

FINAL REPORT

ION BEAM DIAGNOSTICS AND NEUTRALIZATION

by

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1. INTRODUCTION

This document is the final technical report on Contract NAS3-7937, "Ion Beam Diagnostics and Neutralization," between NASA, Lewis Research Center, Cleveland, Ohio, and TRW Systems, Redondo Beach, California. Work under this contract has been performed by the Electric Propulsion Technology Department of the Propulsion Technology Laboratory, Power Systems Division. The period of performance of this contract extended from 14 February 1966 to 21 August 1967. A portion of the work under this contract was a continuation of work begun under a previous contract.*

The program of research and development under this contract has been divided among five tasks briefly identified as follows:

- Research and development, fabrication and delivery of mercury discharge neutralizers
- Research and development, fabrication and delivery of hot-wire Electric Field Strength Meters
- Studies of ion thrust beam neutralization and spacecraft diagnostic methods and instruments
- Investigation of a long-life (10,000 hr) thrust beam collector for ground testing of ion thrusters
- Product Assurance support of the development and fabrication of deliverable hardware

* Contract NAS3-6276, Final Report, NASA CR-54692, February 1966.

2. PROGRAM REVIEW

2.1 MERCURY DISCHARGE NEUTRALIZER

At the beginning of the present program, the mercury discharge neutralizer had been developed to the point where a hollow cathode, internally coated with a standard barium oxide mix, had been operated in a bell jar. This cathode was in the form of a cylinder, about 3/8 inch in outside diameter, and 1/2 inch long. Mercury vapor was introduced into one end of the cylinder; the other was closed off, except for a 0.005-inch-diameter hole through the end plate which was of equal thickness. When the cathode was heated to about 1000°C, supplied with mercury vapor at about 20 torr vapor pressure, and with an electron-collecting plate placed within a few millimeters of the small orifice, an arc could be established between the cathode and the plate. This arc was characterized by a bright luminosity at the hole, a conical region of lesser luminosity (sometimes not visible) extending away from the hole, and the ability to deliver more than an ampere of electron current to the plate at a voltage drop of 10 volts or higher, depending on the cathode to anode spacing.

Means for lowering the surface work function, such as coating the interior of the cathode with barium oxide, were found to enhance discharge formation. The most satisfactory technique investigated was fabrication of the cathode body from barium impregnated porous tungsten.

The objective of developing such a device was its potential use as a neutralizer for a mercury electron-bombardment thruster. A specific application would be on a thruster having a 250 mA mercury ion beam. At the start of the present program it remained to be shown to what degree this arc would operate satisfactorily with a thruster, and whether a dispenser type of cathode would satisfactorily avoid some of the difficulties which are encountered with oxide coatings outside of glass enclosed vacuum tubes. During the course of the program it was shown that the dispenser cathodes withstand repeated air exposures without damage. Even when accidentally exposed to air while hot, they exhibited a temporary period of degraded operation, followed by recovery of pre-exposure performance. These results both proved the desirability of a low work function cathode surface and demonstrated that rugged cathodes could be made.

2.1.1 Research Program

Section 3.1 describes the current work on the discharge neutralizer, the performance goals set for the device, developments which have helped to meet at least some of the goals, and the present understanding of the nature of the arc produced. The major effort in the development has concentrated on maximizing the efficiency with which the neutralizer uses the mercury vapor which flows through it. The design goal, in this respect, has been the delivery of 250 mA of electrons with a mercury efflux of 9 mA or less (equivalent Hg^+). Inasmuch as the total mercury efflux from the thruster is 300 mA equivalent, this represents an additional 3% propellant efflux with respect to the thruster system as a whole. The final design used in deliverable hardware has characteristically neutralized the 250 mA beam of a 15-cm electron-bombardment thruster at flow rates from ~ 9 to ~ 15 mA (equivalent Hg^+) (3 to 5% of 300 mA equivalent). The design feature which contributed most to its performance with respect to the mass utilization goal was the incorporation of an enclosed keeper. This feature helps to collimate the mercury atomic beam which emerges from the cathode orifice so as to maximize the probability of ionization in the space between the cathode and the beam. This aspect is described in Section 3.1.4.

2.1.2 Neutralizer Hardware

Cathodes of two sizes were operated as neutralizers during the research phase of the program. No essential difference in arc formation was seen between the two. It is possible that use of the smaller cathode might lead to a design having a lower power requirement. However, at the time a design freeze was placed upon the deliverable assembly, a complete design for only the larger unit was on hand.

Several cathode assemblies were built to the "design freeze" configuration, and tested with a 15-cm electron bombardment thruster supplied by NASA, Lewis Research Center. The following summary of operating characteristics and performance levels shows typical values for mercury efflux and neutralization parameters obtained with the cathode at operating temperature, neutralizing current of 250 mA, keeper current of 70 mA, with the neutralizer mounted in a plane 1.1 inches from the thruster accel grid and 4.1 inches from the beam axis.

This value of radial position was attainable with the accel shield at ground potential; with the shield at accel potential (-2000 V) the radial position was 3.3 inches.

