the end of the optical fiber. The position of the collimator with respect to the arc lamp is shown in Figure 15. The collimating probe has two fused silica lenses which allow greater transmission of ultraviolet light. Although only single optical fibers were used in this research, the fiber holder of the collimator can be readily adapted to hold a fiber bundle.

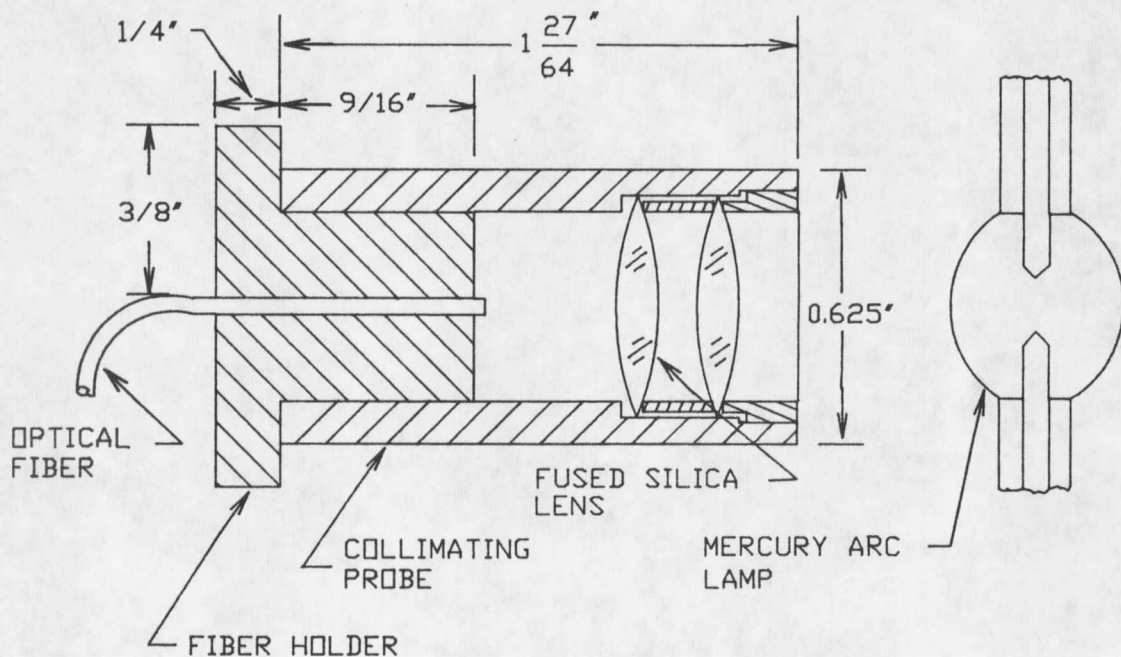


Figure 14. Collimating Probe Dimensions.

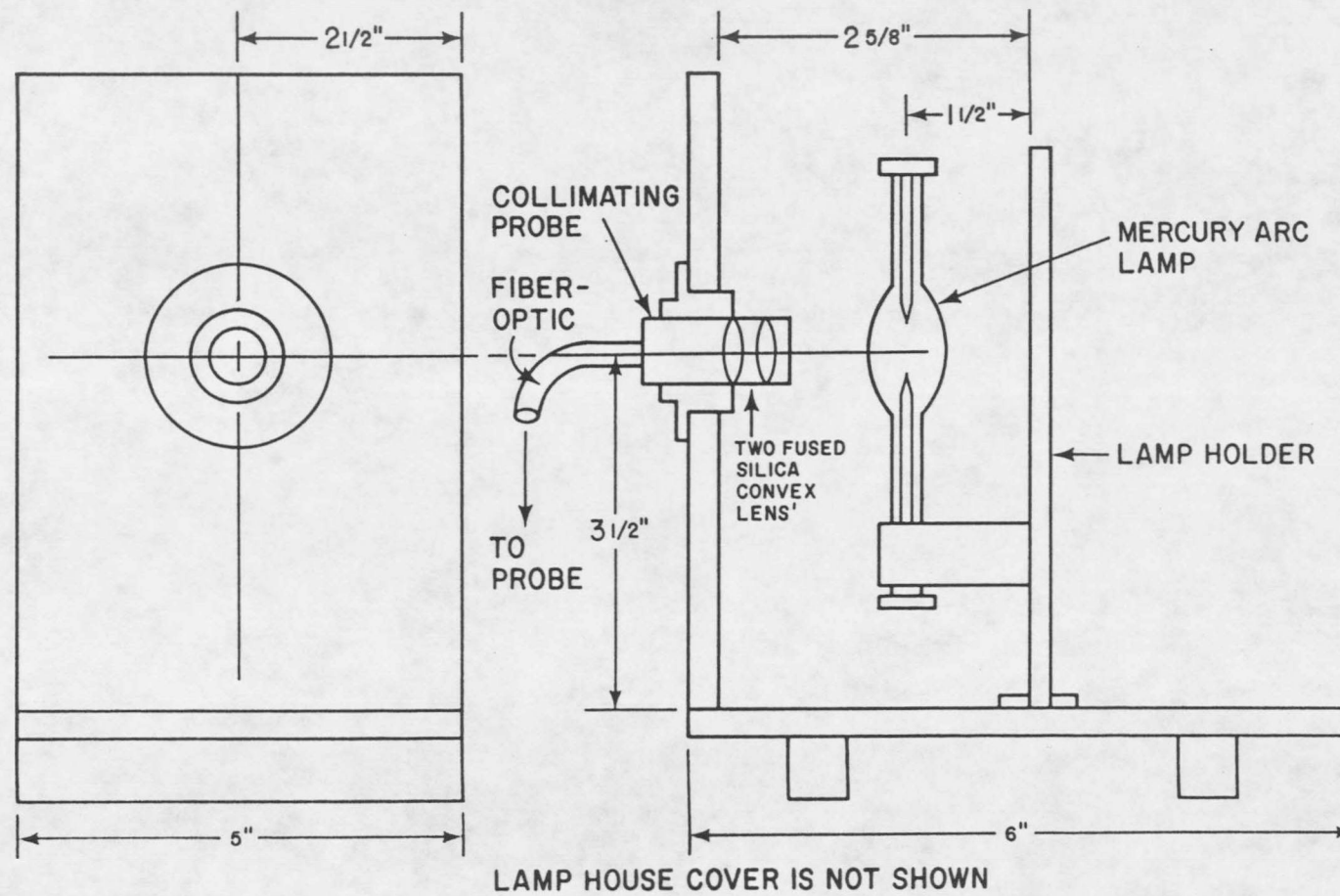


Figure 15. Arc Lamp and Collimator.

Optical Fiber

The optical fiber used in the breakdown probe construction is a PCS (plastic-clad silica) with a fused quartz core that offers low power loss in the ultraviolet range. The fiber has a 200 μm core with a 350 μm outside diameter. The length of fiber used for probe construction varied from 8 to 10 feet. The maximum operating temperature of the fiber is 200 degrees Celsius. The fiber ends at the breakdown probe and the collimator are "cleaved" (sheared smooth at right angles to fiber axis) to allow greater acceptance of light.

Voltage Control Ramp

Three separate circuits are used to control the voltage on the probe electrodes. Basically, what is needed to set up the breakdown is a voltage source that starts at the grounded state on both electrodes and steadily increases the voltage potential across the electrodes. Once a sufficient voltage level is reached to initiate breakdown an arc jumps the breakdown gap and the current in the circuit increases rapidly. The circuit must detect the discharge and immediately stop the current to avoid excessive wear on the electrodes. The circuit must also record the maximum voltage reached at the time of breakdown.

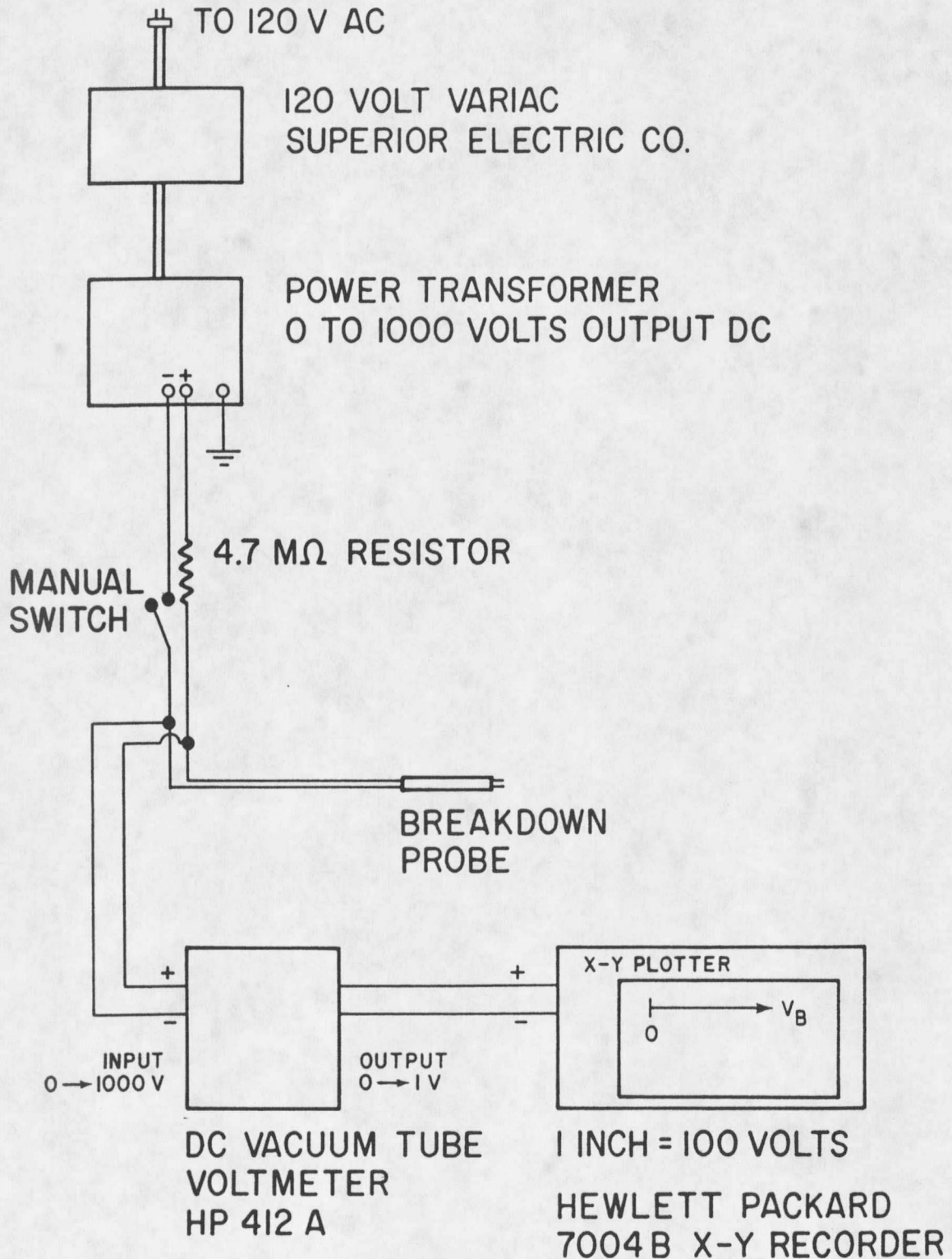


Figure 16. Manual Voltage Control System.

Manual System

The manual voltage ramp as shown in Figure 16 uses a Superior Electric 120-volt Variac in series with a 0-1 kV dc power transformer and a 4.7 megohm resistor for the voltage source. The manual system was the same system used by Dr. George in previous breakdown probe experimentation. The voltage is increased by manually increasing the output of the Variac. For breakdown detection and voltage measurement a HP 412A VTVM volt meter is connected across the probe leads. The voltage is then followed on one axis of a HP 7004B X-Y recorder. The breakdown is detected by the operator on the X-Y recorder. The length of the line on the X-Y recorder provides a measurement of the maximum voltage reached during breakdown. The circuit is interrupted by the operator throwing the circuit switch. This system provides a great chance for human error.

Automatic Single Ramp (ASR)

The manual system was replaced by a system that automatically increases the electrode voltage, detects the breakdown, and interrupts the circuit after breakdown. See Figure 17 for a schematic of the electrical circuit of the ASR. The ASR is capable of producing a maximum of 1200 volts with a source resistance of 5 megohm. Figure 18 shows the voltage versus time characteristic of the ramp. During breakdown, a voltage drop of 10 volts across the electrodes is needed to interrupt the current and stop the ramp. The ASR provides a low voltage output that corresponds to the high voltage across the probe. The output is 1 mV per 1 volt across the breakdown probe. The ramp is slow enough to allow an X-Y recorder (manufactured by The Recorder Company, model #200) to follow the breakdown voltage. The voltage is charted on one axis with the length of the line corresponds to the breakdown voltage.

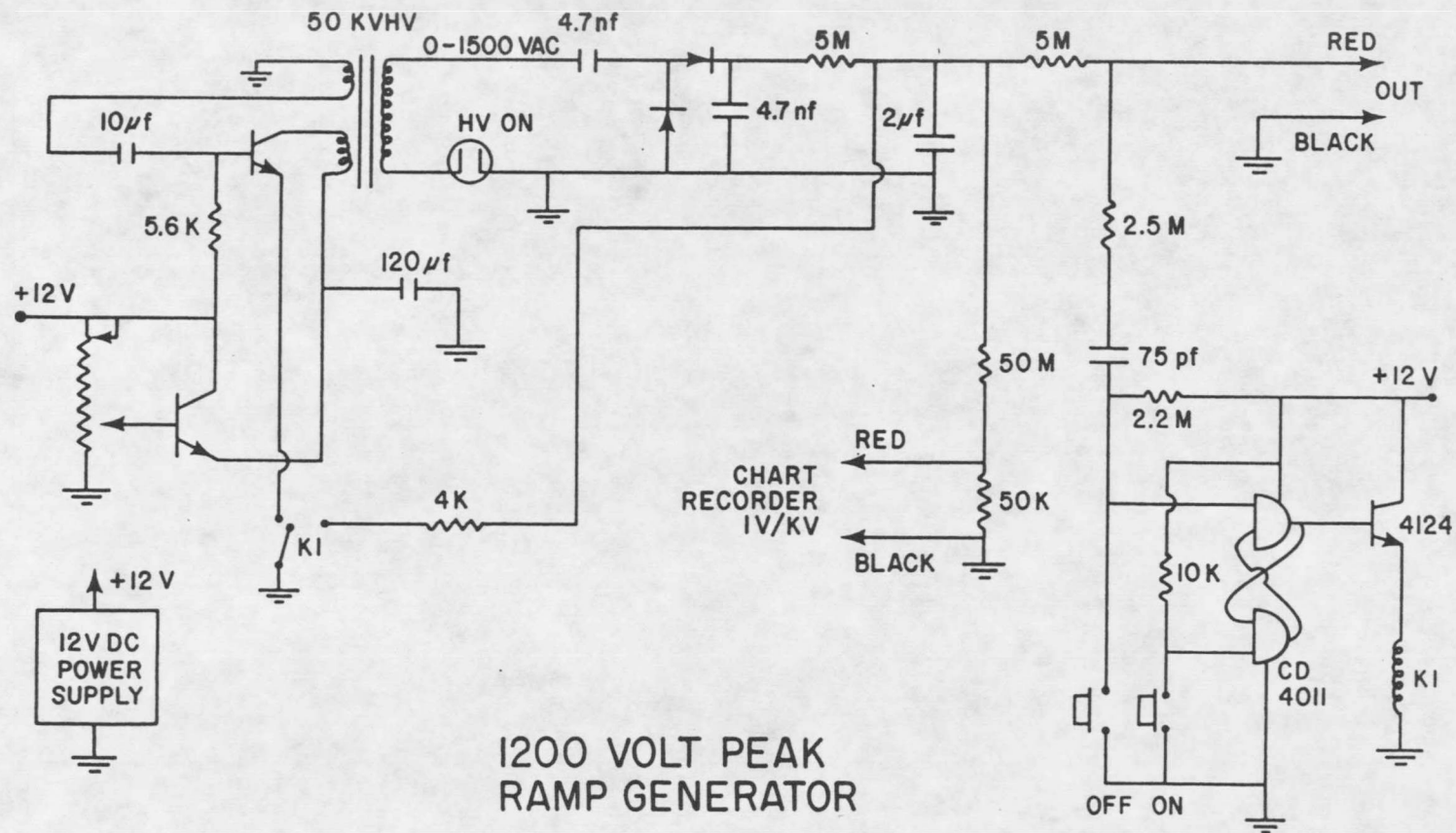


Figure 17. Automatic Single Ramp System.

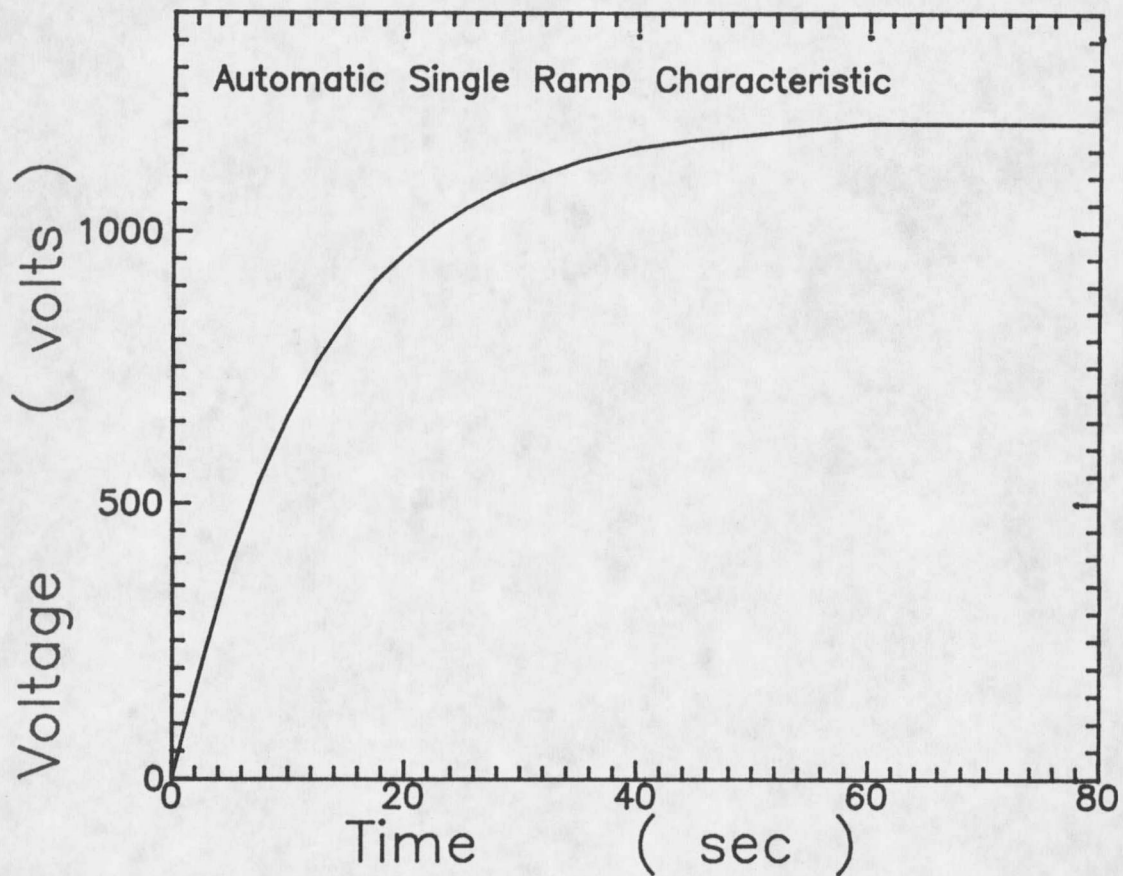


Figure 18. Automatic Single Ramp Characteristic.

Computerized Data Acquisition System (CDAS)

With the goal of measuring turbulence, an electronic device was built that provides a high frequency of breakdown combined with a computerized reading of the breakdown voltage. The CDAS consists of a unit which provides a voltage ramp pulse that is controlled by a Zenith Z100 computer. The user can control the total number of breakdowns N and the time between breakdowns T . See Figure 19 for a flow diagram of the system. The voltage ramp has the characteristic that is shown in Figure 20.

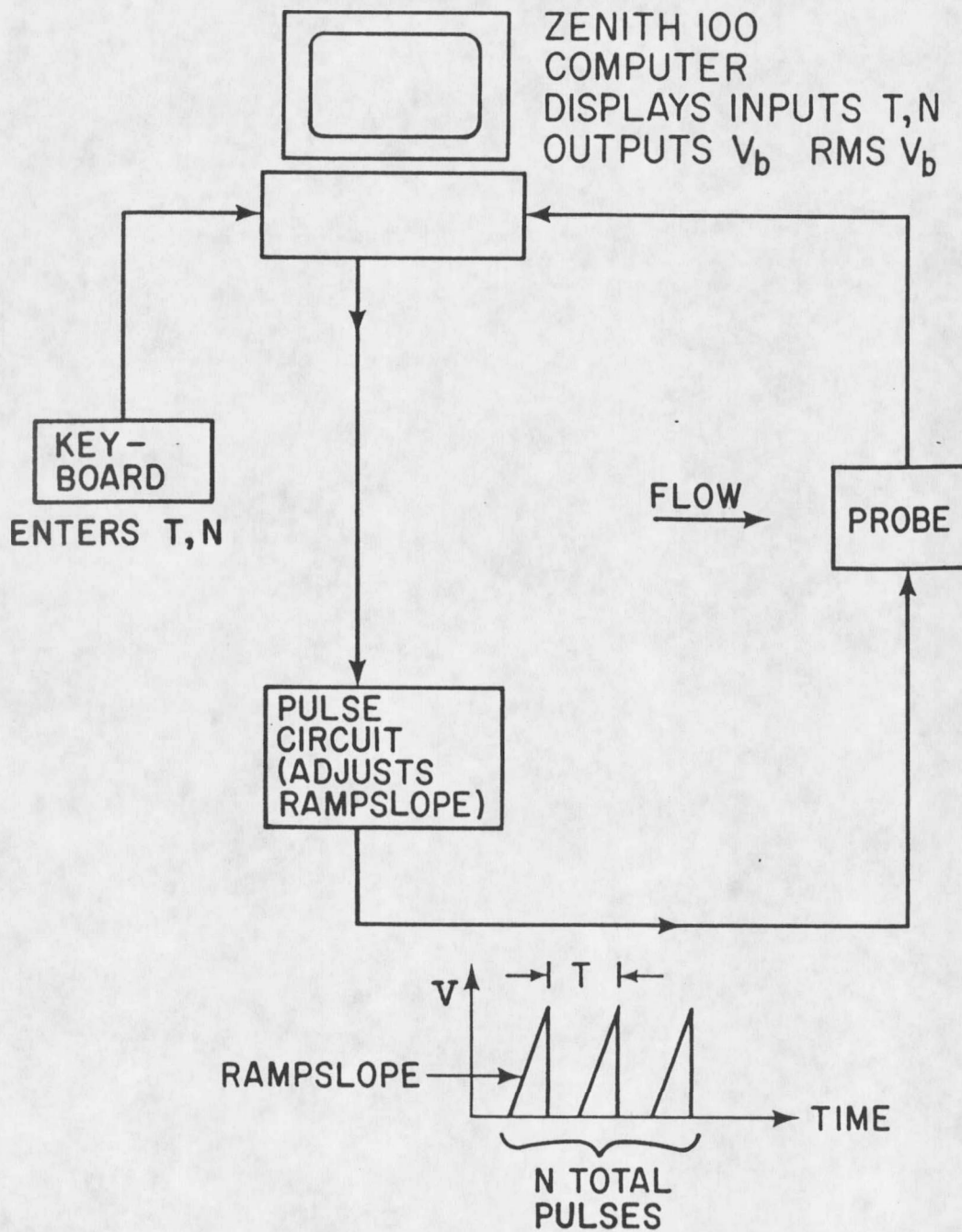
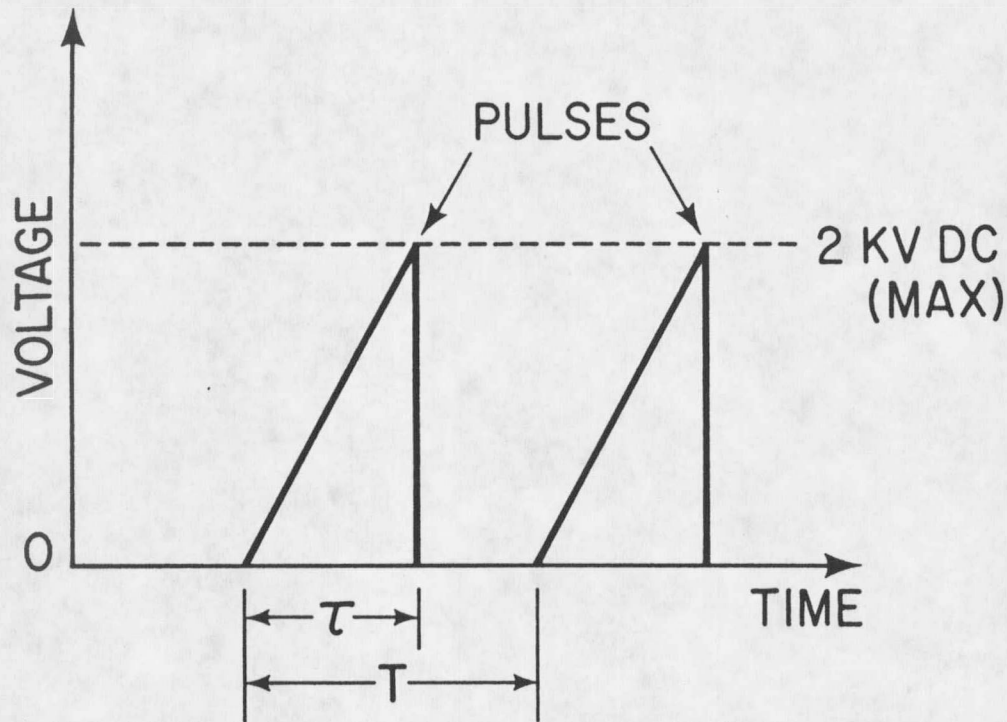


Figure 19. Computerized Data Acquisition System.



Pulse Train Characteristics

- Ramp Slope (Rise Rate): 0–1 volt/microsecond (adjustable)
- Ramp Duration: $\tau = 2$ millisecond (fixed)
- Repetition Rate: (keyboard controlled)
 - Fast Mode: $T = 0.05 - 1$ second
 - Slow Mode: $T = 5$ sec. to 5 minutes
- Maximum Voltage: 2000 volts (fixed)
- Total Events Recorded: 4000 pulses (maximum) (keyboard controlled)

Figure 20. Computerized Voltage Ramp.

The maximum voltage setting of the ramp is variable between 0 and 2000 volts with the pulse duration being constant at $\tau = 2$ millisecond. This will give an adjustable ramp slope (adjustable by a knob on the ramp circuit front panel) between 0 to 1 volt/microsecond. The maximum total number of pulses is set at 4000 with the repetition rate being variable between 1 to 20 breakdowns per second in the fast mode or from 5 seconds to 5 minutes between breakdowns in the slow mode. The computer will record the breakdown voltage of each consecutive breakdown and print each value to the computer screen. Statistical calculations such as the average voltage, r.m.s., and r.m.s./average voltage, are also displayed by the computer. The breakdown voltage along with the statistical calculations can also be stored on disk. The voltage ramp circuit provides for real-time monitoring of the ramp with an oscilloscope. The polarity of the electrodes can easily be reversed by changing a switch on the ramp circuit panel. Appendix C describes the connections between the Z100 computer and the ramp circuit box. The calibration procedure is also included in Appendix C.

Density Controlling System

Vacuum Chamber

A rectangular, steel chamber is used to control the density of the air for probe calibration. The chamber is rectangular (4" $\times$ 6" $\times$ 8") and is pictured in Figure 21 with the dimensions of the chamber and end plates given in Figure 22. The end plates are removable to facilitate cleaning the inside walls or to arrange different components inside the chamber if desired. The end plates are sealed with Permatex high temperature RTV sealant and bolted in place. The chamber provides pressure fittings for mounting a breakdown probe, two thermocouples, and an immersion heater inside the vacuum chamber. A pressure fitting is also

provided for a vacuum line to the pressure station to control the chamber pressure. The internal arrangement of the probe, thermocouples, and heater are shown in Figure 23. The seals on the end plates and the pressure fittings can not be made leak "proof" but a leak rate as low as 0.2 mm Hg per hour can be achieved. This rate is acceptable for the calibration procedure.

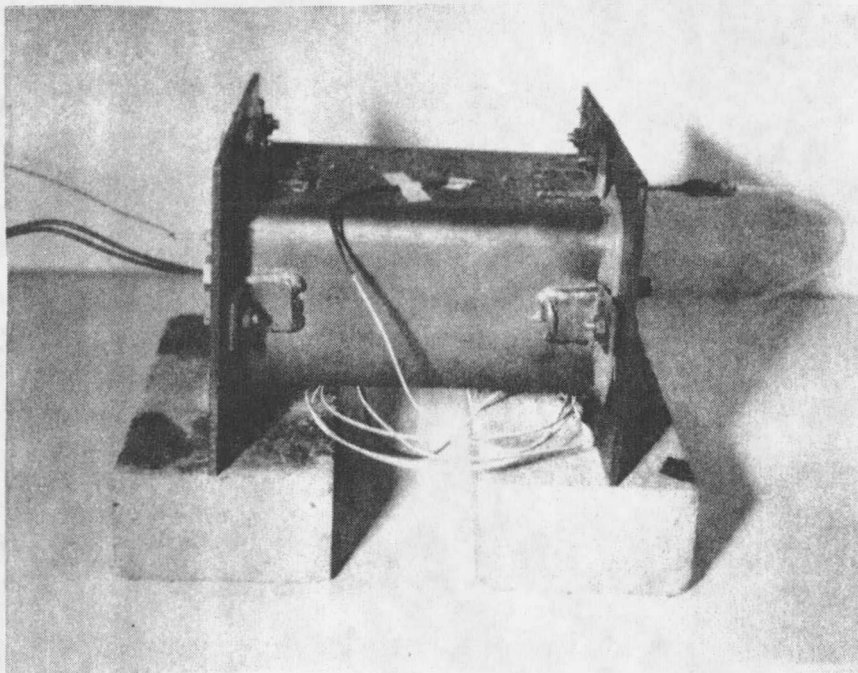


Figure 21. Vacuum Chamber.

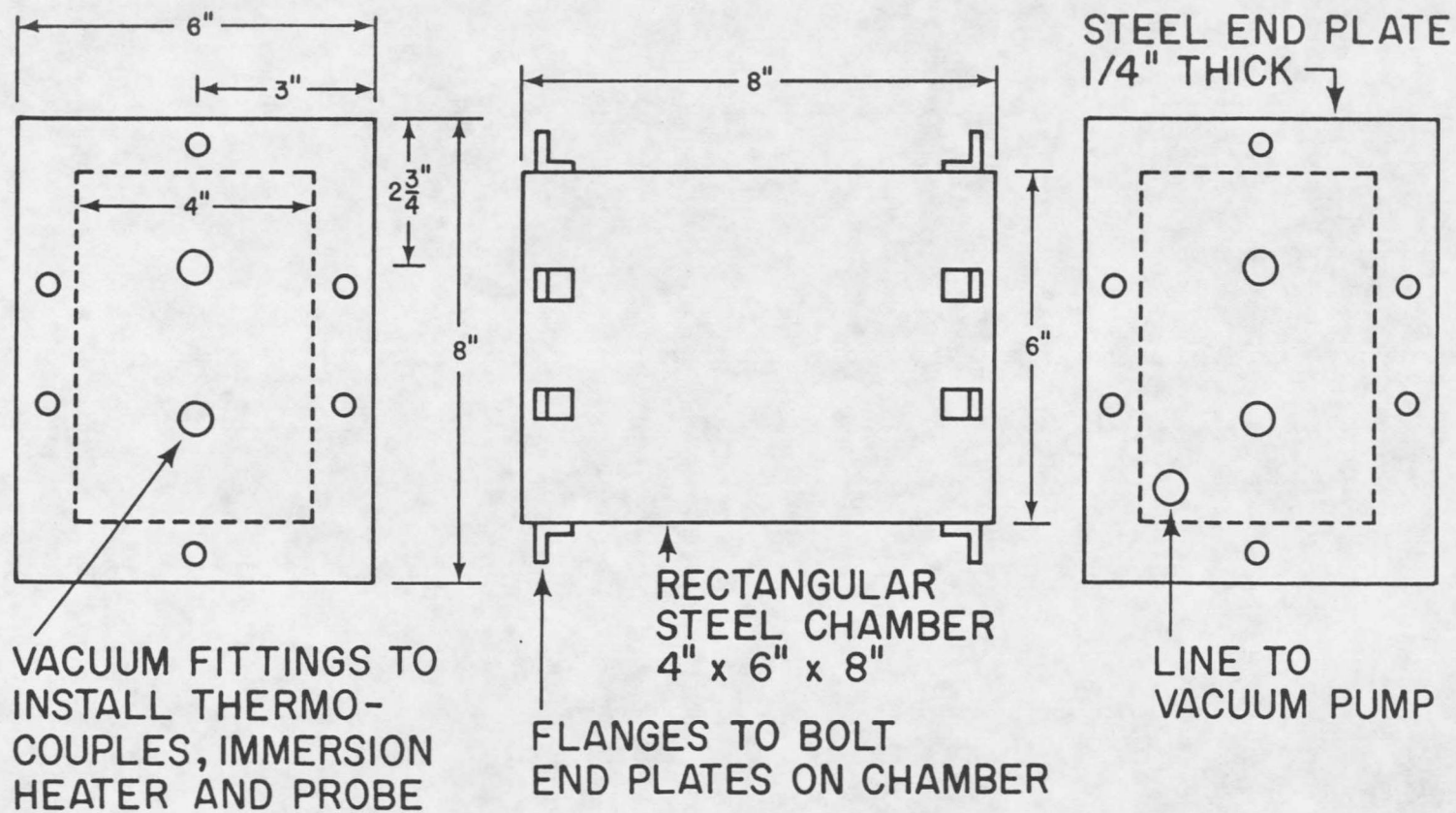


Figure 22. Dimensions of Vacuum Chamber.

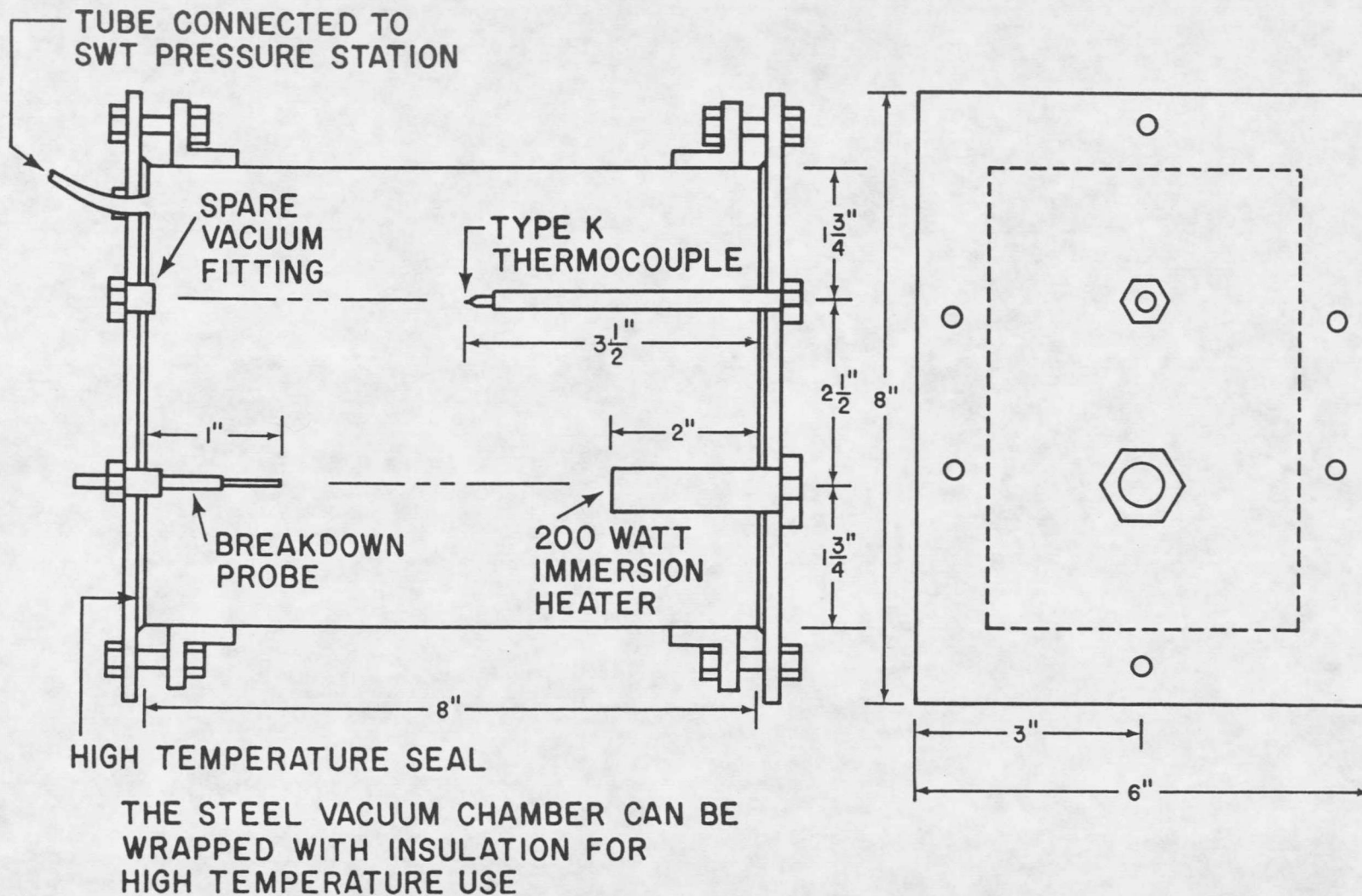


Figure 23. Internal Arrangements of Vacuum Chamber Components.

Pressure Station

The SWT pressure station is used to control the pressure inside the vacuum chamber. The pressure station consists of a manifold connected to a vacuum pump, three absolute pressure gauges, three pressure transducers, twelve access vacuum lines, and a vent to the atmosphere. The pressure inside the vacuum chamber can be controlled by the vacuum pump and the vent in the range of atmospheric pressure (approximately 640 mm Hg) to about 0.05 mm Hg. The range of each of the absolute pressure gauges (manufactured by Pennwalt model #61C) is 0-400 mm Hg, 0-100 mm Hg, and 0-20 mm Hg. From atmospheric pressure to 400 mm Hg the pressure can be measured using one of the three pressure transducers.

Chamber Temperature Control System

For high temperature tests the chamber can be wrapped in approximately 2 inches of insulation to facilitate heating. Figure 24 shows the arrangement used for temperature control. A 200 watt immersion heater (2 inches long, 1/2 inch in diameter) is mounted on one end plate of the chamber. An Omega model 4001 thermostat is used to control the temperature inside the chamber. The thermostat has a variable temperature setting between 0 and 1000 degrees Celsius. The thermostat also has a control for setting the band width of temperature swings. A type K thermocouple is mounted opposite the heater to provide temperature input to the thermostat. The thermostat output is connected to a SCR power control (Loyola Controls, Inc.) which amplifies the thermostat output to drive the immersion heater. Although the maximum temperature used during this research was 200 degrees Celsius, higher temperatures should be easily obtainable.

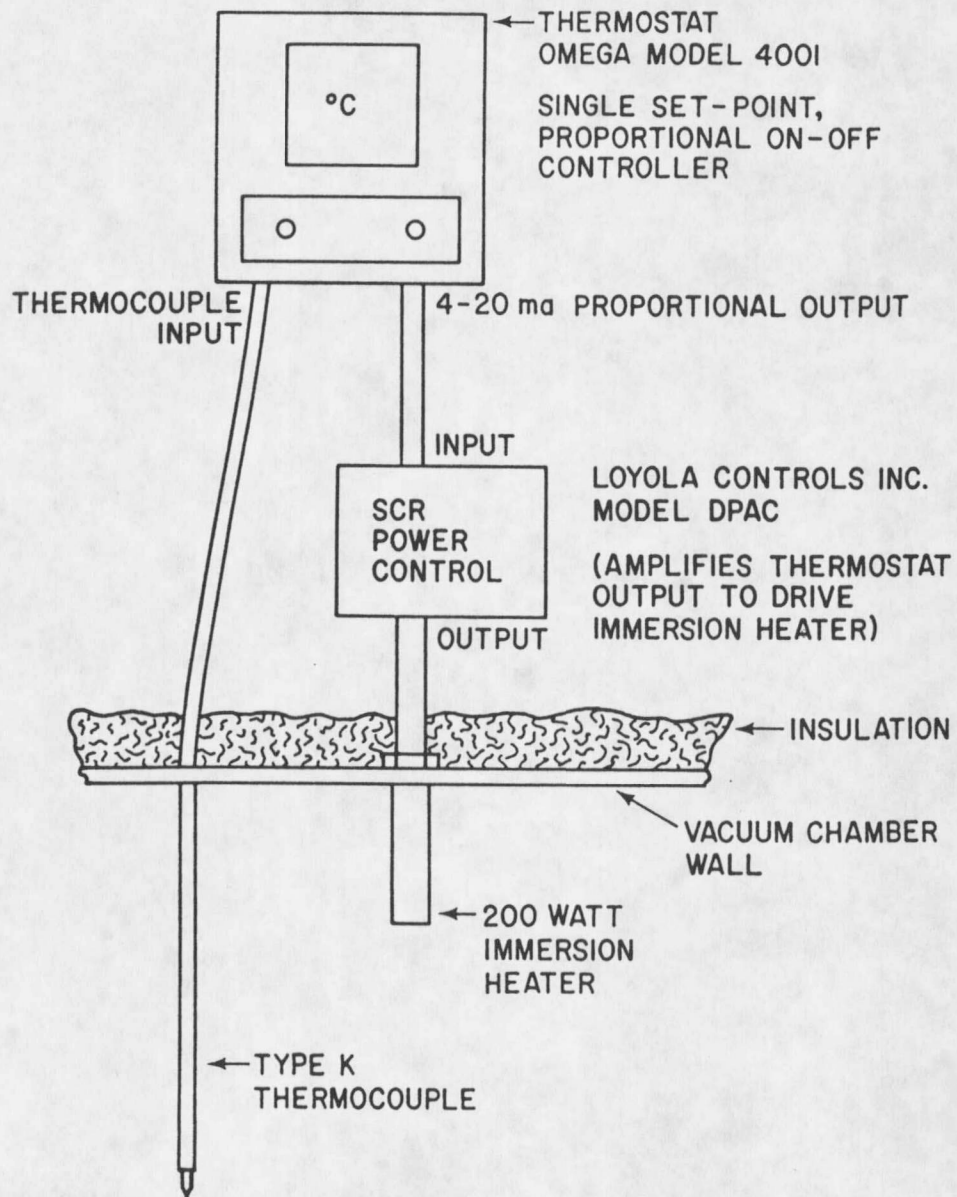


Figure 24. Thermostat System.

SWT Testing Facility

The Supersonic Wind Tunnel is an open circuit, continuous flow wind tunnel. Air is used as the working fluid and Mach 3 flow conditions are obtained. By varying the total pressure and total temperature of the tunnel flow the pitot density at Mach 3 can be varied in the range of $0.42\rho_A$ to $0.75\rho_A$ where ρ_A is the density of air at NTP ($\rho_A \approx 1.2$ kg per cubic meter). The SWT test section provides for mounting of probes and moving them throughout the flow with the use of actuators. Flow obstructions can also be mounted in the test sections to provide various density profiles to test the breakdown probe.