1. Cathode heater

Operating level	4.2 V, 6.2 A ac
Typical pre-heating current	7 A
Maximum current	8 A

2. Keeper

Typical zero-current voltage	300 V dc
Operating range: voltage	5 to 15 V dc
current	15 to 75 mA dc
Series current limiting resistance	1 K ohms (min.)

3. Mercury efflux

<u>Min.</u>	<u>Typ.</u>	<u>Max.</u>
0.6	1.0	1.5 mA/torr

4. Ion beam neutralization

	<u>Min.</u>	<u>Typ.</u>	<u>Max.</u>
Floating collector	9.0	10.0	30 V dc
Hg efflux (Hg ⁺ equiv.)	8.0	10.0	13 mA
Hg vapor pressure	6	9	14 torr

Data on environmental testing and extensive ion beam tests, including a 500-hour endurance test, are presented in Section 3.1.5.

2.2 ELECTRIC FIELD STRENGTH METERS

The concept of an electron device capable of measuring the electric field strength on the surface of a spacecraft, but at the same time relatively insensitive to currents of charged particles from the ambient plasma, was originally reduced to practice at TRW under NASA Contract NAS8-1560.¹ The device was then later developed as a flight instrument under a contract with

the United States Air Force. Although essentially successful, that flight instrument possessed certain difficulties with respect to cathode emission stability and methods of data reduction which the instrument to be developed under the present contract was designed to circumvent. Four months after start of work the E-meter task was terminated at the convenience of the Government. Section 3.2 describes the instrument which was being developed, and the work done up to the date of the stop-work order. Further description of the instrument is given in a reprint from The Review of Scientific Instruments included as Appendix A.

Section 3.2 also includes a brief review of more recent work on another program which is relevant to this topic.

2.3 NEUTRALIZATION DIAGNOSTIC TESTS

Section 3.3 of this report discusses the general problem of ground testing an electric thruster so as to be sure that the performance of its beam neutralization system in space can be accurately predicted. The thesis of Section 3.3 is that the neutralizer interaction with the thrust beam, in the ground test, must be the sole regulator of the neutralizer electron current in order to simulate operation in an environment of infinite geometrical extent. This occurs when operating the thruster and neutralizer systems in a vacuum enclosure in which the beam discharges into a cavity whose boundary surface is electrically isolated from the thruster system. An acceptable, but sometimes more difficult, alternative is to electrically isolate the thruster and neutralizer systems and power supplies from the (grounded) vacuum enclosure.

The section also reviews the present state of spacecraft diagnostic instrumentation which may be used to measure and report on neutralizer effectiveness and on the compatibility of electric propulsion systems with scientific payloads. The need for a fully instrumented flight test is reiterated.

2.4 LONG-LIFE THRUST BEAM COLLECTOR

During a long-duration ground test of an electric thruster, the testing facility must adequately cope with the mass of propellant material discharged from the thruster, the momentum this mass carries with it, and the power level involved. Section 3.4 is devoted to a discussion of design considerations for the thrust beam collector for ion engines in the medium power range ($\sim 10,000$ ampere hours integrated beam). Attention is given to collector durability, compatibility of eroded collector material with the thruster, and cooling techniques, as well as fabrication and operating costs. The design and operation of a frozen mercury collector for thruster life testing is reviewed.

2.5 PRODUCT ASSURANCE

The task of the product assurance support to the hardware phases of this program was to verify that adequate and accurate documentation was made of materials and processes. The objectives of this task were to enable one to relate materials and processes to the ability of the finished unit --

- to perform its intended function,
- to meet its design goals,
- to be capable of further development based on adequate definition of the present configuration.

The scope of this task was significantly reduced by the termination of work on the E-meter. Procedures used in support of the neutralizer task are detailed in Section 3.1.5.4.

3. TECHNICAL REPORTS

3.1 INVESTIGATION, DEVELOPMENT, AND FABRICATION OF MERCURY DISCHARGE NEUTRALIZER

3.1.1 Introduction

Any electrostatic thruster operating in space requires a source of electron current equal in magnitude to the ion current expelled by the thruster. These space-charge neutralizing electrons must be mixed into the ion beam after the ions receive electrostatic acceleration. If the electron source is placed within the ion beam, it is subjected to heavy erosion by ion sputtering. Shielding such "immersed neutralizers" from ion sputtering increases the injection potential² (the potential between the thrust plasma and the neutralizer), with an attendant increase in electrical power expended. Furthermore, the products sputtered from the neutralizer or its shield and returning to the thruster may well be unacceptable.

When a simple thermionic emitter is placed outside the ion beam, high "injection" potentials also result. As in the case of the shielded immersed neutralizer, the space charge of the electrons flowing from the "withdrawn neutralizers" to the thrust beam is not neutralized by ions.