CHAPTER 5

GOALS AND TEST PROCEDURE

Research Goals

The goal of this research is to prove that a breakdown probe can be used to measure the density of a moving air stream. The first step towards this goal is proving that a breakdown probe will show similar static characteristics to those predicted by the Paschen similarity principle. The statement made that the breakdown voltage is dependent on density only and not pressure, temperature, or velocity will be verified. The stability and repeatability of the characteristic curve must also be demonstrated in order to provide a usable density-measuring sensor, since if the calibration changes sporadically then the probe cannot be reliably used to provide flow measurements. The use of the probe to measure mean density values in a supersonic flow will next be shown by comparing the probe with the same measurements taken with other instruments. Finally the possibility of using a breakdown probe to measure turbulent density fluctuations will also be investigated.

Test Matrix

With the intent of developing a "usable" breakdown probe the test matrix was limited to investigating only the probes and voltage ramps that showed promising results. A complete testing procedure that tested all the different probes with all three voltage ramps with the repeatability, density dependence tests, tunnel tests, etc. was not performed due to time constraints. The following test matrix was

utilized:

1. Show that the static characteristic curve for a tunnel usable breakdown probe is similar to the Paschen characteristic.
2. Examine probes and voltage ramps for repeatability of the breakdown voltage.
3. Determine if breakdown is dependent on density only and not pressure or temperature.
4. Perform Supersonic Wind Tunnel tests to measure mean density values.
5. Investigate the possibility of using a breakdown probe to measure turbulent density fluctuations.

CHAPTER 6

PROBE CALIBRATION PROCEDURE

Control of Static Air Density

A room-temperature "calibration" is usually made to determine a breakdown probe's characteristic. The probe is calibrated by exposing the electrode tip to air of known density and then measuring the breakdown voltage at this density.

For this purpose the probe is first mounted in the vacuum chamber through the probe pressure fitting. The SWT pressure station is connected by a vacuum line to the chamber. A leak check is made to see if the probe is sealed properly. For the leak check the chamber is evacuated with the vacuum pump to a pressure near 5 mm Hg and the system is allowed to reach equilibrium. By monitoring the pressure over a period of time the leak rate can be determined. Leak rates less than 0.5 mm Hg per hour are acceptable.

During probe calibration the density is controlled by changing the pressure in the chamber and then allowing the pressure to come to equilibrium. At equilibrium the pressure is read from one of the absolute pressure gauges and the temperature is read from the chamber thermocouple. From the ideal gas law the density of the air is calculated. The density of the air can be controlled in the range from approximately 0.001 to 1.0 kg per cubic meter with this system.

Breakdown Voltage Measurement

With the density of the air known the breakdown voltage can be measured with one of the three voltage measuring systems. The probe lead wires are connected to the desired voltage measurement system and one or several measurements of the breakdown voltage are taken at this one density. For a full calibration the density is changed and the breakdown voltage measurement is then repeated. By this process the breakdown voltage versus density characteristic is generated.

Theoretically, for each individual value of air density there should be one breakdown voltage. If the density is held constant the breakdown voltage should remain the same for repetitive breakdowns. One test to examine the repeatability of the characteristic is to repeatedly measure the breakdown voltage while holding the density constant. The "scatter" is a measure of the variation of the breakdown voltage for repetitive breakdowns during a constant density test. For future reference, a numerical value of scatter is the difference between the high and the low measurements of the repetitive breakdown voltages for a constant density test.

CHAPTER 7

DETERMINATION OF BREAKDOWN PROBE CHARACTERISTIC

Introduction

The Paschen similarity principle (1) is useful as a general statement of breakdown voltage. It cannot be used reliably for a prediction of the exact voltage levels, since the Γ ratio has not and cannot be precisely determined as a function of pressure, electrode material, and surface condition. Differences are also expected to arise when the electrodes are not planar, as assumed in the derivation of the Paschen theory. In fact one of the objectives of this research was to determine the breakdown voltage versus density curve for electrode pairs that are not planar.

Characteristic of Different Electrode Geometry

Of the three different probes described earlier (small wire probe, radioactively enhanced probe, and ultraviolet enhanced probe) there are only two different basic electrode arrangements. The small wire probe and radioactive probe both have round, flat electrodes that are mounted flush with the insulating surface. The ultraviolet probe has electrodes consisting of two wires that are aligned axially with ends that face each other. These two different electrode geometries were tested to see if they would have a characteristic similar to that predicted by Paschen. A small wire probe was calibrated using the manual voltage system and a ultraviolet probe was calibrated with the automatic single ramp system.

Results

The calibrations of the two electrode geometries are shown in Figure 25. Both electrode configurations show a similarity to the Paschen characteristic. Each show a decreasing breakdown voltage with increasing density at low density, a minimum voltage in the characteristic, and then an increasing breakdown voltage with increasing density at higher density. The differences in the two curves result from the dissimilarities in the electrodes (metal used, electrode spacing and configuration, etc.) and from differences in the breakdown voltage measurement systems. Even though these electrode geometries are not the same as the parallel plane geometry used in the derivation of the Paschen equation the characteristic is similar.

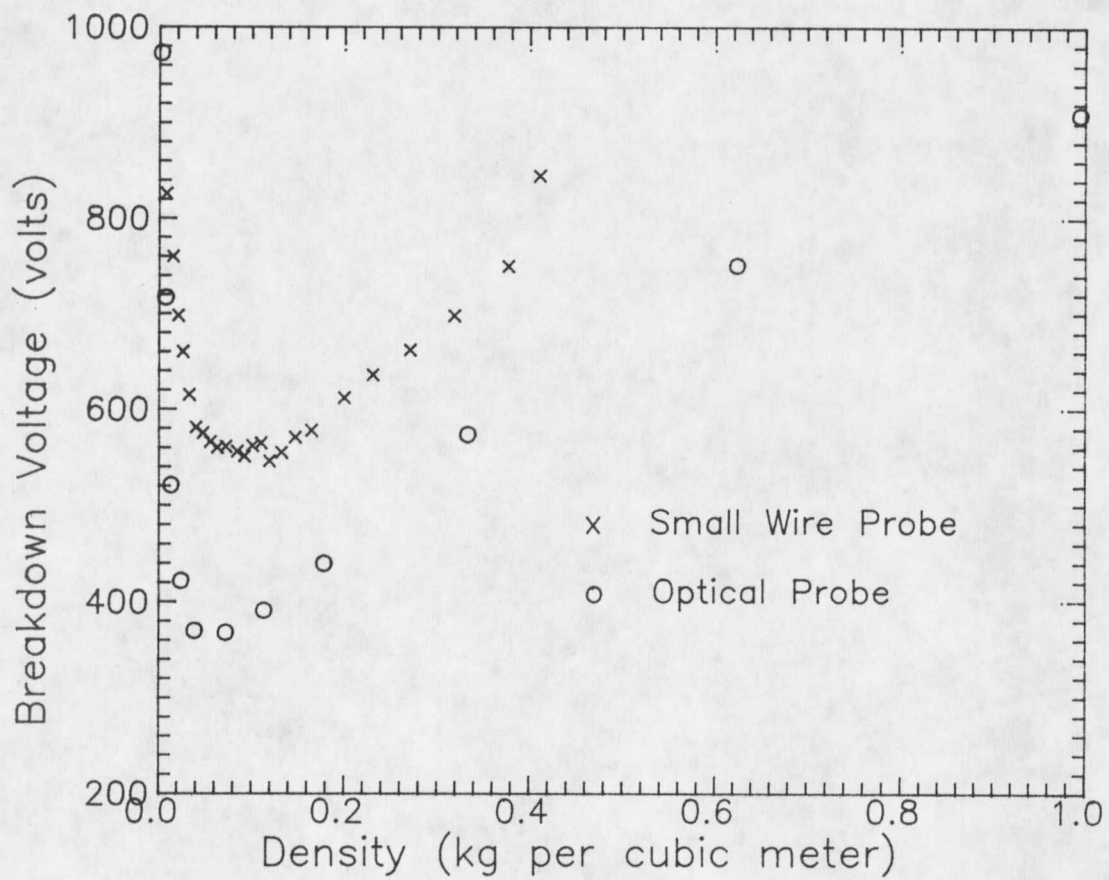


Figure 25. Characteristic For Two Different Electrode Configurations.

CHAPTER 8

REPEATABILITY OF BREAKDOWN VOLTAGE

Introduction

The irregular scatter in the calibration of the breakdown probe was a problem throughout this research. As previously mentioned the scatter in the breakdown voltage should be kept to a minimum to provide a usable probe. The origin of the scatter problems could be found in the voltage supply and measurement circuit or the breakdown probe itself. Several different methods to minimize the scatter were examined.

Initial Tests With the Manual System

In the early stages of research the manual voltage system (see Chapter 4 for description) was used to measure breakdown voltage. A constant density test was performed on a small wire probe and showed that the probe and manual voltage circuit were subject to scatter as high as 100 volts. This scatter originated either from the probe itself or the manual system used to measure the breakdown voltage. With the manual system it is difficult for the user to detect the onset of breakdown; therefore the breakdown voltage measurement is subject to human error. For the remainder of the research the manual system was replaced with the automatic single ramp (ASR) system. The ASR system is not subject to human error in the breakdown detection.

Scatter Reduction Methods

With the manual system replaced by the ASR, the scatter originating from the driving electrical circuit was reduced. The scatter resulting from the probe itself must also be minimized. One method to do this is by "pre-ionizing" the air with primary electrons. The source of the electrons can either be the air itself or the electrode metal. The liberated electrons from the air or electrode metal act as a "catalyst" for the breakdown because they are present in the gap when the voltage is applied. Three possible methods of providing pre-ionization are thermionic emission, radioactive decay, or photo-emission.

Thermionic Emission

The first method to provide primary electrons is by heating the electrodes to a high temperature to cause thermionic emission from the electrode metal. This is undesirable for a practical breakdown probe because the high temperature electrodes will generate a density gradient at the probe tip. This density gradient near the electrodes will interfere with local air density measurement.

Radioactive Enhancement

A second means of producing primary electrons is by the use of radioactivity. The particles emitted by radioactive decay have the ability to ionize air of a breakdown gap. The particles are emitted from the radioactive element and ionize the air molecules as they are accelerated through the electric field. Because the particles can only travel a limited distance in a gas, the radioactive element must be located in very close proximity to the electrodes of the breakdown gap or make up the electrodes themselves.

Electrode Illumination

While testing the repeatability of an electrode gap, it was noticed that the room light that illuminated the electrodes had a significant effect on the scatter of the breakdown voltage. The scatter was lower when the electrodes were exposed to room light than when they were in the absence of room illumination. A review of the literature verified that illuminating the electrodes with ultraviolet light will reduce the scatter in breakdown voltage measurements (Cobine [12]). According to Penning [13], ultraviolet light is of sufficiently short wavelength to liberate electrons (photo-emission) from the surface of platinum and most other metals. The electrons supplied by the photo-emission would be the source of the primary electrons. With this in mind, the idea of incorporating platinum electrodes with UV illumination was tested.

CHAPTER 9

OPTICAL PROBE TESTS

Initial Test of UV Illumination

A simple breakdown gap with platinum electrodes was constructed for the initial ultraviolet illumination tests. The ASR system was used to measure the breakdown voltage with the gap exposed to ambient air density. The type of electrode illumination was controlled and the effects of fluorescent, incandescent, and ultraviolet light were observed. For each test case, the repetitive breakdowns at constant density are shown in Figure 26. The lines were taken from X-Y recorder data. The recorder pen follows the voltage ramp of the ASR and the length of the line corresponds to the breakdown voltage. As shown in Figure 26 the room light only condition displays roughly 120 volts scatter and the incandescent light illumination shows approximately 70 volts scatter. However, with UV illumination the scatter is reduced to approximately 5 volts. This is a considerable improvement in the scatter of the breakdown voltage for the same gap at constant density.

Different Electrode Metals With UV Illumination

Simple breakdown gaps were constructed from several different metals to determine an acceptable metal for optical probe construction. Basically the gaps consisted of two small wires that are axially aligned with the wire ends separated by a gap of approximately 5 to 10 mils.

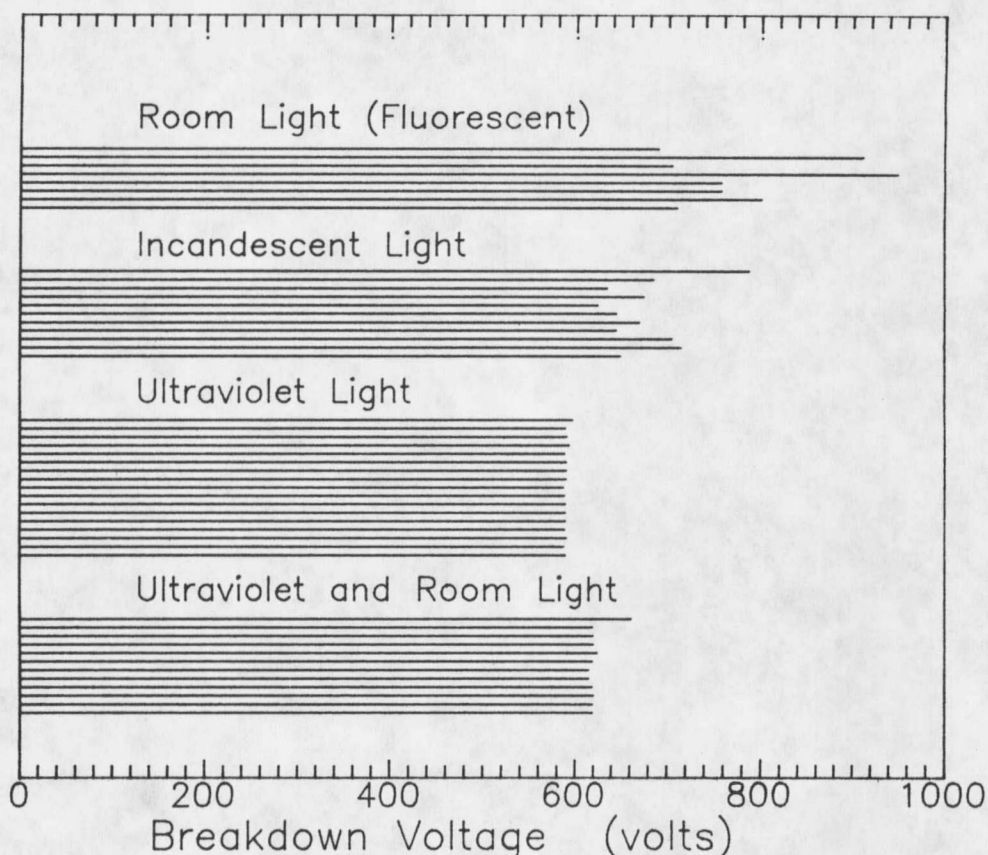


Figure 26. Effects of Different Illumination on Platinum Optical Probe at Constant Density.

The electrode gaps were illuminated by UV irradiation by placing the gap approximately 12 inches directly in front of the mercury arc lamp. The optical fiber and the fiber focusing system were not used to distribute the UV light.

The ASR system was used to measure the breakdown voltage for these different gaps. The metals tested were gold, nickel chromium, stainless steel, platinum, tungsten, and magnesium. Figure 27 shows the results of the breakdown gap tests. A comparison of the average breakdown voltage for each metal cannot be made because each gap has a slightly different separation distance. The comparison to

be made is the differences in the scatter in the breakdown voltage. When each of the metals is illuminated with UV light the scatter for each is relatively small.

Platinum will be used for optical probe construction because it does show minimal scatter when exposed to UV light. Platinum also has good corrosion resistance at high temperatures which is important to help avoid fouling of the electrodes.

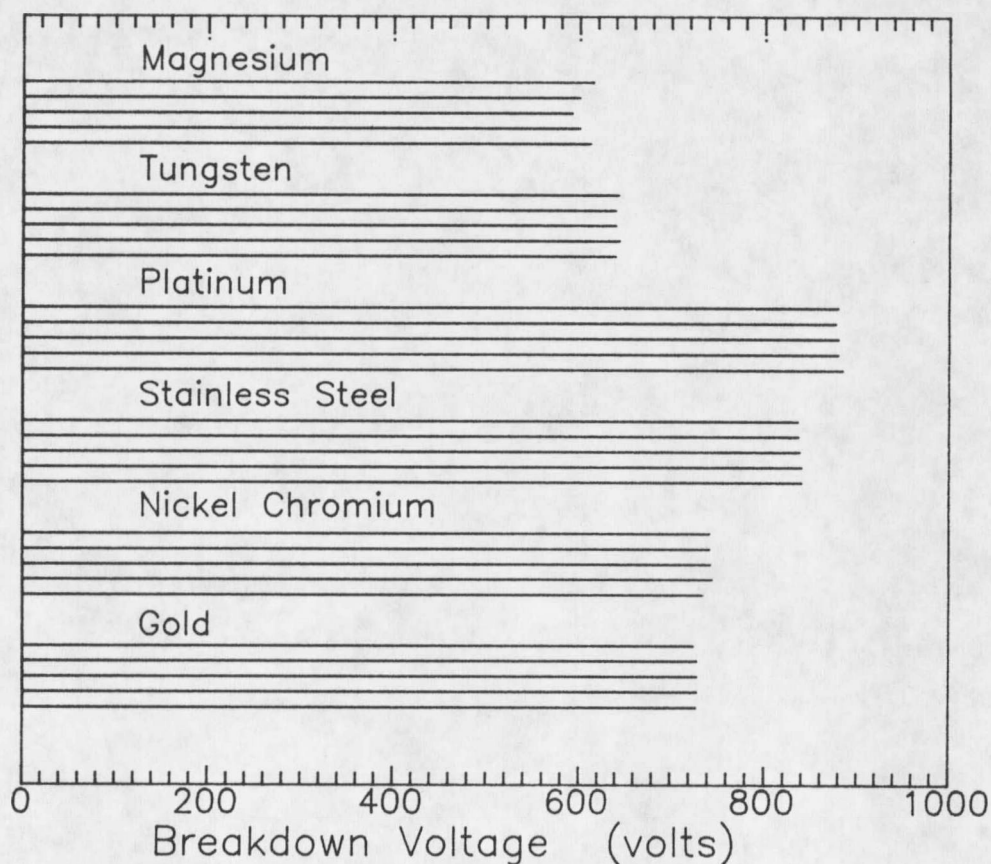


Figure 27. Breakdown Voltage Comparison for Different Electrode Metals Illuminated by Ultraviolet Light.

Optical Probe Calibration

With the success of the initial UV illumination test, optical probe BP4 (see Figure 11 for sketch) was built to test the effects of UV illumination on the probe's characteristic. The ASR system was used to make a full range calibration of probe BP4.

In the first calibration the mercury arc lamp was on which illuminated the electrodes with UV light. For the second calibration the arc lamp was turned off and the electrodes were not illuminated. Figure 28 shows the difference in the two calibrations for probe BP4. For each density there were seven repeated breakdown voltage measurements. From these seven measurements the high and low voltage values along with the average of the seven were plotted. The error bar on each point connects the high, low, and average breakdown voltage for each density. The scatter in the breakdown voltage is the difference between the high and low voltages. Figure 28 shows that the scatter is as high as 350 volts without the UV illumination but as low as 15 volts with the UV illumination.

Variation of Arc Lamp Intensity

The sensitivity of the breakdown voltage to the intensity of illumination at the probe electrodes was investigated. Optical probe BP12 was tested at constant ambient density. The light intensity at the probe electrodes was varied by (a) altering the alignment of the optical fiber and the focusing lens assembly and (b) changing the intensity of the mercury arc lamp.

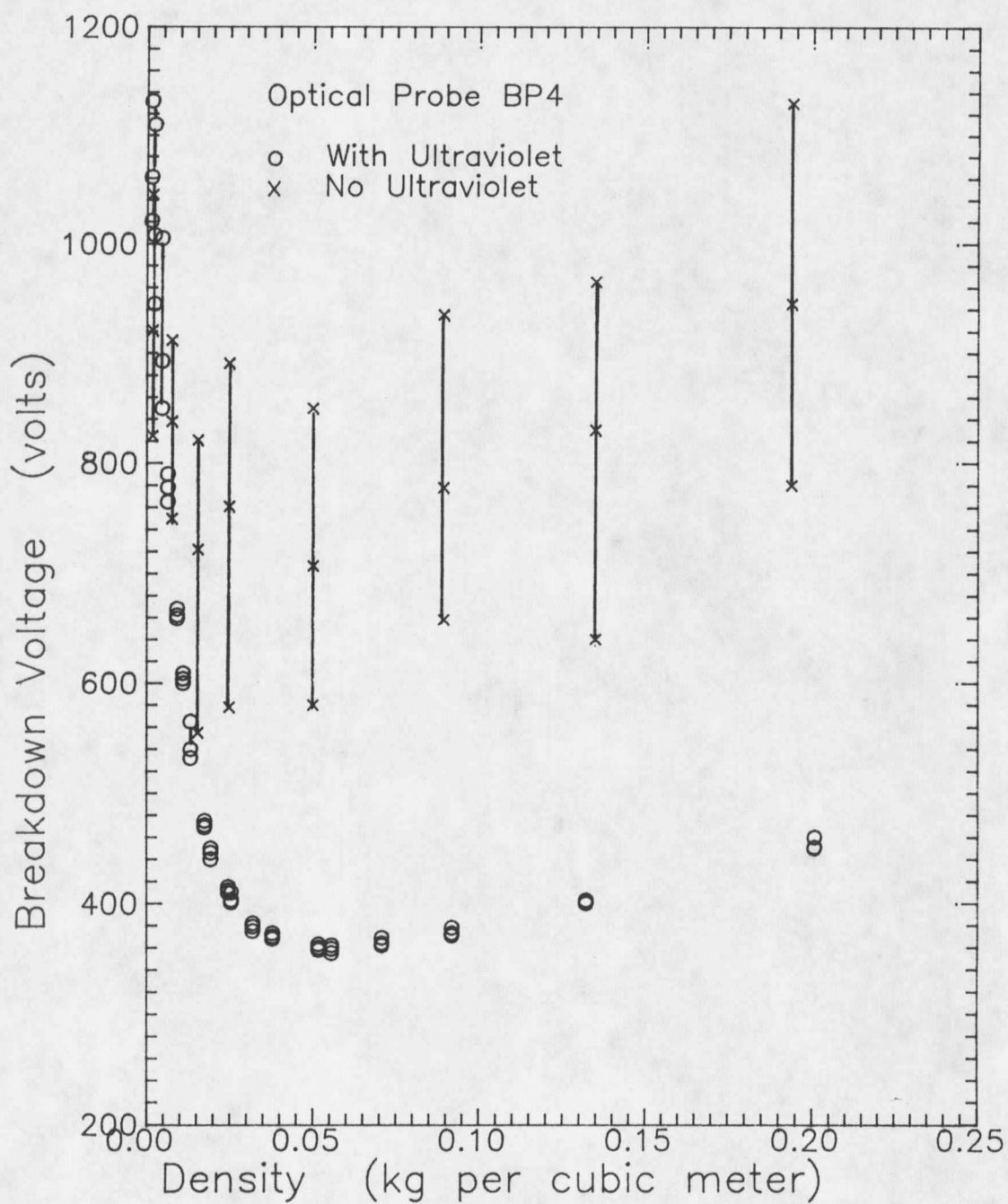


Figure 28. Comparison of Probe Calibration With and Without Ultraviolet Illumination.