The "discharge neutralizer" largely overcomes the space charge disadvantage of a withdrawn neutralizer by connecting the electron source and the thrust beam with a low energy plasma. It is a gaseous discharge positioned 1/4 inch to 1 inch from the "boundary" of the primary ion beam and produces both the neutralizing electrons and the low energy ions necessary to form a "plasma bridge" to the thrust beam. A typical embodiment of the device is shown in Figure 3.1-1. As indicated in the sketch, mercury vapor is fed to the hollow cathode from a boiler or vaporizer at a pressure P_{Hg} which is taken as the vapor pressure corresponding to indicated vaporizer temperature. The vapor escapes through the orifice (usually about 0.005 inch dia.) into the vacuum chamber. An electron current is drawn to the keeper electrode to initiate and sustain the discharge. The working current is drawn through the aperture in the keeper to a plate (usually molybdenum) if the experiment is done in a bell jar, or to the thrust beam

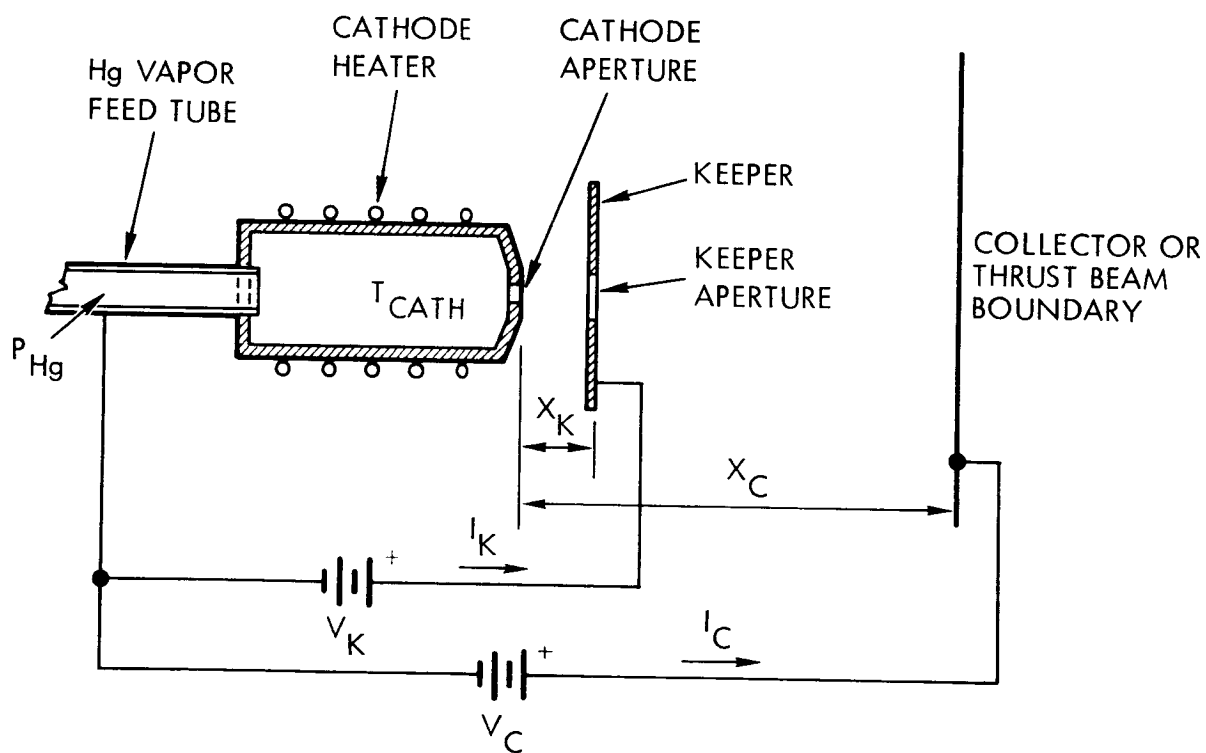


Figure 3.1-1. Hollow Cathode Experimental Configuration with Identification of Some of the Measureable Variables

of an ion engine. Measurable distances, voltages, and currents are indicated in the figure.

Task I of this contract included the investigation, fabrication, and test of mercury discharge neutralizers with the following design goals:

- 1) An electron emission of 250 mA
- 2) An electrical efficiency, η_E , of 15 mA/watt (67 eV/el)
- 3) A mercury flow of 9 mA equivalent (mass utilization, η_m , of 28 el/Atom)
- 4) A potential life of 10,000 hours
- 5) Little degradation upon repeated exposure to atmosphere
- 6) Capability of being further developed into space flight hardware with no major conceptual changes.

3.1.2 Early Experiments With Hollow Cathode Discharges

The first experiments with small-orifice hollow cathodes at TRW were undertaken to duplicate the results of Ernstene, et.al.³ with the cesium plasma bridge neutralizer as described in July 1965. The effort then turned to the attempt to achieve corresponding results with mercury. Several exploratory experiments were performed which indicated that "cold-cathode" arcs of high current density could be readily produced at a small orifice with mercury vapor pressures of about 1/3 atmosphere. Another early result was that a low work function coating on the inside of the cathode was effective in initiating a discharge if the coating extended up to the edge of the hole. Encouraging results were then obtained from a neutralizer cathode made of solid nickel having a 5-mil orifice and coated on the inside with a standard barium carbonate mix (which was later activated in vacuum); the propellant expended by the early devices, however, approached 30 percent of that used by the thruster.

One special version of the internally-coated neutralizer cathode contained an electron-emissive probe.⁴ This cathode was mounted in a bell jar so that a discharge current could be drawn to a movable molybdenum anode. Voltage was applied to the anode through a current-limiting

resistance. With the emissive probe operating in a floating mode, the data plotted in Figure 3.1-2 were obtained for a cathode to anode spacing of about 1 millimeter. Later, the collector was moved to a distance of about 1 centimeter and the internal potential as a function of anode current remained unchanged although much higher anode potentials were required for the same current values. This experiment indicated that the internal low-work-function surface was not likely to be subjected to ion sputtering erosion.

The low internal potentials of the hollow cathode gave hope that a dispenser type of cathode could be used to avoid the problems of either activating a neutralizer cathode in space after launch or of exposing an activated oxide cathode to air before launch (either of which might prove disastrous). Accordingly, since January 1966 our work has been concentrated on barium impregnated porous tungsten cathodes type 41180.* With one of these cathodes in a bell jar test, the potential of the bridging plasma between the cathode and a molybdenum anode at a spacing of 1 inch and 30V potential was mapped with a floating emissive probe. These results are shown in Figure 3.1-3. During this experiment the anode current was 130 milliamperes. Later the current was increased with the probe near the orifice, with the result that the probe filament melted.

The gaseous discharge at the cathode aperture can be maintained at boiler pressures above approximately 5 torr. It is sometimes necessary to raise boiler pressure to about 10 torr in order to initiate the discharge, whereupon it will persist as the pressure is again lowered. Similarly, after exposure to air the cathode temperature is usually raised to $\sim 1000^{\circ}\text{C}$ to facilitate starting the discharge but a discharge has been observed to persist at cathode temperatures as low as 500°C .

Two basic discharge modes have been observed, as well as several subtle variations. In the "spot" mode the luminous volume is quite small

* Spectra-Mat, Inc. Catalog #B740. The first 3 digits of the type number are molecular ratio of BaO, CaO, and Al_2O_3 ; the last two are W density in percent.

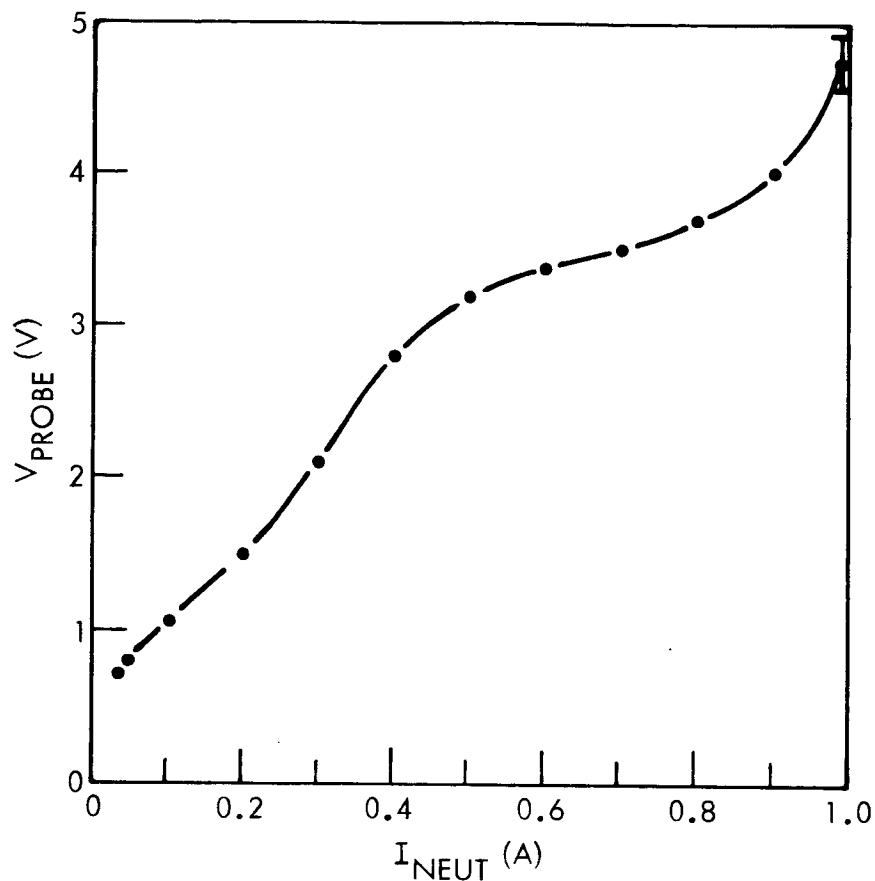


Figure 3.1-2. Floating Potential of Electron Emissive Probe in the Interior of a Hollow Cathode as a Function of Electron Emission Current. The Function Repeats for Different Anode Spacings.