Altering Fiber Alignment

The position of the optical fiber within the lens focusing system was altered from its normal operating position. The probe response to different alignments was observed. The data taken with the ASR system is displayed in Figure 29. For each test condition five repetitive breakdowns were made at a constant density. The first four test variations in Figure 29 show the effect of varying the fiber alignment. The first set (at the top of the graph) is the response of the probe when the arc lamp and collimating probe are used properly. The mercury arc lamp is operating at 200 watts and the light is correctly focused on the end of the fiber. The data set shows that the scatter is minimal during normal light system operation. The second set of breakdowns show the effects of having the fiber end slightly off focus inside the collimating probe. The effects of changing the focus further are shown in the third set of breakdowns. Finally, the collimating probe was completely removed from the lamp house and the bare fiber end was aimed at the arc lamp. The fourth set of breakdowns is the response of the probe for no focusing assembly. Without the focusing assembly the light at the probe tip was very dim yet the breakdown voltage measurements are still consistent.

The fifth set of breakdowns show the effects of having the mercury arc lamp off (no UV) for a comparison. These results agree with the tests of Figure 26. The ultraviolet illumination aids in reducing the scatter.

Altering Arc Lamp Current

The current through the mercury arc lamp can be controlled by a potentiometer on the control panel of the lamp power supply. For normal operating conditions for a 200 watt lamp output the current is set at 4.2 amps. The current can be changed with the potentiometer from 2 amps to 6 amps which varies

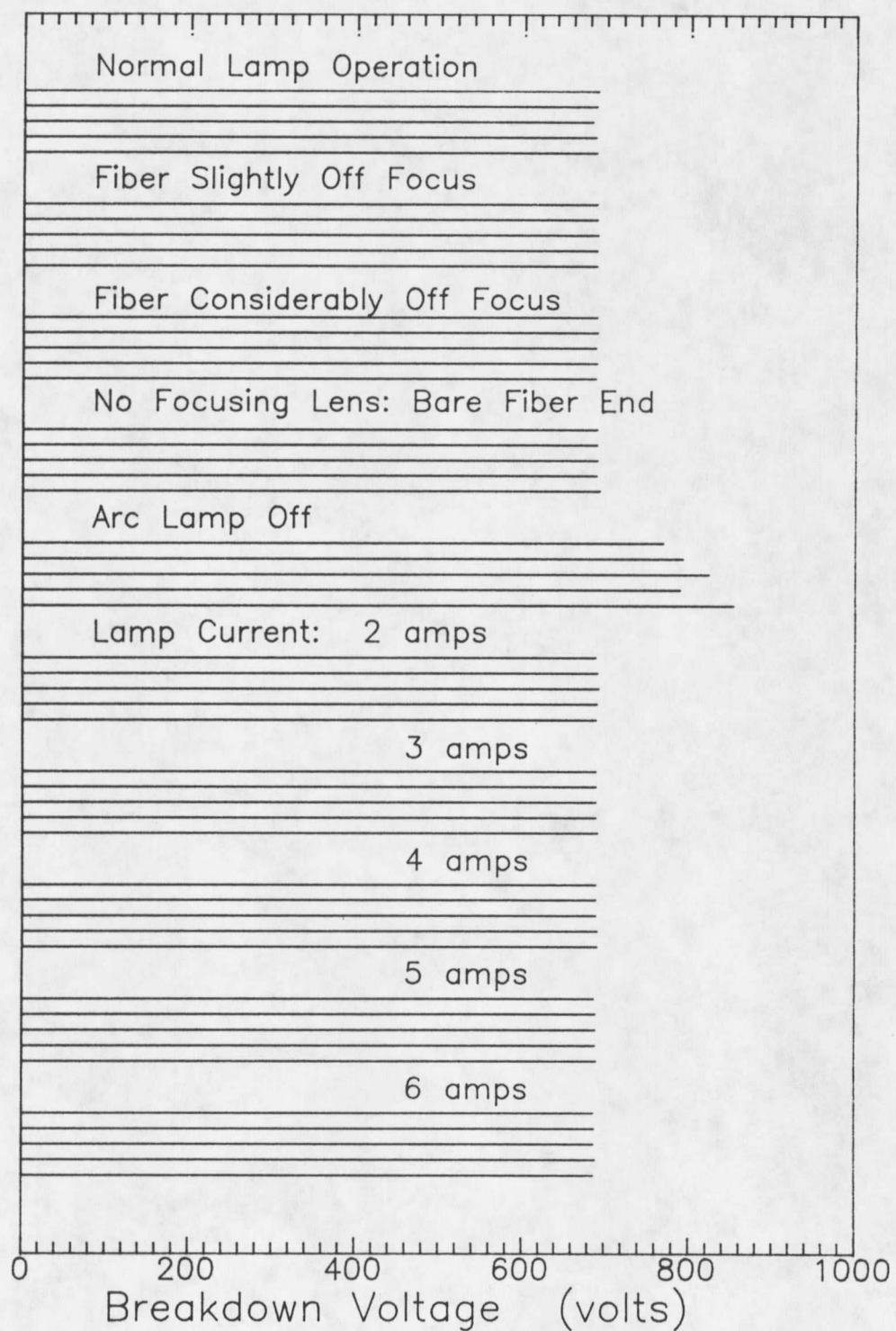


Figure 29. Effects of Varying UV Intensity On the Breakdown Voltage for the Same Probe at Constant Density.

the intensity of the arc lamp. With the focusing lens system in place and the fiber correctly positioned the same probe BP12 was tested under constant density. Breakdown voltage sets 6 through 10 in Figure 29 show the probe response to variations in the arc lamp current. The average breakdown voltage remains unchanged and the scatter is minimal.

Repeatability of Calibration

To demonstrate the feasibility of using a breakdown probe to measure density, the calibration must remain steady while the probe is being used. If the calibration changes with use then the probe will be unreliable. The repeatability of the calibration was demonstrated by periodically recalibrating a probe.

Optical probe BP6 was periodically calibrated with the ASR system. In between calibrations the probe was removed from the vacuum chamber, the optical fiber was disconnected from the collimator, and the electrical connections to the probe were disconnected. The probe was then mounted in the wind tunnel, all connections were reassembled, and various tests were made in the running tunnel (tests to be described later). After the tests were completed the probe was removed from the tunnel and reassembled in the vacuum chamber for another calibration. This process was repeated four times over a period of four days with one calibration per day. Each calibration is plotted in Figure 30 with each calibration denoted with a different symbol. For each density five repeated breakdown voltages were measured. The high, low, and average breakdown voltages are plotted for each density. As shown in Figure 30 the probe's calibration remains relatively unchanged despite the frequent handling and use. The scatter is also minimal.

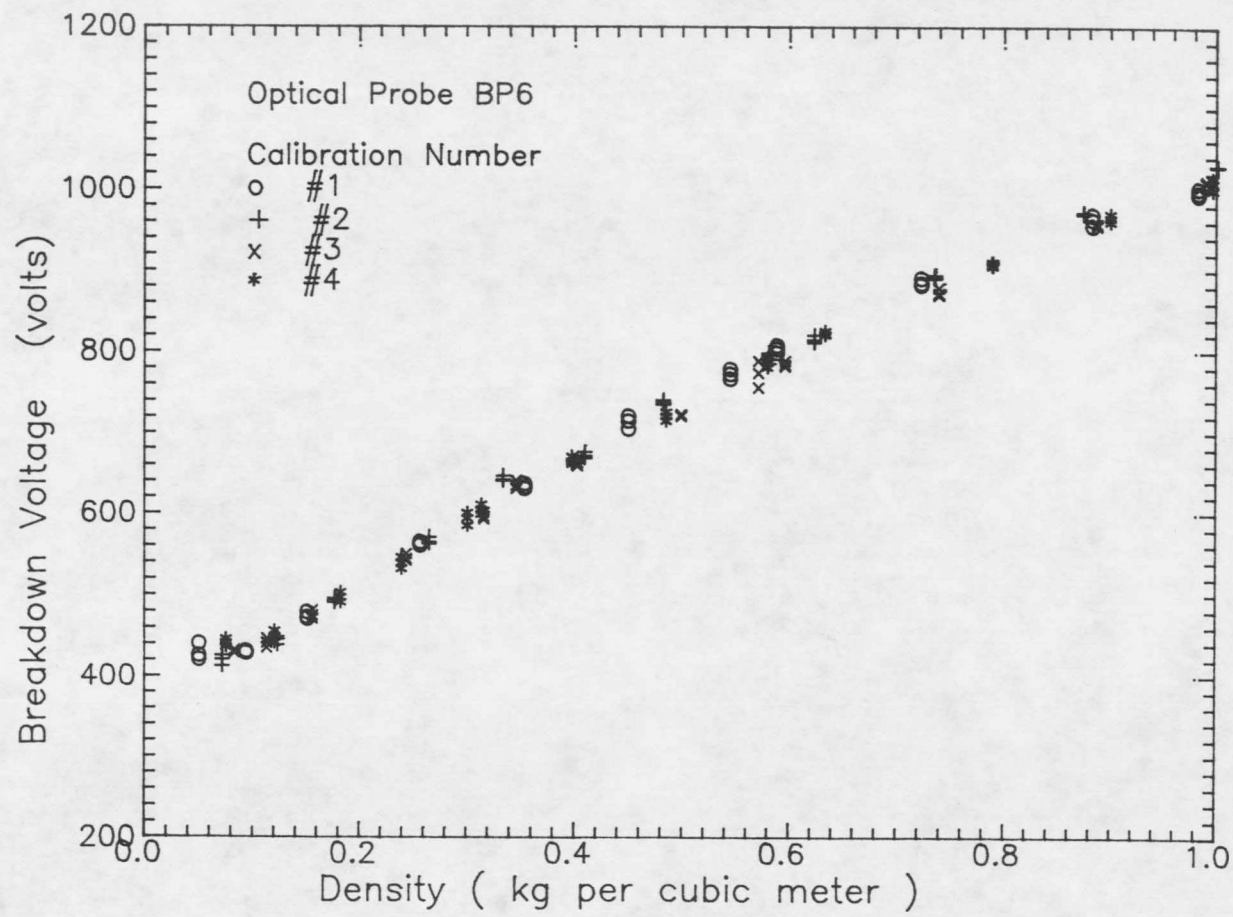


Figure 30. Repeated Calibration of Probe BP6.

CHAPTER 10

RADIOACTIVE BREAKDOWN PROBE

Initial Test With Simple Gap

The preliminary test of the simple Lead 210 breakdown gap (described in Chapter 4) was to determine the effects of using radioactivity as an ionization enhancement mechanism. The gap was tested with the wire as the positive electrode and the needle as the negative electrode. The ASR system was used to measure the breakdown voltage. The characteristic curve obtained is shown in Figure 31. The plot shows the high, low, and average of five breakdown voltages for each density. The characteristic curve for the radioactive gap follows the Paschen similarity principle while the scatter is within reasonable limits. Since the preliminary test for using a radioactive source to ionize the breakdown gap was encouraging, it was decided to construct a probe using a radioactive source.

Radioactive Probe Test

Radioactive probe BP7 was constructed as described in Chapter 3. This probe was calibrated with the ASR in the vacuum chamber at room temperature. The calibration is shown in Figure 32. For each density there were five readings of the breakdown voltage. As before the high, low, and average breakdown voltages are plotted in Figure 32. The radioactive probe BP7 shows minimal scatter in the breakdown voltage.

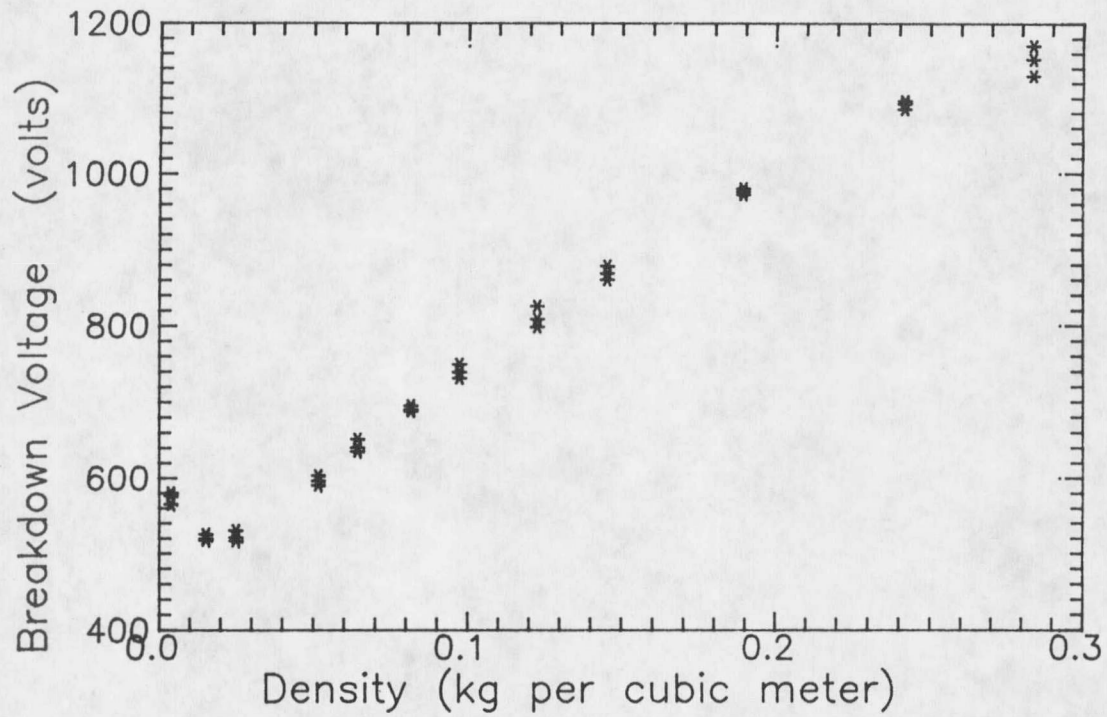


Figure 31. Calibration of Simple Radioactive Gap.

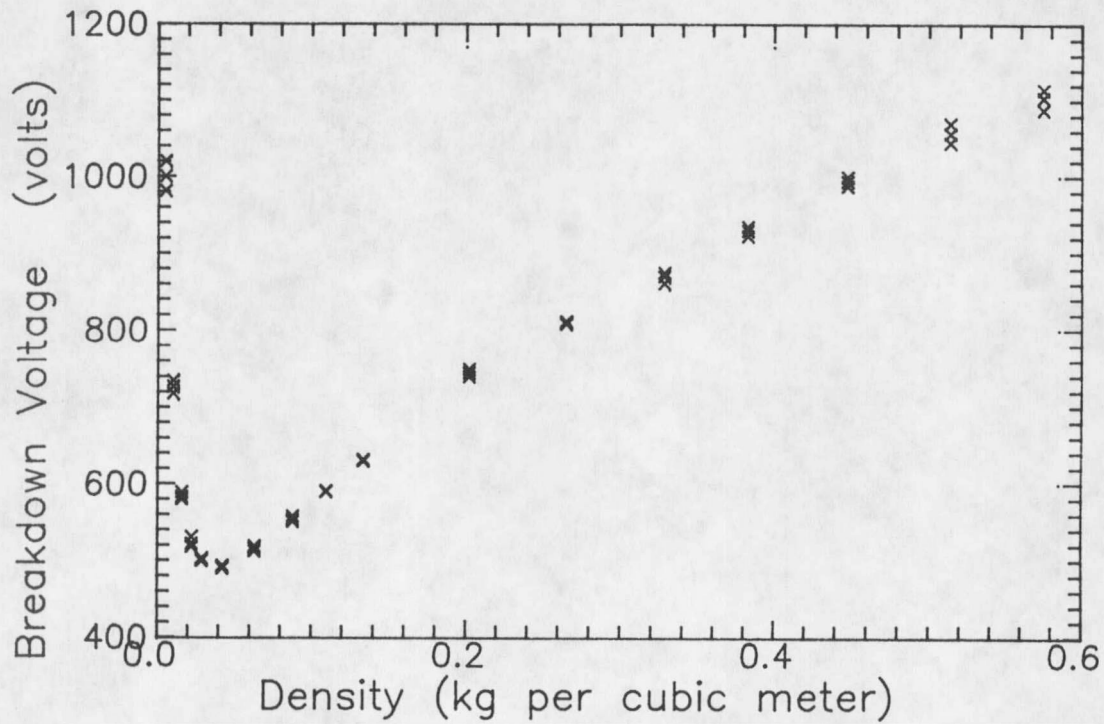


Figure 32. Calibration of Probe BP7.

Radioactivity Effect

A calibration of radioactive probe BP7 shows a similar characteristic to that of an optical probe. Both probes show a smooth characteristic with minimal scatter. However, it is uncertain whether the radioactivity is actually the cause of the good response of probe BP7.

A simple test was made with a small wire probe that had a similar tip geometry to the radioactive probe BP7. First the non-radioactive small wire probe was tested at ambient density and showed approximately 60 volts scatter. The tip was then dipped in the radionuclide C-14 for approximately 20 seconds and then allowed to dry. Next, the probe was again tested at ambient density and it still showed approximately 60 volts scatter. The radioactivity did not reduce the scatter of the test probe.

This test demonstrates that the radioactivity was not the single contributor to the good response of probe BP7. Some other factor such as the electrode size may be the cause of the low scatter. The radioactivity may have a slight effect on reducing the scatter but it is not the dominating scatter reducing mechanism.

CHAPTER 11

TEST OF CDAS VOLTAGE RAMP

Introduction

In preparation for wind tunnel testing the CDAS voltage ramp was used to calibrate an optical probe to investigate the system's performance. The same evaluation of the Paschen characteristic must be made for the CDAS voltage ramp as was previously determined for the ASR system. The same questions of repeatability of the breakdown voltage for a constant density test must be kept in mind when evaluating the CDAS ramp.

Optical Probe Calibration

Optical probe BP6 was calibrated at room temperature with the CDAS ramp. For each density there were 20 total breakdowns at a rate of 20 breakdowns per second. The calibration is shown in Figure 33 with the average breakdown voltage plotted for each density along with the standard deviation of the 20 breakdowns.

Notice that the average breakdown voltage does not follow a smooth curve and the standard deviation is quite large. When this same probe is calibrated with the ASR system the curve is smooth and the scatter is minimal (Figure 30).

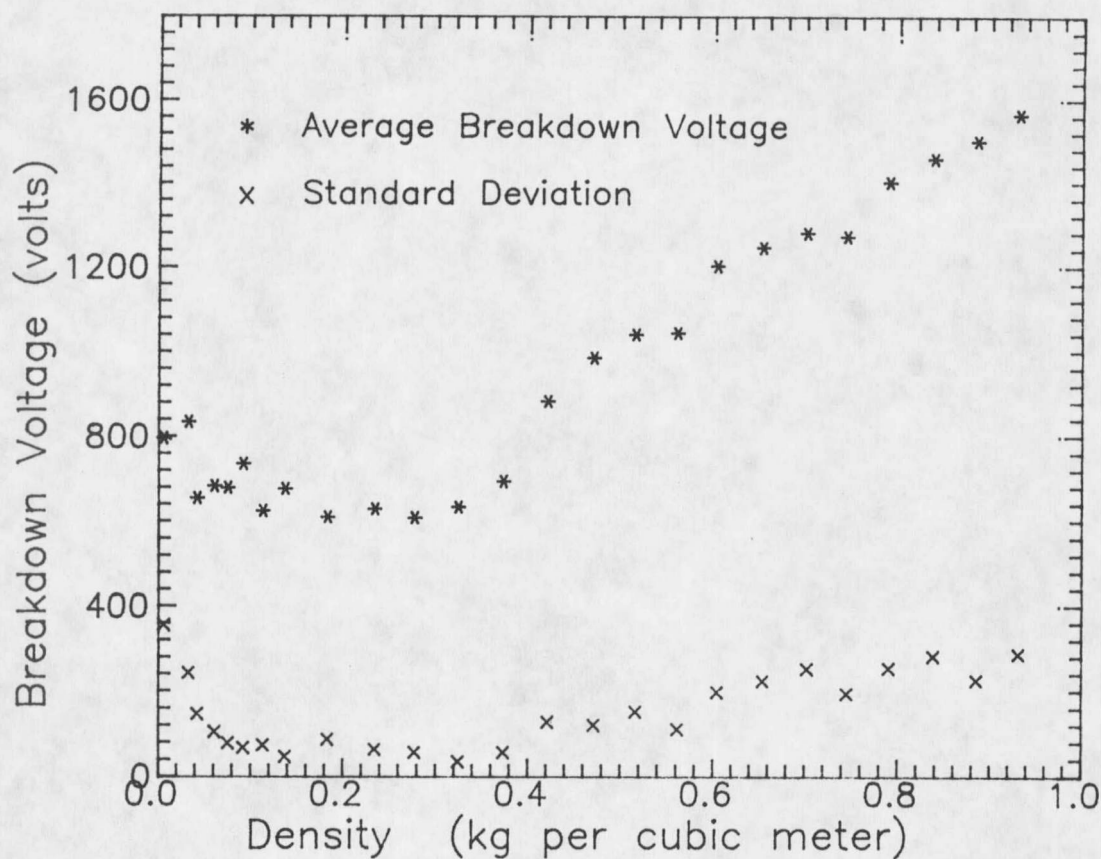


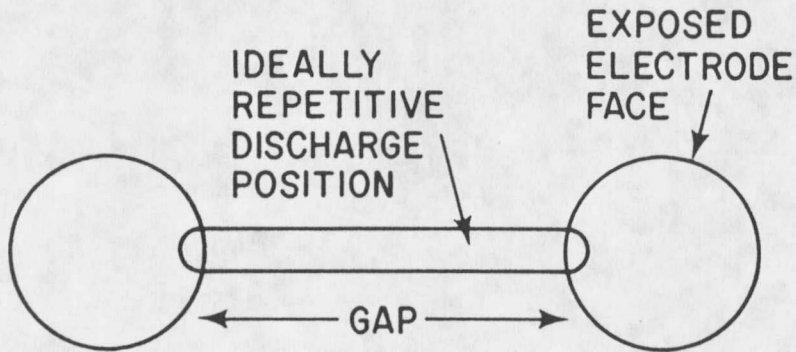
Figure 33. Calibration of Optical Probe BP6 With the CDAS Ramp.