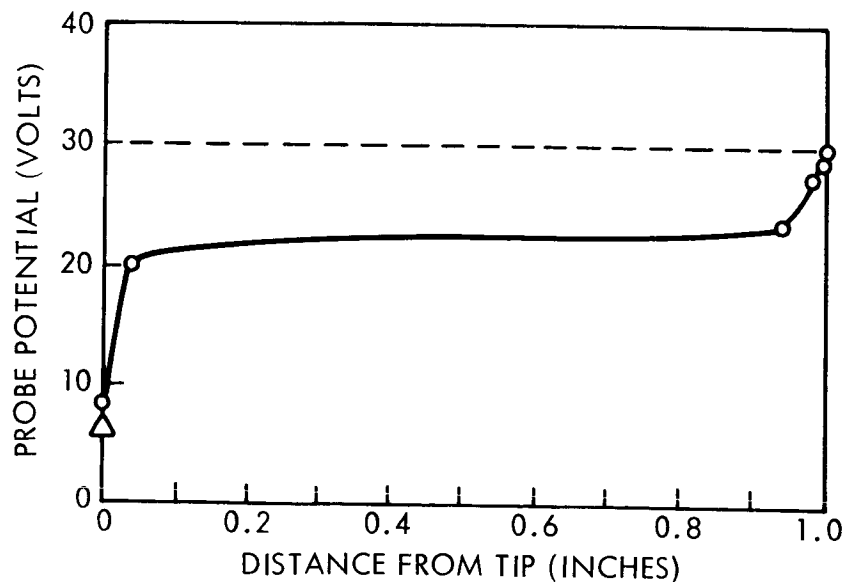


Figure 3.1-3. Floating Emissive Probe Potential Measurements Between a Hollow Cathode and an Anode at One-Inch Spacing and 30 Volt Potential. Cathode Emission Current = 130 Milliamperes.

and restricted to the immediate vicinity of the cathode aperture. It produces less electromagnetic radiation than the other mode and has therefore also been referred to as the "quiet" mode. In the "plume" mode the luminous volume is much larger and much less intense than in the spot mode. The name derives from the feather-like shape of its axial cross section. Because it produces noticeably more electromagnetic radiation than the quiet mode, it is also referred to as the "noisy" mode. The rf produced by this mode may require the experimenter to employ rf by-pass circuits and rf shielding to keep electronic instrumentation functioning properly. The effect of this radiation on spacecraft electronics and telemetry should be investigated. The spot mode is associated with boiler pressures in excess of 10 torr and high discharge currents. Often in bell jar tests it is possible to switch modes of operation by simply varying the discharge current. Some hysteresis is usually observed in mode switching and the amount of current needed to effect a mode change has been observed to depend on the boiler pressure and the L/D ratio of the aperture. The spot mode has not been observed to persist below discharge currents of 200 milliamperes. The light from the discharge is blue to the eye and contains ultra-violet radiation. It should not be viewed with the naked eye through quartz windows. The discharge is a very copious source of electrons, and in the absence of space charge limitations, is capable of delivering many amperes of current. In all configurations investigated to date the mass utilization η_m increases with discharge current to such an extent that one may expect to obtain 100 electrons per mercury atom at electron currents of 2 amperes and probably less. On the other hand, obtaining efficient performance at 250 milliamperes has proved difficult. A reduction in orifice size from 5 mils to 2 mils resulted in increased boiler pressure more than increased η_m . The power required to operate the neutralizer is virtually independent of I_c ; it consists of ~ 20 watts to heat the cathode. Currents in excess of 5 amperes are easily drawn into a contiguous plasma with $V_p \approx 10$ volts by increasing the rate of mercury flow.

3.1.3 Laboratory Techniques

Experimental research and development on the mercury discharge neutralizers was conducted both in bell jar experiments with metallic collectors and in a 4 by 8 foot vacuum chamber with the exhaust beam of an electromagnetic version of the 15-cm Lewis mercury bombardment thruster. The bell jar experimental techniques are first described.

Most of the bell jar experiments were conducted in the 6 inch oil diffusion pump system shown in Figure 3.1-4. During experiments the diffusion pump trap was always LN_2 cooled and provisions were available to separately cool the tank liners indicated in the figure. The cathode to collector spacing and the cathode to keeper spacing could be independently controlled by the coaxial motion feed-through mounting. Mercury vapor was supplied to the cathode by an electrically heated boiler whose temperature was accurately measured and controlled with one or more iron-constantan thermocouples spot welded to the boiler body below the mercury level. The reference junction temperature near room temperature was measured with a glass thermometer. Often the tip temperature was also monitored with a chromel-alumel thermocouple spot welded to the outside of the cathode near its aperture. Again, reference junction temperatures were monitored.

As indicated in Figure 3.1-4, several other rotary motion feed-throughs were available for various plasma diagnostic devices, principally an emissive probe and a Langmuir probe.

The collector configuration, the cold liners behind it, and the location of the ion gauge all form a mercury efflux detector system. Because of its utility in the development of mercury devices such as the discharge discharge neutralizer, and because much of the data to be reported was obtained by this technique, it is described here. As will be shown in Section 3.1.4, reservoir pressure is not an adequate indicator of efflux rate.

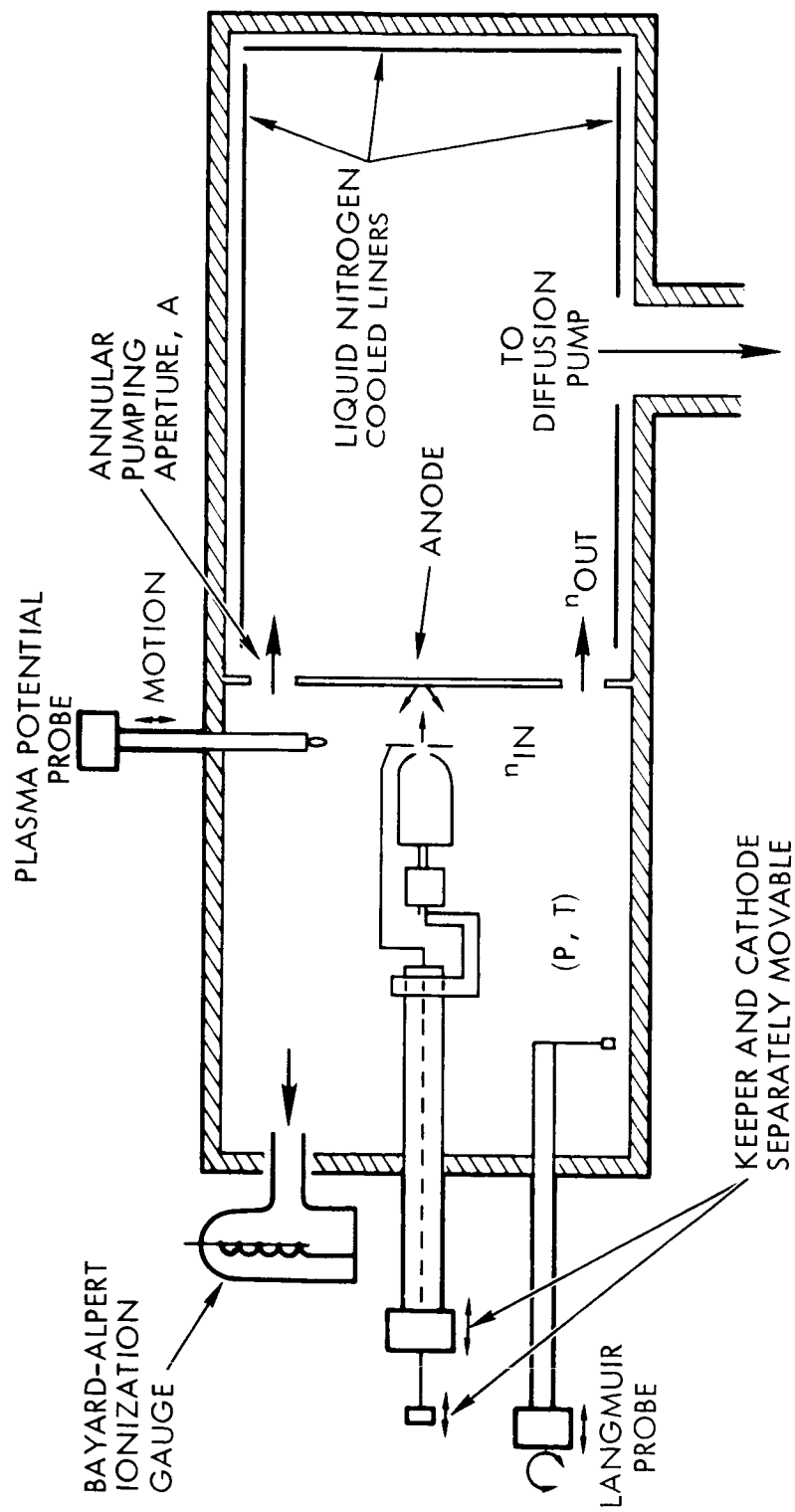


Figure 3.1-4. The 18 by 50-Inch Vacuum Facility for "Bell Jar" Studies of Mercury Hollow Cathode Discharges.

The technique is a novel application of well known physical principles. It is based on the expression for the arrival rate of random Maxwellian particles at a planar surface:

$$\Gamma = P [2\pi mkT]^{-1/2} \frac{\text{atoms}}{\text{sec} \cdot \text{m}^2} \quad (1)$$

where P is the partial pressure of the particles in N/m^2 , m is the particle mass in kg, k is Boltzmann's constant, and T is the temperature of the gas in °K. It follows that mercury atoms will leave an enclosed volume through a "perfect" pumping aperture of area A at a rate

$$n_{\text{out}} = PA [2\pi mkT]^{-1/2} \frac{\text{atoms}}{\text{sec}} \quad (2)$$

so long as A is not large enough to destroy the Maxwellian distribution of velocities.

Assume now that this chamber contains a source of mercury vapor. In equilibrium, its efflux rate, n_{in} , is equal to the rate leaving the chamber,

$$n_{\text{in}} = n_{\text{out}} \quad (3)$$

so that if the source is situated such that a Maxwellian distribution of velocities obtains in the bulk chamber volume, then equation 3 becomes

$$n_{\text{in}} = PA [2\pi mkT]^{-1/2} \quad (4)$$

Therefore, from a knowledge of the pressure and temperature of mercury vapor within the chamber, and the pumping area from the chamber, the rate of mercury efflux from the source is determined.