Origin of Irregularity of Breakdown for CDAS Ramp

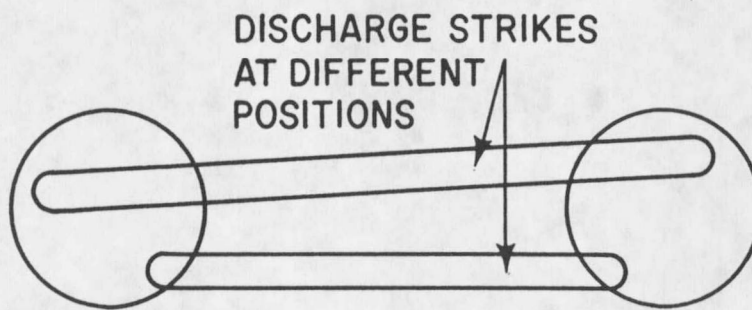
The large standard deviation in the breakdown voltage for the optical probe may originate in (a) the probe itself or (b) the CDAS voltage ramp and breakdown detection system. Scatter originating from the probe itself was investigated by physically observing the breakdown and the arc path. A theoretical explanation for scatter that arises from the CDAS voltage ramp will be given in a later section.

Electrode Diameter

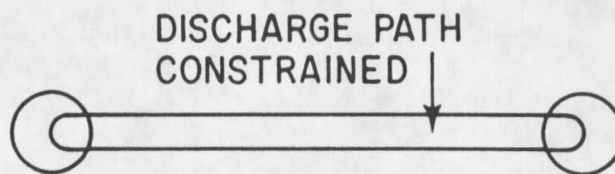
The breakdown gap of the optical probe BP6 cannot be observed under a microscope because of the light intensity coming through the optical fiber. For this reason a small wire probe was used to determine the breakdown path under repeated breakdowns with the CDAS ramp. By observing the electrode tip of a small wire probe under a microscope, it was determined that the diameter of the electrode effectively controls the variation of the breakdown voltage. For minimal scatter the arc path must be located in the same position on the probe face for repetitive breakdowns. As shown by the Paschen characteristic (1) the breakdown voltage is a function of electrode separation or in other words the distance the arc must travel to connect the electrodes. Case 1 in Figure 34 shows the ideal arc path for repetitive breakdowns. The arc path remains constant for all breakdowns. By observing the arc path under a microscope the actual discharge was seen to "jump" across the face of the relatively large electrodes as shown in Case 2 in Figure 34. Since the discharge path varies the breakdown voltage will change due to the change in discharge length. By using small diameter electrodes the discharge path can be constrained (Case 3, Figure 34). With a steady discharge path the scatter in the breakdown voltage will be reduced. By observing (with a microscope) different diameter electrodes during breakdown this was proven to be the case. With the discharge path constrained the scatter was reduced.



1. IDEAL LARGE-ELECTRODE BREAKDOWN PATH



2. ACTUAL LARGE-ELECTRODE DISCHARGE PATH



3. DISCHARGE CONSTRAINED WITH SMALL ELECTRODES

Figure 34. Effects of Electrode Diameter on Discharge Path.

Inconsistency of CDAS Ramp

The large range of the breakdown voltage standard deviation for calibrations using the CDAS ramp may be the result of the ramp itself. Since the slope (1 volt per μsec) of the CDAS ramp is several orders of magnitude greater than that of the ASR system, the two breakdown voltage measurements will be considerably different.

One reason for this is that the faster ramp experiences a "time lag" in measuring the breakdown voltage. A more thorough explanation of the time lag than that given here is given by Cobine [14]. It takes a finite amount of time for the primary electrons to form once a sufficient voltage level is reached to initiate a breakdown. During this finite time the ramp voltage is steadily increasing and a "overvoltage" is applied to the electrodes. If the ramp slope is very steep then a higher overvoltage will be reached before the primary electrons have been formed. The finite time it takes for primary electrons to form is random in nature and will vary from one breakdown to the next. A ramp with the steep slope will have a larger "time lag" when compared to a ramp with less of a slope. The random time lag becomes more evident when a voltage ramp with a steep slope is used. The time lag may account for the large standard deviation in the tests with the CDAS ramp.

CHAPTER 12

DENSITY DEPENDENCE OF CHARACTERISTIC

Introduction

In Chapters 1 and 2 it was stated that the breakdown voltage is a function of density only for a given gas and electrode configuration. The density effect was determined for optical probe BP12 with the ASR system measuring the breakdown voltage. Constant pressure, temperature, and density tests were made to confirm that the breakdown is a function of density alone.

Constant Pressure Test

Optical probe BP12 was tested with the ASR system for the constant pressure test. While holding the pressure constant at $P = 400$ mm Hg, the breakdown voltage was then measured at five temperatures between room temperature and 200°C . Since the pressure was held constant the density of the air was decreased while the temperature was raised.

For comparison probe BP12 was calibrated at room temperature in the density range of 0.65 to 0.3 kg per cubic meter. Figure 35 shows the room temperature calibration along with the breakdown voltage at each temperature. Each point plotted in Figure 35 is the average of five breakdowns. When the constant pressure breakdowns are plotted they follow the room temperature calibration. Since the pressure was held constant in this case, this test shows that the breakdown voltage does not depend on temperature only. If the breakdown were dependent

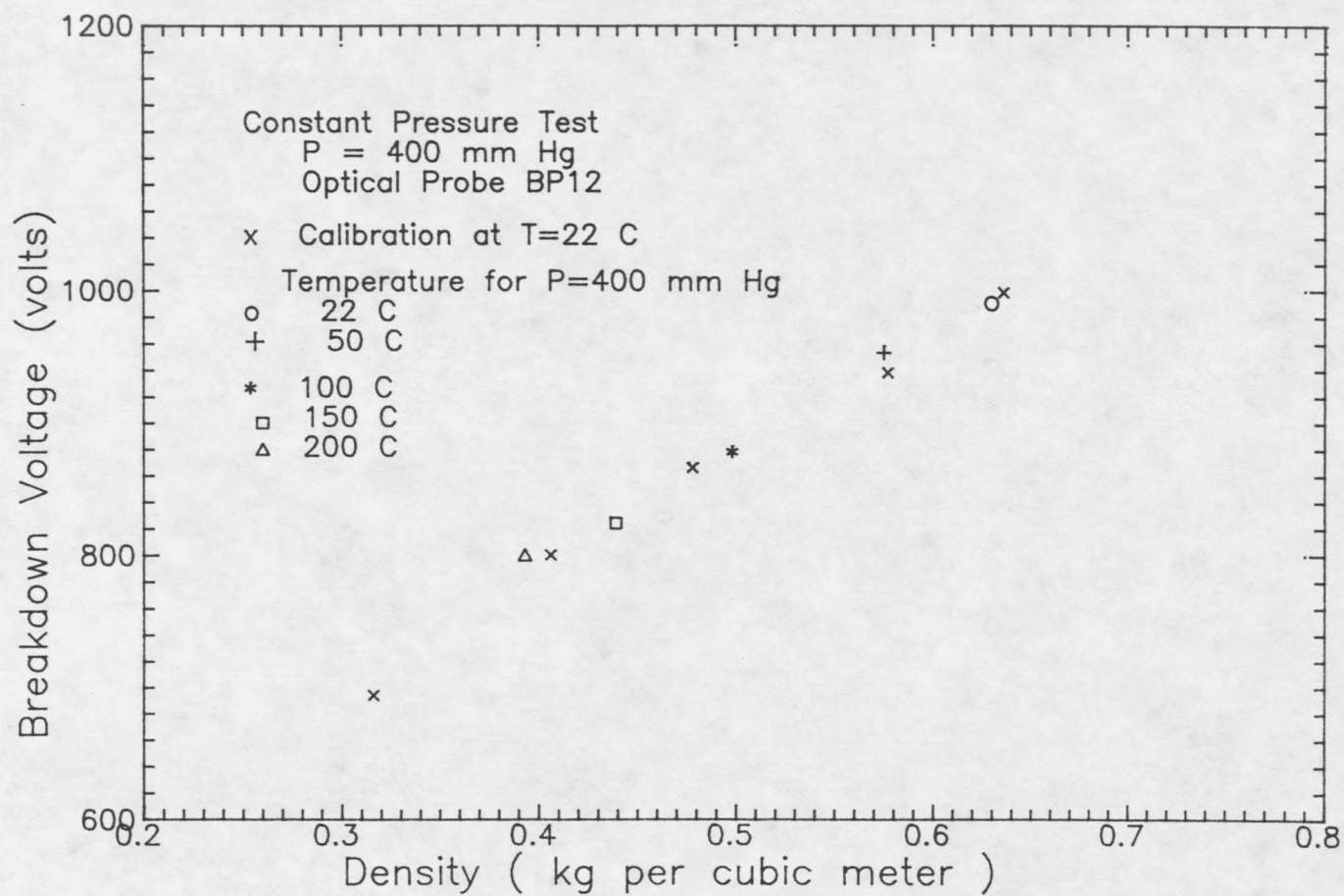


Figure 35. Constant Pressure Test of Probe BP12.

on air temperature only then the high temperature, constant pressure breakdowns would not follow the room temperature calibration.

Constant Temperature Test

Probe BP12 was calibrated at three different temperatures, 21° C, 100° C, and 200° C. A full range calibration using the ASR system for several pressures was made at each of the three temperatures. Figure 36 shows the breakdown voltage plotted versus pressure for each temperature. Each of the three temperatures shows a different curve on the breakdown voltage versus pressure plot. The same data has been replotted on a standard calibration curve, breakdown voltage versus density, in Figure 37. Note that in Figure 37 the curves for all three temperatures follow the same characteristic. This demonstrates that the density is the controlling factor of the breakdown voltage and not the pressure and temperature acting alone. If the breakdown had a strong pressure dependence then the different temperature curves on the breakdown voltage versus density characteristic would not show the same similarity.

Constant Density Test

With probe BP12 mounted in the vacuum chamber the chamber was evacuated to a pressure near 300 mm Hg. With a constant mass of air inside the pressure station and vacuum chamber the density must remain constant because of the constant volume. Changing the chamber temperature will not change the density. With a constant density, probe BP12 was tested over a range of temperatures from 25° C to 200° C. Figure 38 shows the response of the probe at constant

density with varying temperature. The breakdown voltage remains relatively constant over the range of temperature. This means that the breakdown voltage does not depend on temperature or pressure only.

The breakdown voltage depends on pressure and temperature combined. The density is the true controlling factor. This follows the theory that the breakdown voltage is a function of density only.

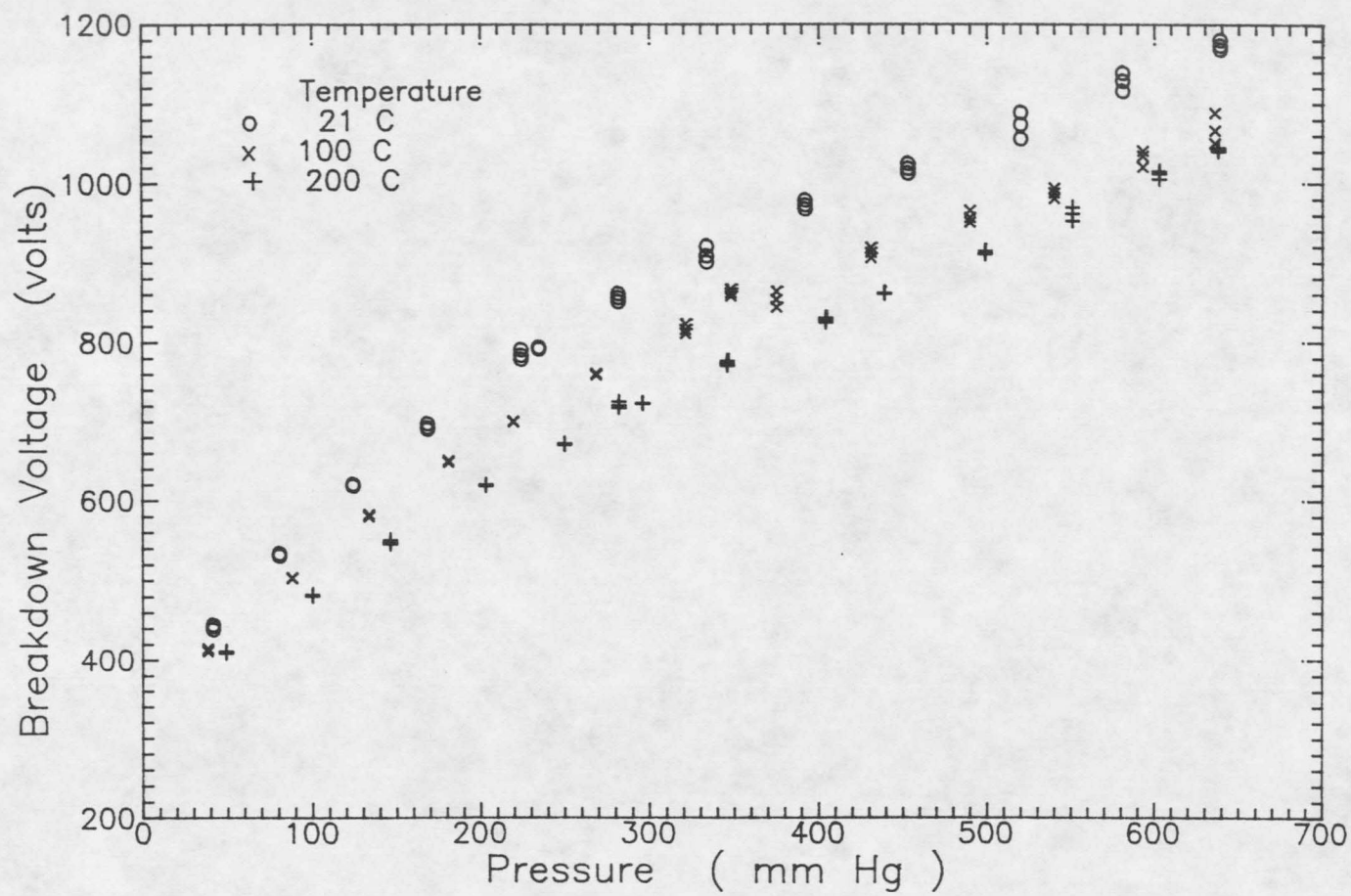


Figure 36. Breakdown Voltage Versus Pressure Characteristic of Probe BP12.

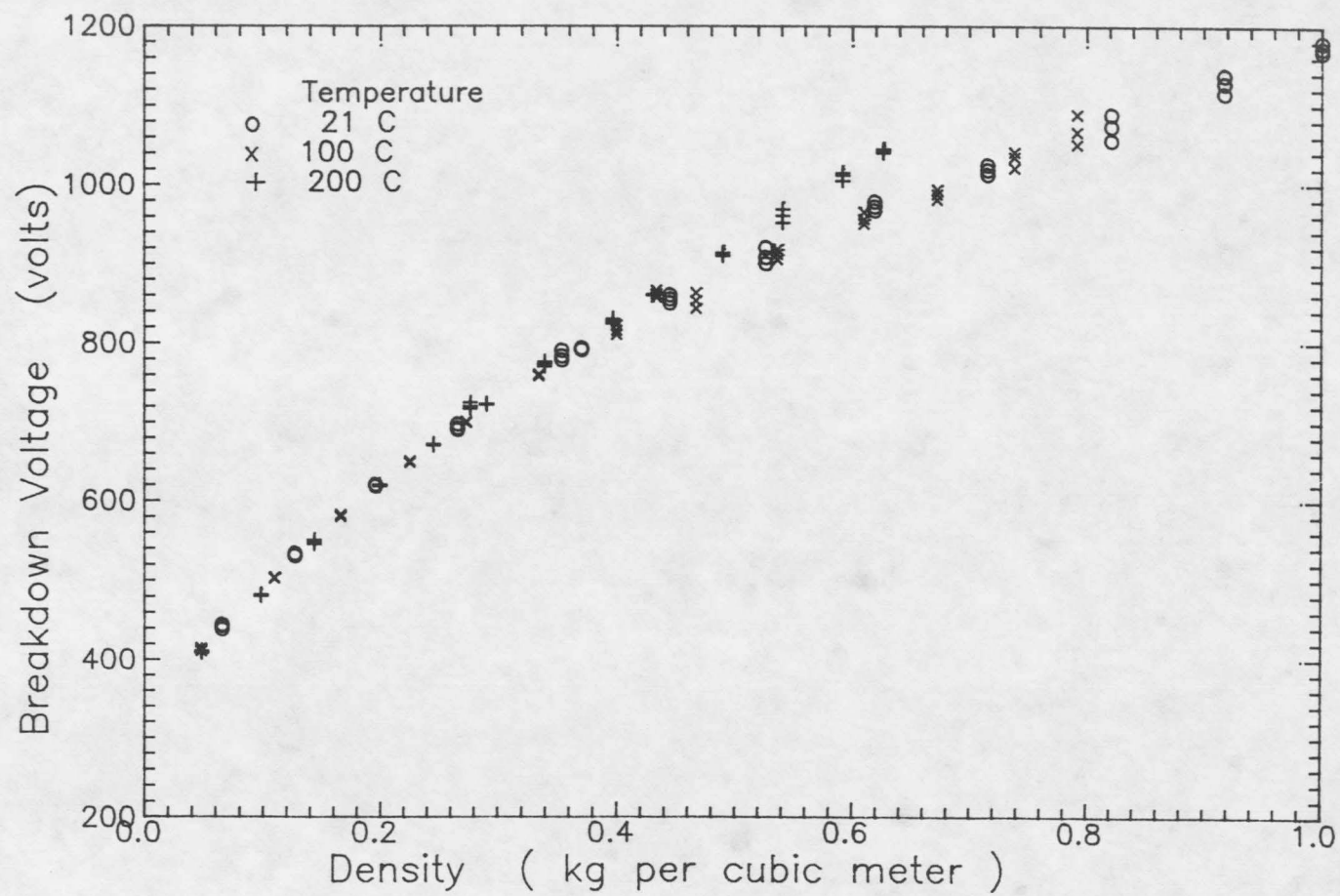


Figure 37. Breakdown Voltage Versus Density Characteristic of Probe BP12.

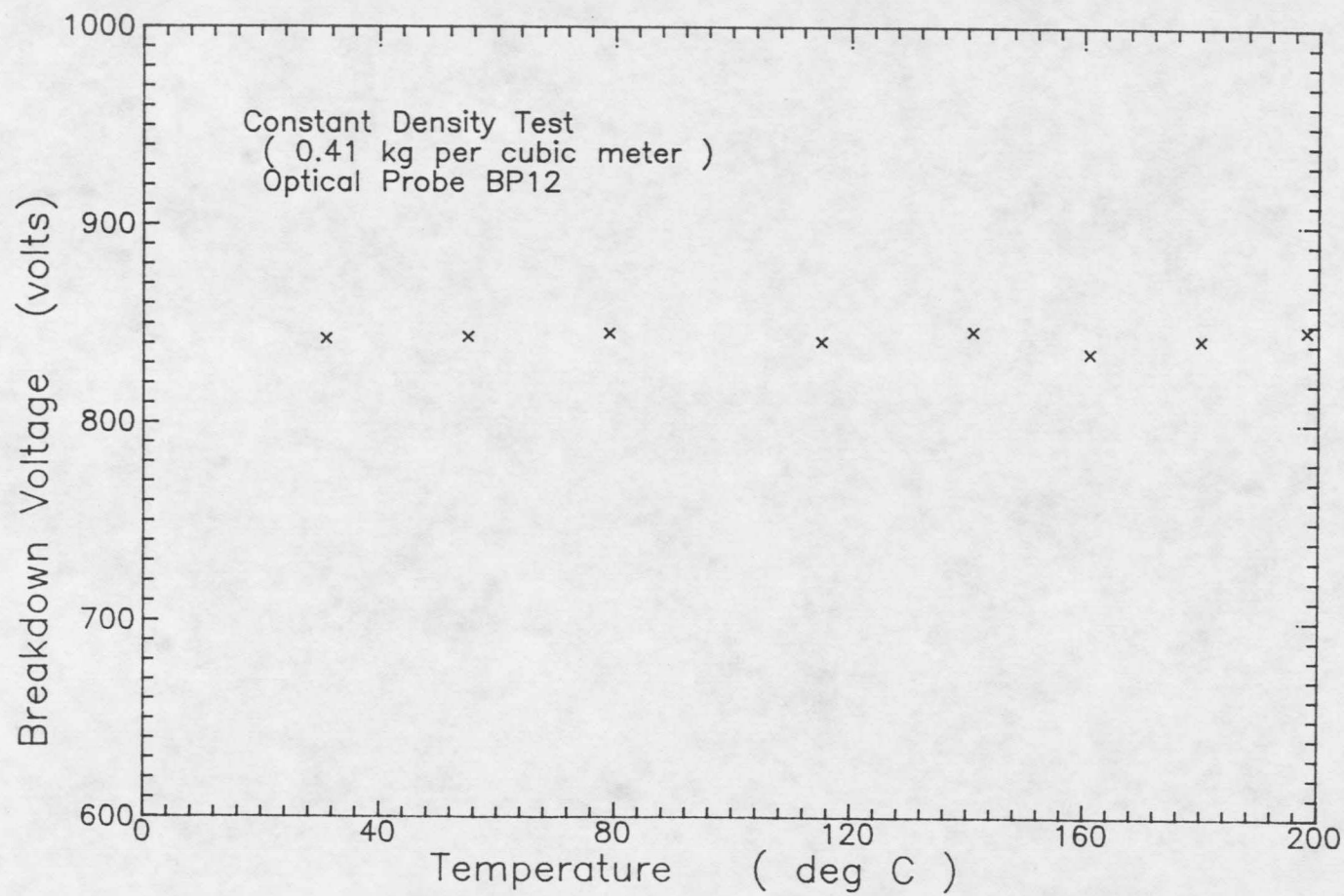


Figure 38. Constant Density Test of Probe BP12.