The temperature of the mercury vapor in a properly designed experiment will be near that of the chamber walls; it is not important to know its value

precisely since it enters equation (4) as the square root. In the absence of amalgamation, condensation, or chemical processes with or on the walls of the test chamber, the effective pumping area from the chamber may be made equal to the physical area of one or more pumping apertures by placing liquid nitrogen cooled liners behind such apertures. By choosing the area of these apertures, the pumping speed is adjusted so that for mercury source efflux rates of interest the partial pressure of mercury far exceeds that of other gases present yet does not exceed the pressure gauge capability or produce condensation. A common Bayard-Alpert type ionization gauge is a convenient device for indicating chamber pressure. However its sensitivity to mercury is significantly different from its sensitivity to air, and some means of determining its mercury sensitivity must be employed.

Rather than independently determining the gauge sensitivity to mercury, the effective pumping area, and the temperature of the mercury vapor, it is usually more convenient to experimentally determine a single calibration constant for the efflux measuring system. Equation (4) may be rewritten

$$n_{in} = CP_{meas} \quad (5)$$

where k is the system constant, and P_{meas} is the gauge reading in torr uncorrected for its mercury sensitivity. Then C is determined by one or more gravimetric runs:

$$C = \frac{W_L}{\left[\sum_{\ell} P_{meas, \ell} \Delta t_{\ell} \right]} \frac{1}{3.34 \times 10^{-25} \text{ kg/atom}} \frac{\text{atoms}}{\text{torr} \cdot \text{sec}} \quad (6)$$

where Δt is an increment of running time in seconds, and W_L is the total mercury lost from the source in kg.

Having determined the constant C , the experimenter may then directly relate the instantaneous ionization gauge readings to the instantaneous rate of mercury efflux from the source and study the response of this dependent

variable to changes in source variables. In particular the mass utilization, η_m , is

$$\eta_m = \frac{I}{I_{\text{Equiv.}}} = \frac{I}{q C P_{\text{meas}}} \quad \frac{\text{electrons}}{\text{atoms}} \quad (7)$$

I is electron current, $I_{\text{Equiv.}}$ is the Hg^+ current equivalent of the total mercury flow, and q is the electronic charge. (Note that $C P_{\text{meas}}$ includes mercury ions produced and collected on chamber or external neutralizer surfaces, since, like neutrals, they will reevaporate and contribute to the mercury gas pressure being monitored.)

In the experimental configuration illustrated in Figure 3.1-4, the following parameters and components were used:

$$T \simeq 300^\circ\text{K}$$

$$A \simeq 4.7 \times 10^{-2} \text{ m}^2$$

Gauge (Veeco RG 75K) Operating Point:

$$V_{\text{grid}} = +175 \text{ V}$$

$$V_{\text{fil}} = +25 \text{ V}$$

$$V_{\text{collector}} = 0 \text{ V}$$

$$\text{Gauge Const} = 10/\text{torr (Nitrogen, nominal)}$$

$$i_- = 0.05 \text{ mA (typically)}$$

A Granville-Phillips Series 236 Model 02/006 was employed as the ionization gauge controller. It provides considerable flexibility in changing emission current I_- in that the user may vary both the basic electrometer gain and the emission current over a factor of 1000. Observation of the indicated pressure at 0.05, 0.5, and 5 mA was one of several procedural checks employed to verify the proper functioning of the ion gauge.

Ideally, indicated pressure will scale exactly on emission current according to the relation

$$i_t = K p i_- \quad (8)$$

and if it fails to do so by more than a few percent below 1×10^{-4} torr, trouble is indicated.

Prior to each experimental run, the gauge grid and collector wire were outgassed by electron bombardment at powers up to 100 watts for periods of the order of 1/2 hour. Outgassing progress was monitored on another gauge. Occasionally even higher power was used to outgas support leads. The glass envelope was often heated with a heat gun.

Additionally, before each run, and before the mercury boiler was heated, the LN_2 liners behind the collector were fully cooled. The resulting pressure was always between 4 and 7×10^{-7} torr, and the particular pressure obtained was subtracted from subsequent readings as background. Occasionally after an experiment was completed the liners were maintained cold until the boiler temperature was at or near room temperature. The end-of-run background pressure was then compared to that obtained prior to the run.

Another check on the credibility of the mercury efflux detector performance was to maintain a constant mercury efflux from the neutralizer and vary the cathode to collector distance, x_c between 1/16 and 5 inches. Detector readings were virtually independent of x_c as they should be.

Finally, during experiments the reproducibility of points was frequently checked.

The neutral detector calibration constant C (Equation 6) was determined with three gravimetric runs at 4.3, 210, and 250 torr, which yielded 1.55×10^{22} , 1.46×10^{22} , and $1.62 \times 10^{22} \frac{\text{atoms}}{\text{torr} \cdot \text{sec}}$, respectively. Comparisons of P_{Hg} and P_{meas} were also made both with and without a discharge and an approximately linear dependence was noted. Unlike gravimetric data, these comparisons are sensitive to variations in A , T , (Equation 4)

and discharge conditions. All the η_m data presented in this report is based on $C = 1.62 \times 10^{22}$. This value, along with that quoted for A and T, implies that this ionization gauge is 4.1 times more sensitive to mercury than its nominal sensitivity to nitrogen. Dushman⁵ has reported on enhanced sensitivity of the VG-1 (internal filament) tube to mercury as 3.2 with $i_- = 1.0$ milliamperes.