CHAPTER 13

MEAN DENSITY MEASUREMENTS IN THE SWT FOR OPTICAL PROBE

Introduction

A breakdown probe was tested in the Supersonic Wind Tunnel by taking breakdown voltage measurements at various locations in the flow. Depending on where the measurements are taken the pitot density may be found from theoretical relations or it may be measured by another instrument. In either case it is desired to test the breakdown probe and compare the results with another method. The two methods used for this research are (a) testing the probe in a flow of known Mach number and (b) comparing the probe to measurements taken by a different measurement.

Free Stream Measurements

Pitot Density at Mach 3

The test section of MSU's supersonic wind tunnel has Mach 3 flow conditions. With the Mach number known the pitot density relation (equation (7)) gives for $M = 3$ and $\gamma = 1.4$:

$$\frac{\rho_p}{\rho} = 4.31 \quad (37)$$

The relation between the pitot density and the SWT supply stagnation density ρ_o is given by:

$$\frac{\rho_p}{\rho_o} = \frac{\rho_p}{\rho} \frac{\rho}{\rho_o} \quad (38)$$

The last term that can be found from compressible flow tables and for air at Mach 3 is 0.0762, therefore:

$$\frac{\rho_p}{\rho_o} = (4.31)(0.0762) = 0.328 \quad (39)$$

From the SWT stagnation pressure P_o and the stagnation temperature T_o the stagnation density ρ_o can be calculated from the ideal gas law. From the stagnation density the pitot density at Mach 3 is given by equation (39). This provides a theoretical comparison for breakdown probe testing.

Test Procedure

Probe Calibration. Optical probe BP6 was calibrated with the ASR system in the vacuum chamber at room temperature. The calibration is plotted as calibration #2 in Figure 30. From this calibration an equation for the density as a function of the average breakdown voltage V_b was generated by a least squares regression technique. The third order polynomial for this calibration is:

$$\rho_p = -0.4251 + (1.350E - 3)V_b - (5.802E - 7)V_b^2 + (5.947E - 10)V_b^3 \quad (40)$$

which is valid in the density range $0.1 < \rho_p < 1.0$ kg per cubic meter. A comparison of equation (40) with the calibration data is given in Figure 39.

Tunnel Testing. Probe BP6 was mounted in the wind tunnel test section and positioned where the flow is known to be at Mach 3. All electrical connections and optical fiber connections were reconnected as in the previous calibration. With the tunnel running the stagnation pressure and temperature were varied to give a supply stagnation density in the range $0.55 < \rho_o < 0.95$ kg per cubic meter. Five values of the breakdown voltage were measured at various stagnation pressures and temperatures.

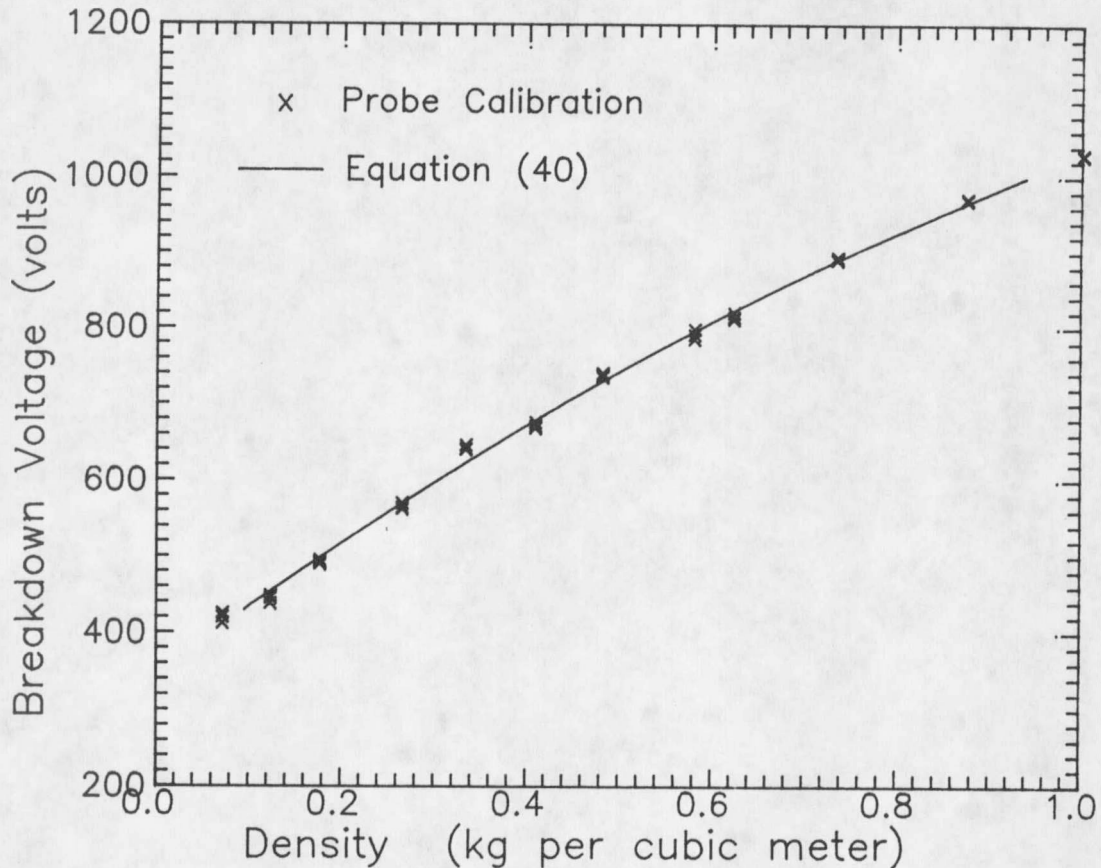


Figure 39. Comparison of Curve Fit Equation With Calibration Data.

Results. From the average breakdown voltage for each stagnation density the measured pitot density was calculated from equation (40). This was then compared to the theoretical calculation of the pitot density from equation (39). Figure 40 shows the comparison. The pitot density measured by the breakdown probe does not exactly follow the theoretical but it is close. In the worst case (lowest stagnation density) it is off by 31%. In the best case, however, it is almost exact.

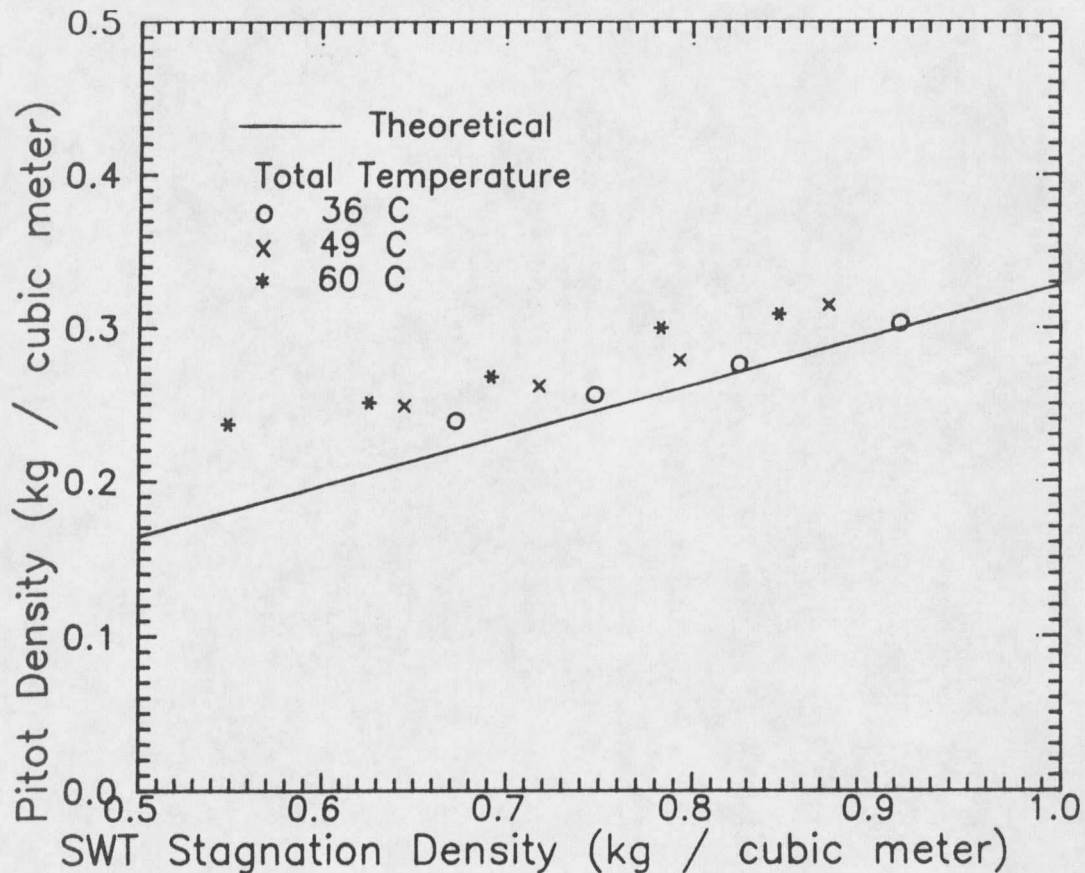


Figure 40. Comparison of Exact Pitot Density with Pitot Density Measured by Probe BP6 at Three Different Total Temperatures.

Flow Behind Wedge

Wedge Description

A small two dimensional wedge was mounted on a strut at the top of the tunnel in the SWT test section. The wedge dimensions are given in Figure 41. The flow directly behind the wedge centerline will be two dimensional because the wedge is 1 inch wide. The trailing corner of the wedge is rounded to provide a Prandtl-Meyer expansion fan in the flow. Figure 42 shows the wedge mounted in the tunnel. Figure 43 shows Mach 3 flow over the wedge. Notice in Figure 43 that the expansion fan can be seen as the lighter area that extends from the rounded corner. The oblique shock can be seen extending from the wedge tip.

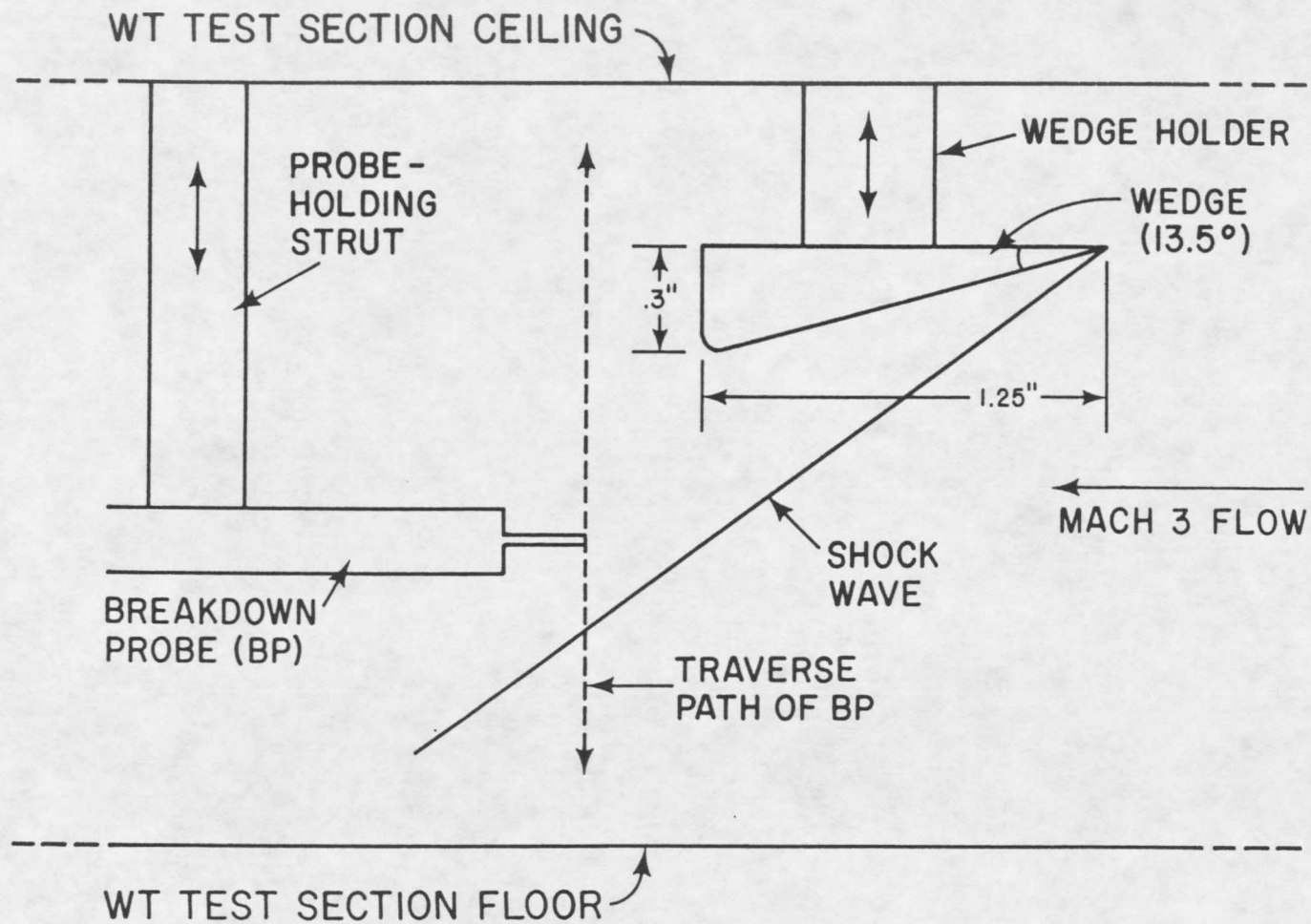


Figure 41. Dimensions of Two Dimensional Wedge.

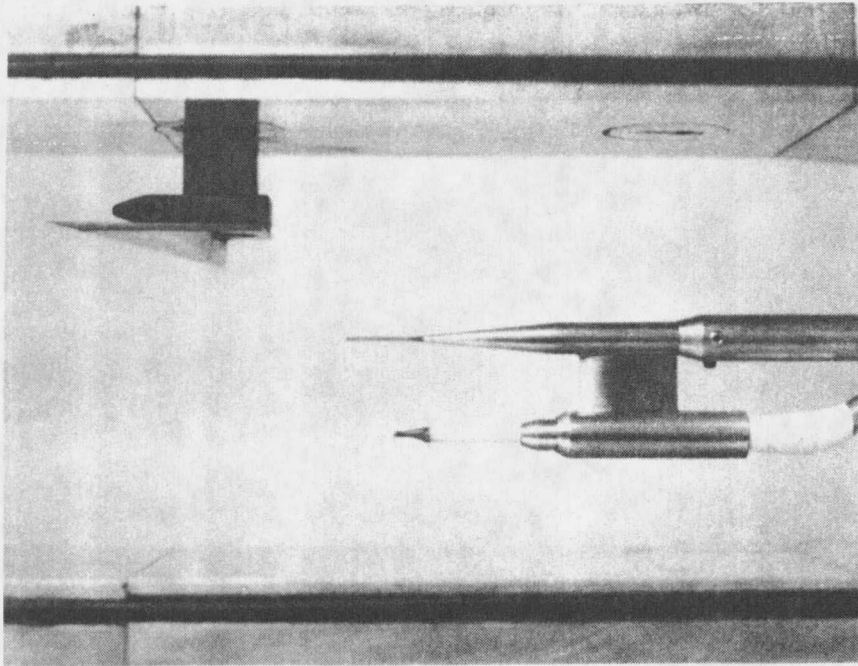


Figure 42. Pitot Tube (Top) and Breakdown Probe (Bottom) in Position Behind Wedge. Flow Is From Left to Right.

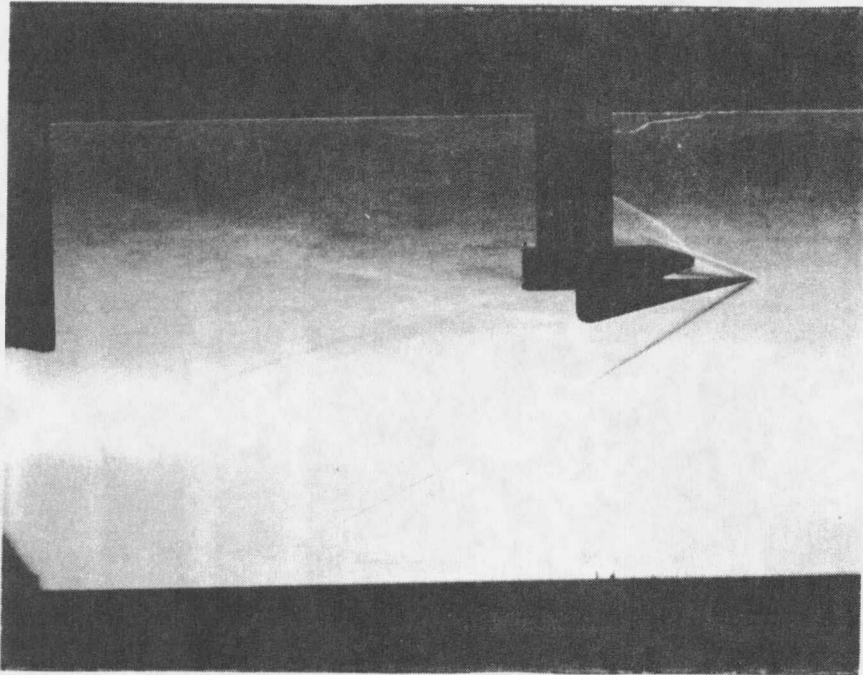


Figure 43. Wedge in Mach 3 Flow. Flow is From Right to Left.

Density Measurement

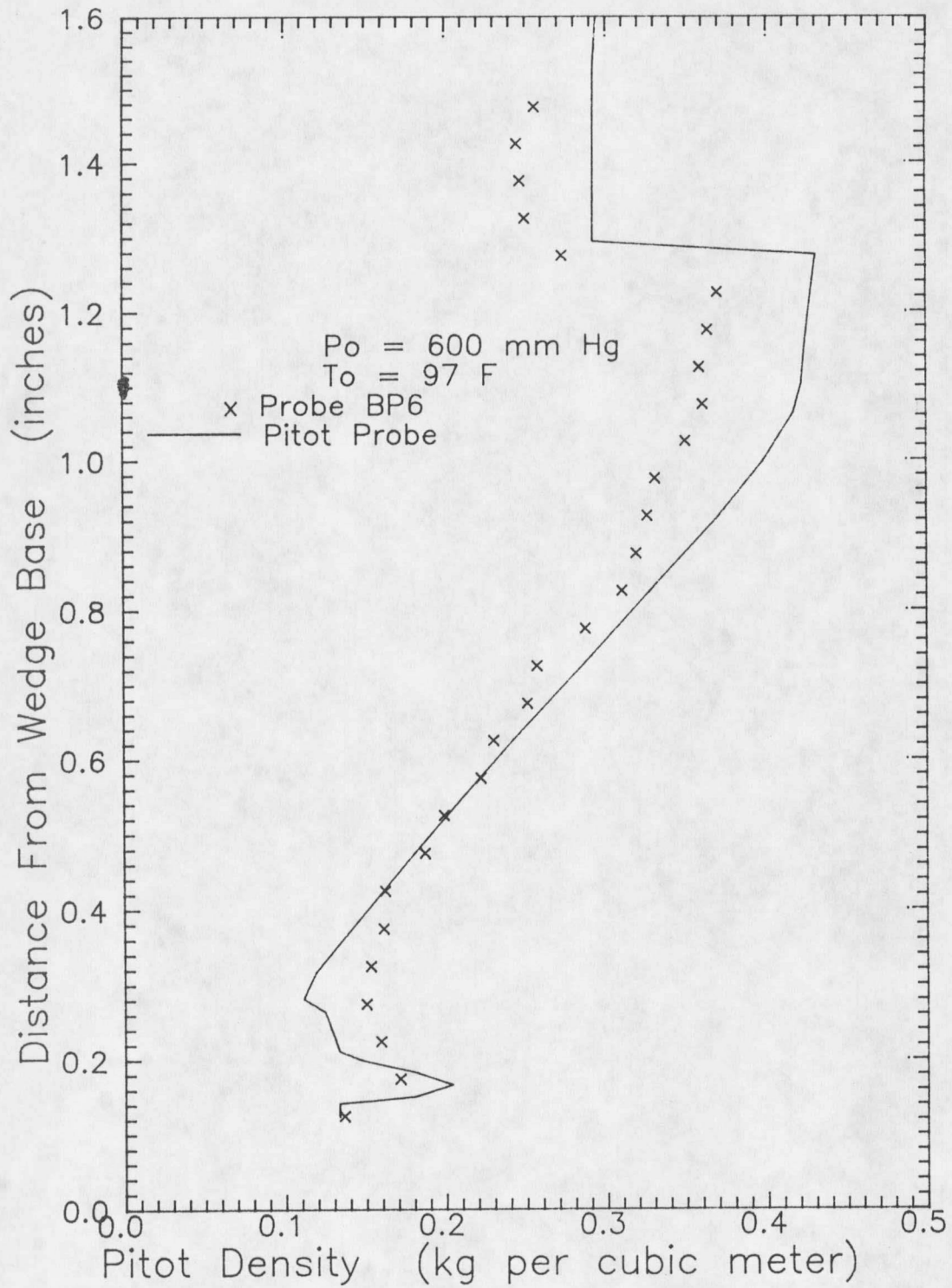
Pitot Tube. First, a pitot tube was used to take a pressure profile 1 inch behind the trailing edge of the wedge. The pitot tube is the top instrument in Figure 42. The wind tunnel was run at $P_o = 600$ mm Hg and $T_o = 97^\circ\text{F}$. The pressure profile was taken by traversing the flow with the pitot tube while the output of a pressure transducer was connected to an X-Y recorder to record the pressure profile. Since the total temperature T_o is constant throughout the flow the pitot density profile can be calculated from the pitot pressure profile and the total temperature using the ideal gas law.

Breakdown Probe. This same traverse was made with optical probe BP6 with the ASR system measuring the breakdown voltage. Probe BP6 is shown as the lower instrument in Figure 42. Three measurements of the breakdown voltage were taken at 50 mil increments in position along the traverse. The three voltage measurements were averaged and from the calibration curve fit (equation 40) the density at each position was calculated.

Results

The traverse with the pitot probe is shown as the solid line in Figure 44. Note that the ordinate scale (Distance From Wedge Base) is the vertical distance through the traverse that is zero at the plane extending back from the wedge tip and is positive downward. The pitot probe traverse shows the Prandtl-Meyer expansion as the near linear region between 0.4 and 1.0 inches on the ordinate. The shock wave can be seen at 1.28 inches.

The traverse with the breakdown probe is also plotted in Figure 44. Although the breakdown probe does not exactly follow the pitot tube profile the general shape of the profile is reproduced. The near linear expansion fan region can be seen. The shock wave was detected in the region close to where the pitot tube detected it. Differences in position could result from incorrectly starting each profile with the pitot tube and breakdown probe in slightly different positions.



CHAPTER 14

FLUCTUATING DENSITY MEASUREMENTS IN SWT

Introduction

For a turbulence measuring device, it is desired to use the breakdown probe to measure density fluctuations. The breakdown voltage must be measured at a high frequency to be able to measure the time varying component of the stream density. The computerized data acquisition system (CDAS, see Chapter 4 for a description) was used with radioactive probe BP7 behind the wedge in flow to test for density fluctuations.

Calibration of Probe BP7

Probe BP7 was calibrated with the CDAS voltage ramp in the vacuum chamber at room temperature. At each density in the calibration there were 50 total breakdowns at a rate of 10 breakdowns per second. The calibration is shown in Figure 45. During the static calibration the standard deviation for the 50 total breakdowns averaged around 50 volts. The standard deviation for a CDAS calibration can be compared to the scatter for the ASR system.

By curve fitting this data by the method of least squares, the second degree polynomial for the density as a function of breakdown voltage is:

$$\rho = 0.1386 + (-4.761\text{E} - 4)V_b + (5.893\text{E} - 7)V_b^2 \quad (41)$$

This equation is valid for the density range $0.1 < \rho < 0.8$ kg per cubic meter.

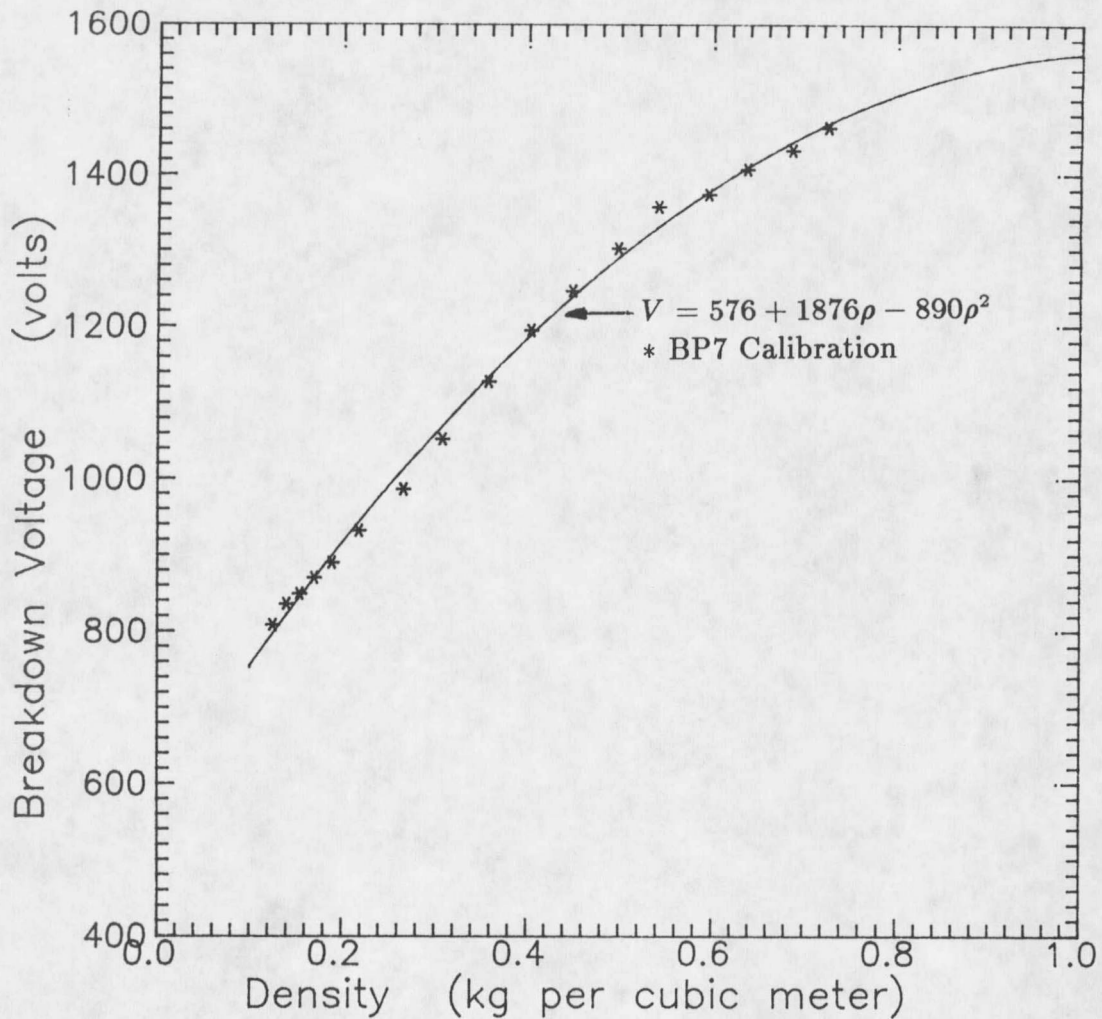


Figure 45. Calibration of Probe BP7 With CDAS Voltage System.

Density Measurement Behind Wedge

With the wedge in place in the SWT (see Figure 42), a pitot pressure profile was plotted 1/2 inch behind the trailing edge of the wedge. The wedge was in Mach 3 flow and the tunnel stagnation conditions were $P_o = 619$ mm Hg and $T_o = 102^\circ\text{F}$. This same traverse was repeated with Probe BP7 using the CDAS to measure the breakdown voltage. At each position a total of 30 breakdowns were

recorded with the rate being 10 breakdowns per second. The average breakdown voltage for each position along with the standard deviation of the breakdown voltage was recorded. Two traverses behind the wedge were taken consecutively to see if the probe response would change.

Results

Density Profile

From the pitot pressure profile and the fact that the total temperature remains constant throughout the flow, a pitot density profile was generated. The pitot density profile is displayed as the solid line in Figure 46. The two traverses made with probe BP7 are also shown in Figure 46. Both traverses follow the general shape of the pitot tube profile. The two traverses made with the breakdown probe also follow each other relatively well.

The standard deviation in the breakdown voltage for the two runs as a function of position is shown in Figure 47. The standard deviation up to 0.5 on the ordinate shows a considerable increase over the rest of the profile. At this position there is a shear layer coming off of the wedge. The increase in the standard deviation is due to density fluctuations in this shear layer.

The standard deviation throughout the rest of the profile is around 50 volts which is about the same as the static calibration. A standard deviation of 50 volts is relatively high.

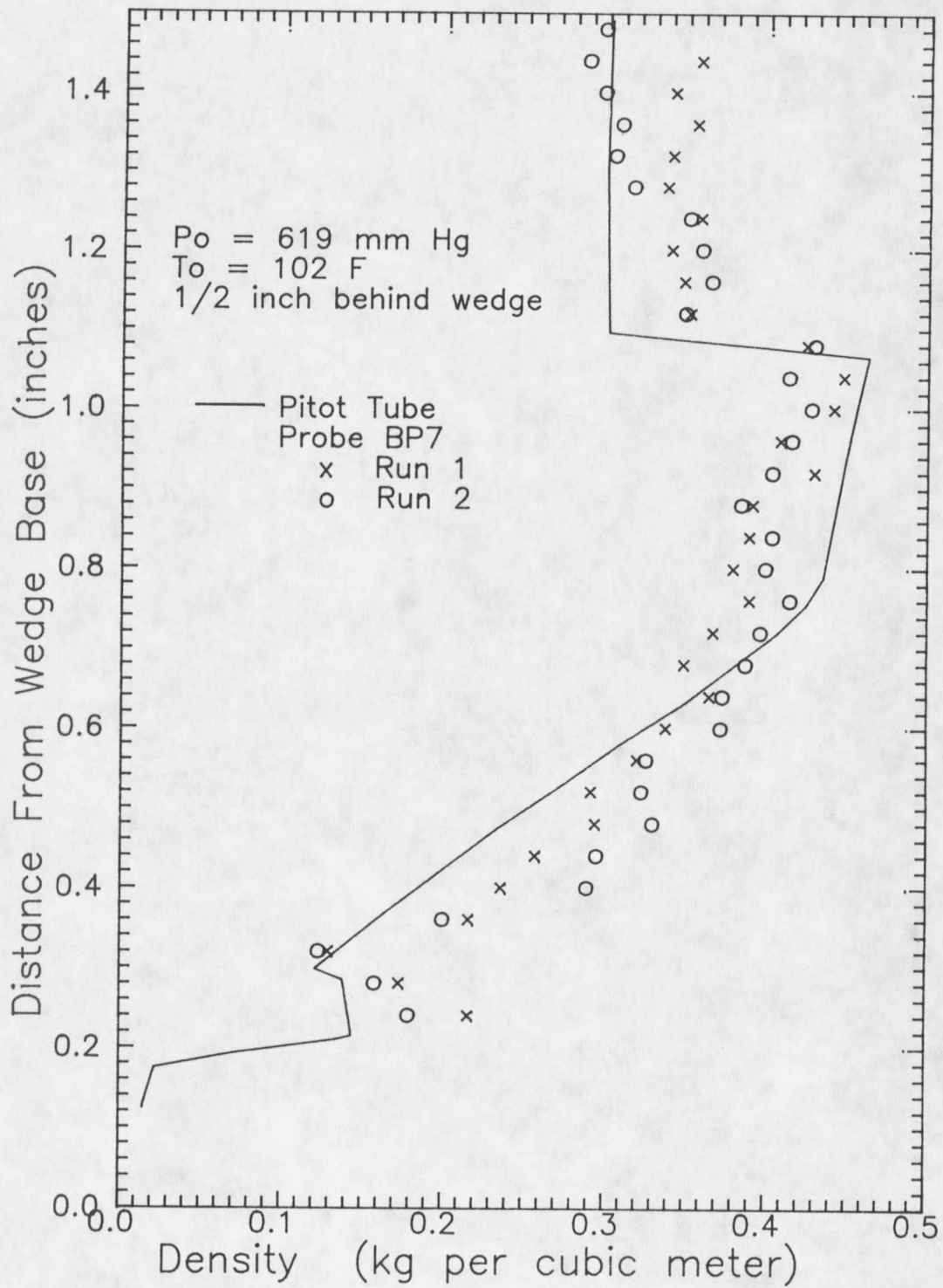


Figure 46. Pitot Density Profile Behind a Wedge in Mach 3 Flow.

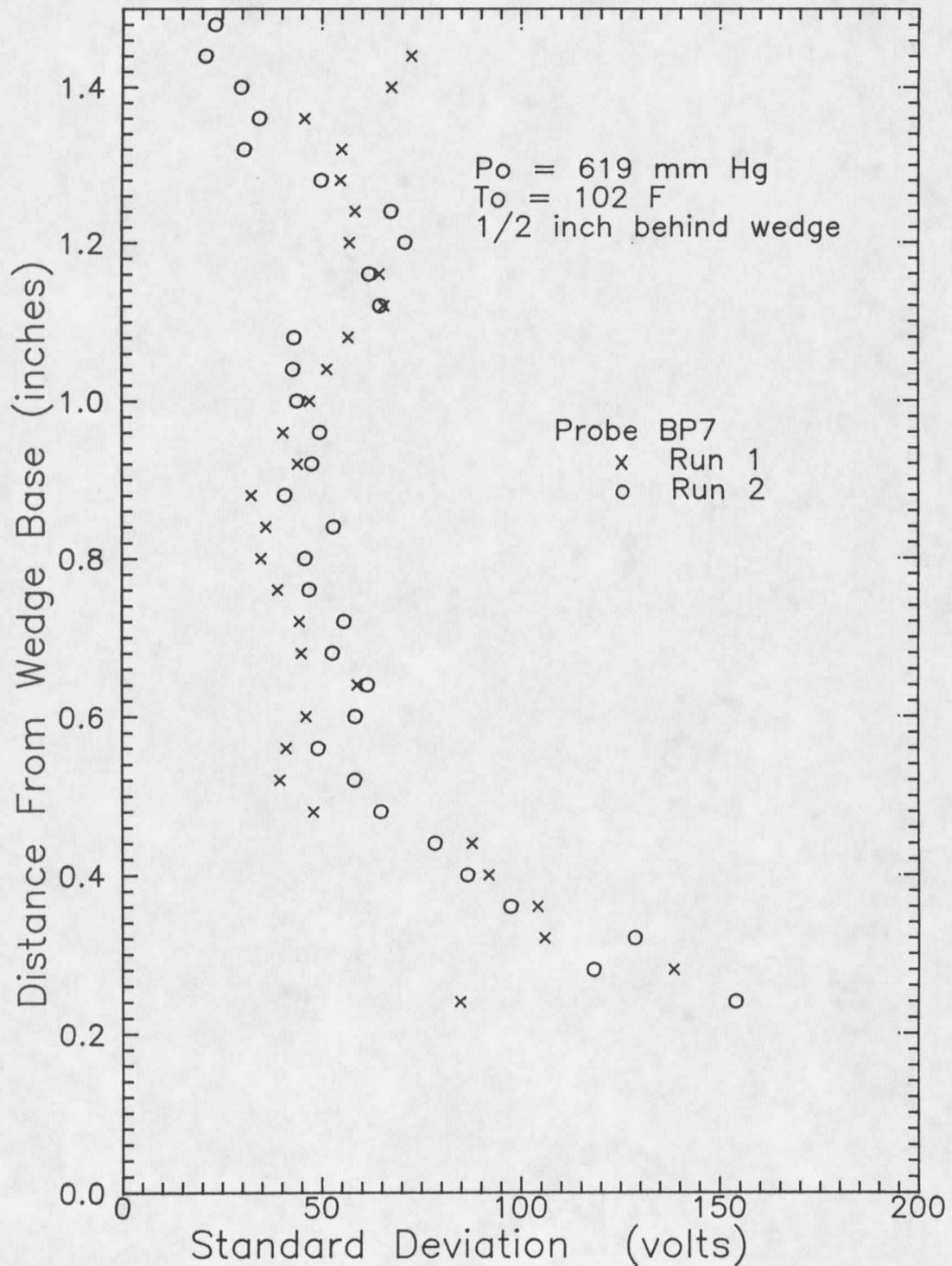


Figure 47. Standard Deviation of the Breakdown Voltage for the Profile in Figure 46.

Sensitivity Coefficient

To relate small r.m.s. fluctuations in the breakdown voltage to pitot density fluctuations, the sensitivity coefficient S will be determined as explained in Chapter 3. The pitot density fluctuations are related to the breakdown voltage fluctuations by equation (36). By curvefitting the calibration of probe BP7 (Figure 45) the second order polynomial of the breakdown voltage versus density curve is given by

$$V_b = 576 + 1876\rho - 890\rho^2 \quad (42)$$

which is valid in the density range $0.1 < \rho < 0.8$ kg per cubic meter. Substituting equation (42) and its derivative into (35) will give the sensitivity coefficient as a function of density. The sensitivity coefficient is plotted in Figure 48 as a function of density. The maximum sensitivity is around 0.4 at a density of 0.4 kg per cubic meter.

Calculation of Stream Density Fluctuation for the MSU/SWT

The objective of this calculation is to show (a) how the free stream density fluctuations can be calculated from r.m.s. voltage fluctuations and (b) that the standard deviation of 50 volts in the free stream at Mach 3 is too large to provide reasonable stream density fluctuation measurements.

In the free stream where $M = 3$ the pitot density can be found from equation (39). For the wedge test, $P_o = 619$ mm Hg and $T_o = 102^\circ$ F which gives $\rho_o = 0.921$ kg per cubic meter. From (39) the pitot density is $\rho_p = 0.303$. At this pitot density the sensitivity coefficient for Probe BP7 is $S = 0.395$ as shown in Figure 48.

The average breakdown voltage at this pitot density is $V_b = 1063$ volts (equation (42)). The r.m.s. fluctuation of the breakdown voltage in the free stream is around 50 volts from Figure 47.

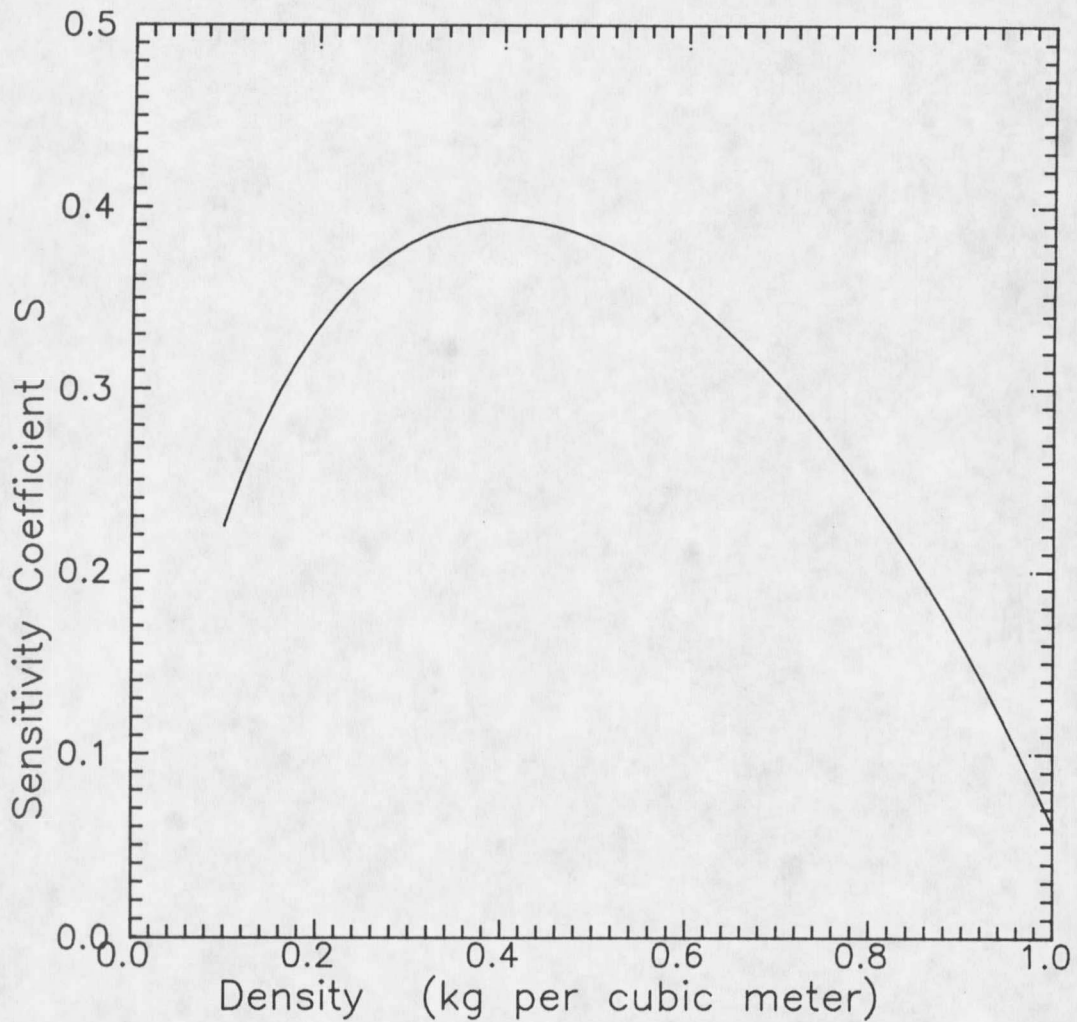


Figure 48. Sensitivity Coefficient for Probe BP7.

Substituting the above quantities into equation (36) gives the normalized pitot density fluctuation.

$$\frac{\rho'_p}{\rho_p} = \frac{1}{S} \frac{V'_b}{V_b} = \frac{1}{0.395} \frac{50}{1063} = 0.119 \quad (43)$$

From Figure 7 the relation between the stream fluctuation and the pitot density fluctuation is 1.5 at Mach 3 therefore the normalized stream density fluctuation

is:

$$\frac{\rho'_p}{\rho_p} = 1.5 \frac{\rho'}{\rho} \quad (44)$$

Substituting the results of (43) and rearranging,

$$\frac{\rho'}{\rho} = \frac{0.119}{1.5} = 0.079 \quad (45)$$

Thus from this calculation the r.m.s. stream density fluctuation is 0.079 in the free stream.

A value of 0.079 for the r.m.s. stream density fluctuation is of one order of magnitude greater than what would be expected in the free stream test section of the SWT. The SWT test section is considered to be a "quiet" tunnel with minimal fluctuations of the free stream flow properties.

This calculation points out that a standard deviation of 50 volts in the breakdown voltage is too large for useful measurements. The probe BP7 and the CDAS ramp system together are the cause of the large deviation which means they cannot be used to measure stream density fluctuations.

For a usable fluctuating density measurement system, the breakdown voltage standard deviation in a static calibration should be less than 5 volts r.m.s. This reduces the pitot density fluctuation by an order of magnitude as can be seen in equation (43).

CHAPTER 15

CONCLUSIONS

The results of the experiments performed during this research demonstrate that it is possible to use a breakdown probe to measure the density of air. Although none of the breakdown probes tested were extremely accurate the probes can be used to provide density measurements in a flow.

Some individual conclusions on specific topics are summarized as follows:

1. The Paschen similarity characteristic has been confirmed for probes that are suitable for wind tunnel use. The probes have small diameter tips (less than 15 mils) with closely spaced electrodes. The probe characteristic exhibits the decreasing breakdown voltage with increasing density in the low density region along with the increasing breakdown voltage with increasing density in the higher density region.
2. The use of ultraviolet light to illuminate the electrodes to ionize the breakdown gap is effective in reducing the scatter and increasing repeatability of the data. The intensity of the ultraviolet light is not a critical factor.
3. The tests of the radioactive Carbon 14 breakdown probe (BP7) to test the use of radioactivity as an ionization enhancing mechanism were inconclusive. The same results may have been obtained with the same probe even if it had not been exposed to the radioactivity. However, using a stronger radioactive source may be an effective ionizing agent.

4. The use of different electrode metals and the electrode configuration is not crucial to obtaining the similarity characteristic. Platinum was chosen as the electrode material because of its resistance to corrosion and oxidization.
5. The concept that the breakdown voltage for a given electrode configuration and given gas is a function of gas density only has been confirmed. The temperature and pressure acting alone do not control the breakdown voltage.
6. An optical probe can be used to measure mean density values in supersonic flow with reasonable accuracy. The probe does show a response to pitot density changes within supersonic flow. The optical probe will follow a density profile that was measured by a pitot tube, but the accuracy of this measurement needs improvement.
7. The use of the breakdown probe to measure turbulent density fluctuations in a flow has been investigated. The r.m.s. measurements taken by the breakdown probe show only rough trends in the stream density fluctuations. The problem of poor r.m.s. density measurements is in the probe and CDAS voltage ramp system.

REFERENCES CITED

REFERENCES CITED

1. Lindvall, F.C., "A Glow Discharge Anemometer", *Transactions of A.I.E.E.*, Vol. 53, pages 1068-1073, July 1934.
2. Werner, F.D., "An Investigation of the Possible Use of the Glow Discharge as a Means for Measuring Air Flow Characteristics", *The Review of Scientific Instruments*, Vol. 21, No. 1, pages 61-68, January 1950.
3. Cobine, J.D., *Gaseous Conductors*, McGraw Hill Book Company, 1941.
4. *Encyclopedia of Physics*, Volume XXII, "Gas Discharges II", Edited by S. Flugge, Springer-Verlag, 1956.
5. Brown, S.C., *Introduction to Electrical Discharges in Gases*, John Wiley & Sons, Inc., page 211, 1966.
6. Cobine, J.D., *Gaseous Conductors*, McGraw Hill Book Company, page 163, 1941.
7. Brown, S.C., *Introduction to Electrical Discharges in Gases*, John Wiley & Sons, Inc., page 189, 1966.
8. Liepmann, H.W., and Roshko, A., *Elements of Gasdynamics*, John Wiley & Sons, page 149, 1957.
9. Laderman, A.J., and Demetriades, A., "Turbulent Shear Stresses in Compressible Boundary Layers", *AIAA Journal*, Vol. 17, No. 7, pages 740-743, July 1979.
10. Kistler, A.L., "Fluctuation Measurements in a Supersonic Turbulent Boundary Layer", *The Physics of Fluids*, Vol. 2, No. 3, pages 294-295, May-June 1959.
11. Maxstadt, F.W., "Insulator Arcover in Air", *Electrical Engineering*, Vol. 53, page 1063, 1934.
12. Cobine, J.D., *Gaseous Conductors*, McGraw Hill Book Company, page 172, 1941.
13. Penning, F.M., *Electrical Discharges in Gases*, Macmillan Company, pages 7-11, 1957.
14. Cobine, J.D., *Gaseous Conductors*, McGraw Hill Book Company, page 187, 1941.

APPENDICES

Figure 1

APPENDIX A

UNSATISFACTORY PROBE DESIGNS

Unsatisfactory Probe Designs

Several different basic designs of probes were built and tested. The probes of better designs and response (see Chapter 4) were used for the main part of this research.

Three unsatisfactory probes of different design are shown in the next three figures. An explanation of why the probes were rejected is given below:

Probe A: Figure 49

This probe was constructed from a large 0.25 inch diameter plastic holder which was unsuitable for wind tunnel testing because of its large size. The electrodes were sharpened copper wires. The probe showed considerable scatter when tested in a constant density test.

Probe B: Figure 50

This probe is similar to the small wire probes (Chapter 4) except it is of more complex construction. The small wires coming out the back of the probe were subject to breakage. The probe also showed poor response to constant density tests because of the lack of ionization enhancement.

Probe C: Figure 51

This probe is the preliminary design for the optical probe. The construction is very complex compared to the optical probe described in Chapter 4. Construction of this probe was very time consuming. The electrical connections made with the silver conductive coating proved to be unreliable when the probe was used at elevated temperature.

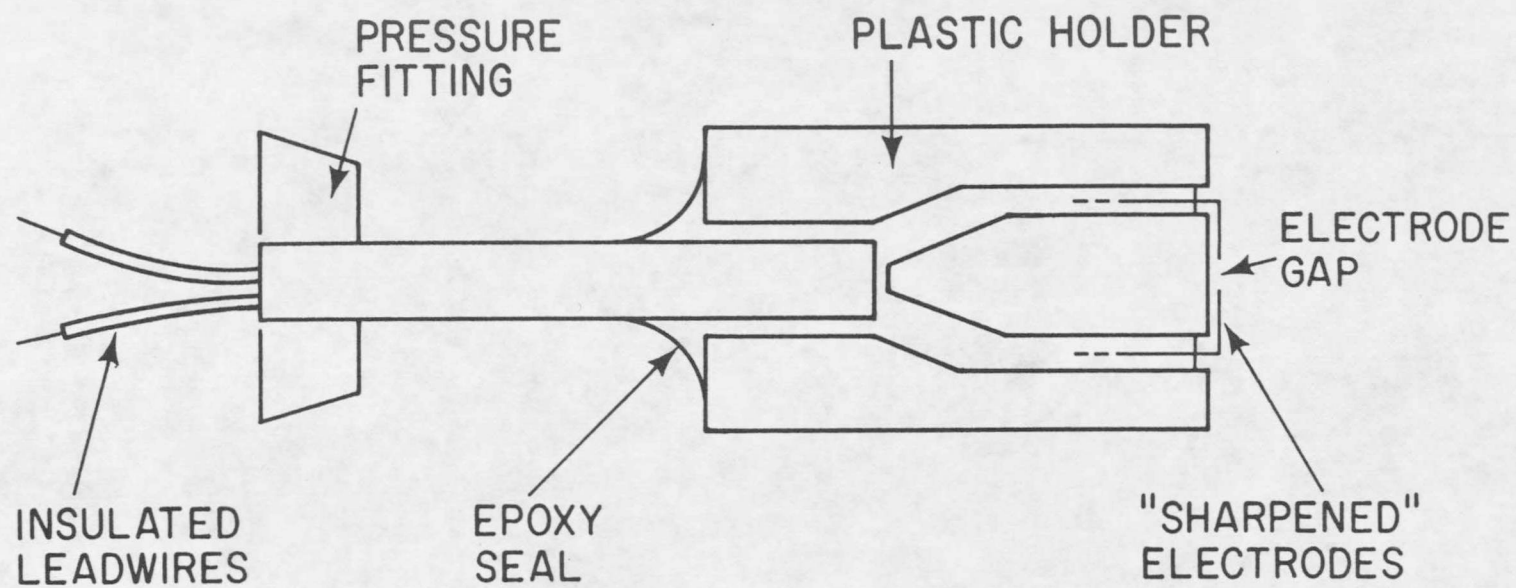


Figure 49. Sharpened Electrode Probe.

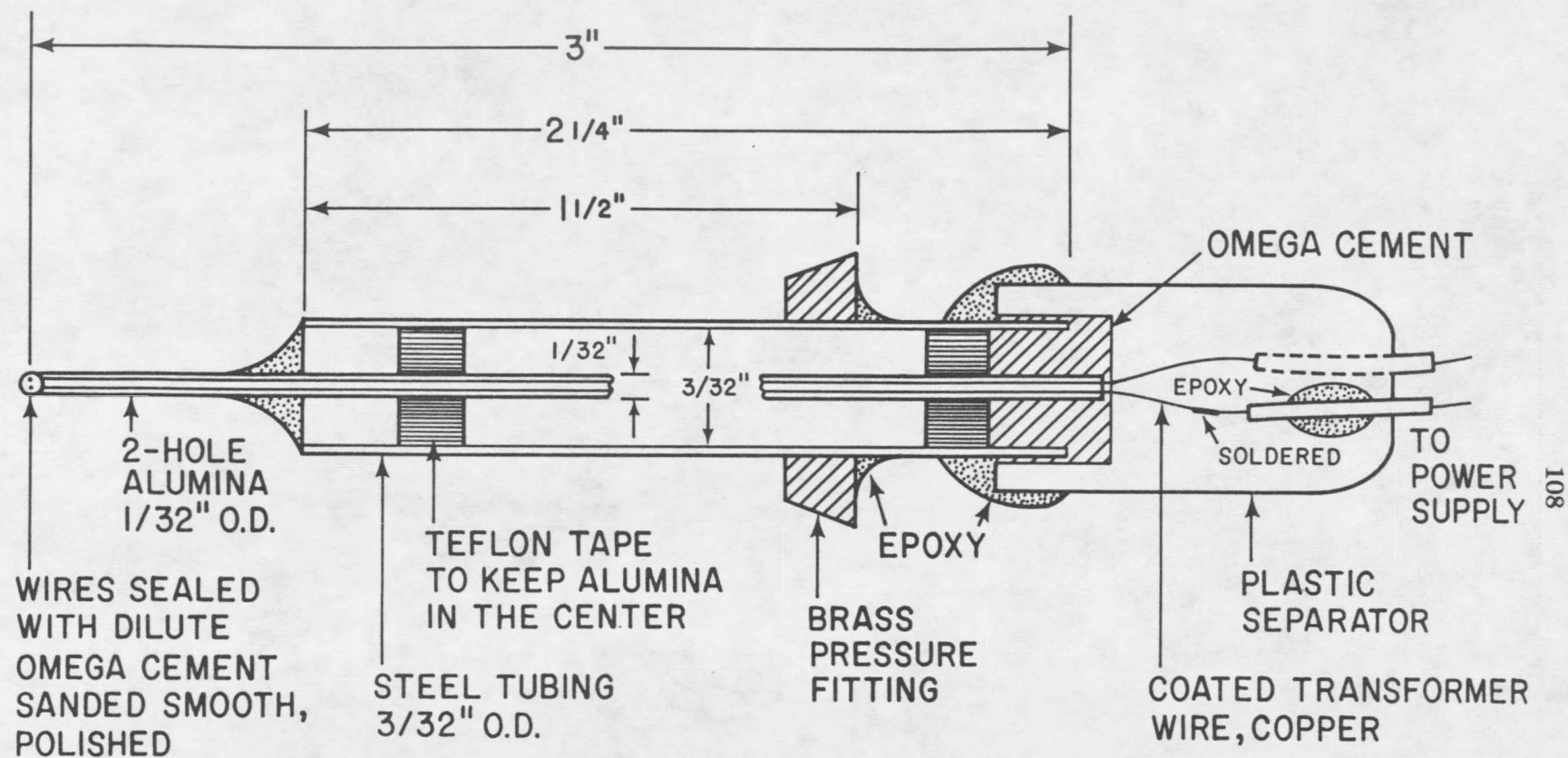


Figure 50. Copper Wire Breakdown Probe.

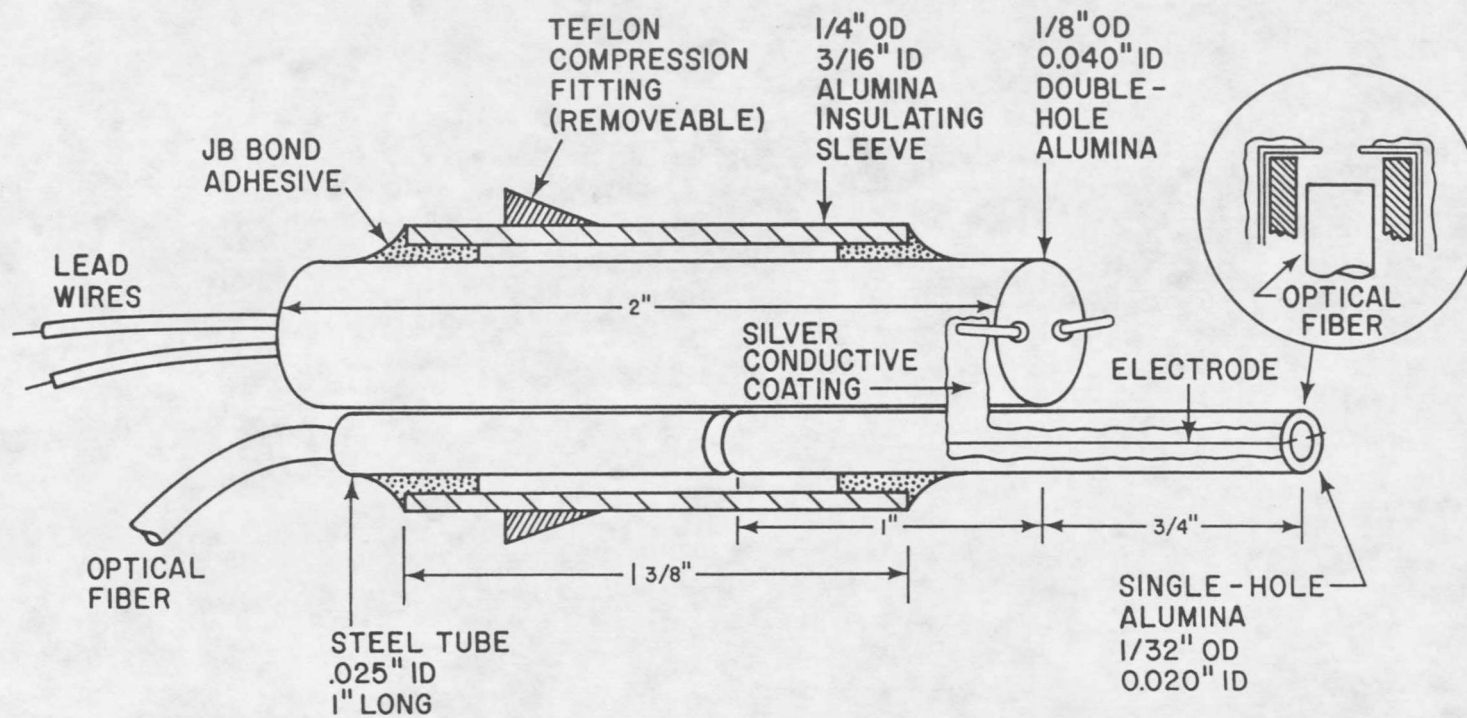


Figure 51. Preliminary Optical Probe Design.

APPENDIX B

ARC LAMP OPERATING INSTRUCTIONS

Operating Instructions of the Mercury Arc Lamp and Power Supply

NOTE: Read all instructions before installing and operating arc lamp.

Arc Lamp Installation

1. Make sure power supply switch is in the OFF position and that the power supply is unplugged.
2. Connect negative black tipped lead from the power supply to the upper (negative) terminal on the back side of lamp holder.
3. Connect positive yellow tipped lead from the power supply to the lower (positive) terminal on the back side of lamp holder.
4. Remove the mercury arc lamp from its protective shipping carton. Handle lamp by metal end caps only! Touching the quartz bulb will deposit salts on the quartz which will weaken it with use.
5. Install the mercury lamp in the rectangular brass holder with the positive end down. The positive end is the one with the writing on the end cap.
6. Tighten positive end screw securely. Arc lamp will be pulled down into the brass holder as the screw is tightened.
7. Connect white lead wire to negative terminal (upper) of lamp. Tighten holding screw being careful not to twist or bend the arc lamp or it may break.
8. Clean bulb with absorbent cotton soaked in an organic solvent such as ether, carbon tetrachloride, or absolute alcohol. Dry bulb with clean absorbent cotton. Do not touch bulb with fingers.

Arc Lamp Operation

1. Make sure the lamp is installed correctly and all connections are tight.
2. Place lamp house cover in its correct position on the lamp holder. The arc lamp is very intense when turned on.
3. Make sure the ventilation hose is connected to the lamp house cover. Turn on ventilation blower.
4. Plug in the power supply and turn the switch to the ON position.
5. Set the output potentiometer at mid-range (50%). It is the black knob in the center of the power supply panel.
6. Press the momentary switch 1/2 to 1 second to ignite the lamp. Do not hold down this switch or press it while lamp is operating. Doing so will result in severe damage to the power supply and arc lamp.
7. Monitor the arc lamp current on the current meter. Do not let current rise above 8 amps or the power supply fuse will blow. The current can be decreased on start up by manually reducing the potentiometer setting.
8. Adjust output current to 4.2 amps with the potentiometer. Current will stabilize in this range after 1 to 2 minutes on start up.
9. Never allow lamp to operate at currents greater than 4.2 amps or the arc lamp life will be greatly decreased.

Arc Lamp Shut Down

1. Turn potentiometer to zero. Arc lamp should extinguish itself.
2. Allow ventilation fan to run for 15 to 20 minutes to cool arc lamp and lamp housing.
3. Turn ventilation fan off.
4. Turn switch on power supply off.

APPENDIX C

CALIBRATION OF CDAS VOLTAGE MEASUREMENT SYSTEM

Calibration of CDAS Voltage Measurement System

STEP

1. Boot up the Zenith Z100 computer.
 1. Put DOS Master Disk in left drive (drive A).
 2. Turn computer on.
 3. Turn moniker on.
 4. Enter date and time if desired.
2. Load Spark program which is on the disk in drive B.
 1. Type B:SPARK <cr>
3. Disconnect the silver cable that connects the computer to the voltage ramp box. The connection is on the upper left side of the voltage ramp box. The connection is labeled: A-D-A.
4. The computer screen should now read:
 1. Ground pin 13 to 14.
 2. Hit RETURN after you have completed step 1.
5. To do this short the red and black connectors on small aluminum box in back of computer with a connecting wire.
6. Press RETURN while the red and black connectors are shorted.
7. The computer screen should show a value for the intercept:
$$\text{Intercept} = \text{XXX}$$
8. As a check, the Intercept value should be around 121.
9. The computer screen will now read:
 1. Connect an appropriate known voltage to pins 14(+) and 13(-).
Input voltage must be < 2.5 volts.
Input voltage must be > 1.0 volts.
 2. Input the voltage value here: _____ .
10. Remove the shorting wire from the red and black connectors.
11. Connect a voltage power supply and a voltage meter in parallel to red (+) and black (-) connectors. Make sure the polarity is correct. Figure 52 shows the proper connection.

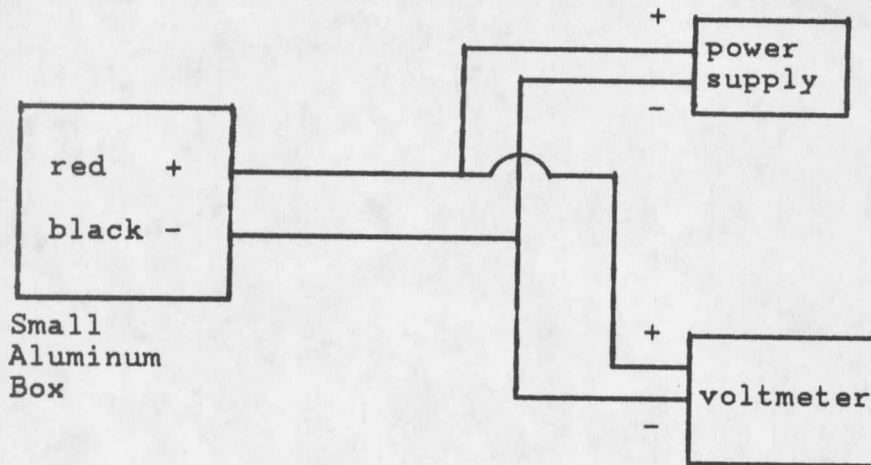


Figure 52. Correct Connections for Input Voltage and Measurement.

12. Set the voltage supply between 1.0 and 2.5 volts.
13. Input the voltage reading from the voltmeter into the computer with the keyboard. Press RETURN. The voltage should appear on the screen.
14. Disconnect power supply and the voltmeter from the small aluminum box. The red and black pins should have nothing connected to them.
15. Connect the silver cable to A-D-A connection.
16. Turn the power on to the voltage ramp box.
17. The CDAS ramp is now ready to be used.

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