Early in the program we discovered that mercury discharge neutralizers are extremely complicated in their operation with strong functional relationships between several of many system variables. The contract goals and resources seemed to preclude both a fundamental research program into the plasma physics of the device and an elaborate engineering-type parametric study. Consequently the attack chosen was "enlightened trial and error" where crude models of the device operation were advanced and the device modifications they suggested were tried.

The results of this approach were identification of the important device variables, a qualitative understanding of their interdependences, and hardware whose tested performance either met or approached each of the design goals insofar as it was tested.

3.1.4 Experimental Results

One of the first important discoveries made after the location of the ionization gauge in a position such that it measured total mercury efflux from the neutralizer, was that mercury flow rate was reduced as the arc current was increased. This phenomenon was observed many times on many occasions; it failed to appear only once. Figures 3.1-5 and 3.1-6 demonstrate this phenomenon. In both figures (data taken on different cathodes and in different vacuum systems) the experimental chamber pressure is regarded as proportional to the total mercury efflux from the cathodes. The proportional reduction in mercury efflux with arc current does vary with some of the experimental conditions. Further evidence of this effect was

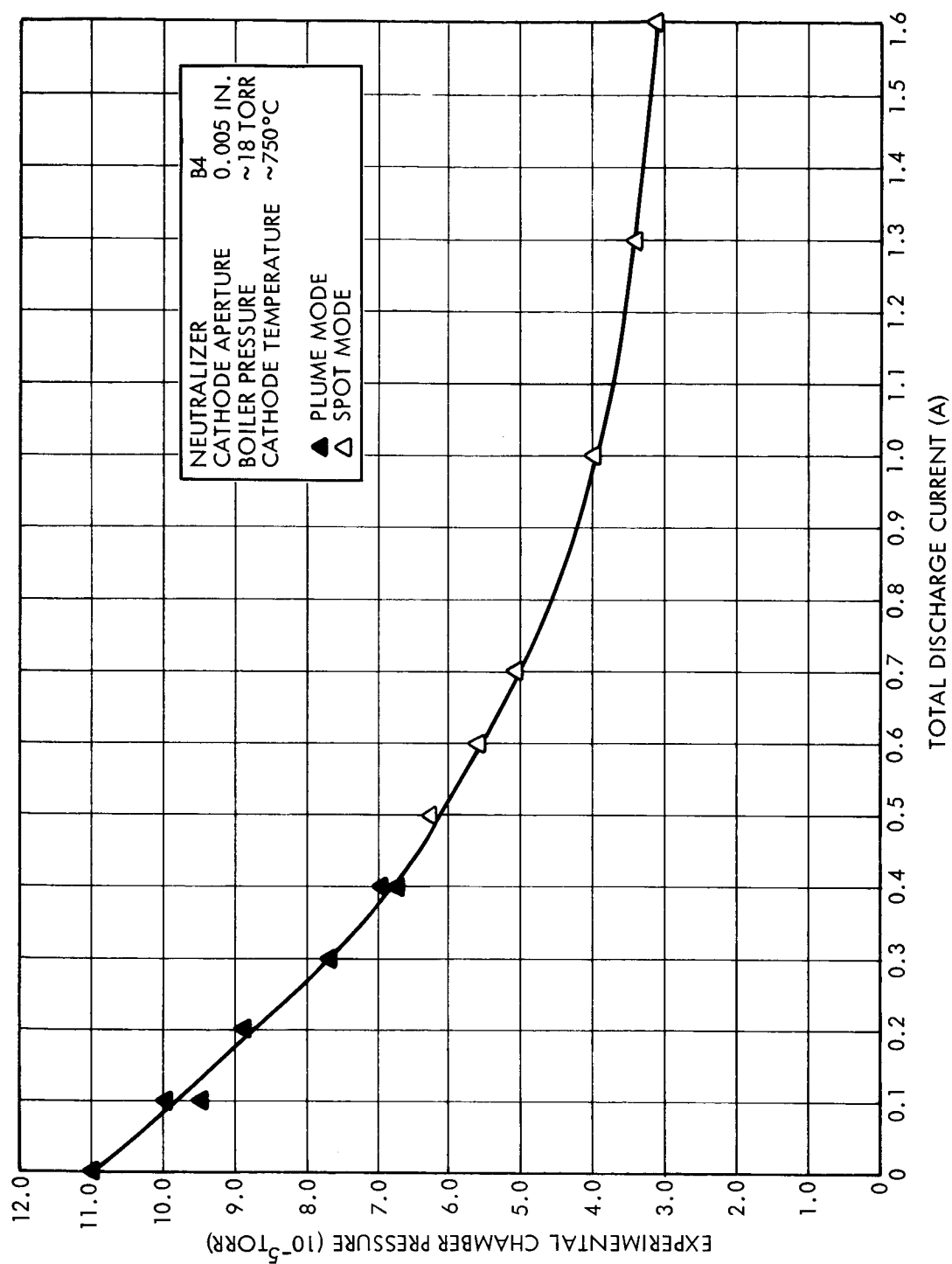


Figure 3.1-5. Chamber Pressure (and hence, Mercury Efflux From the Cathode) as a Function of Discharge Current

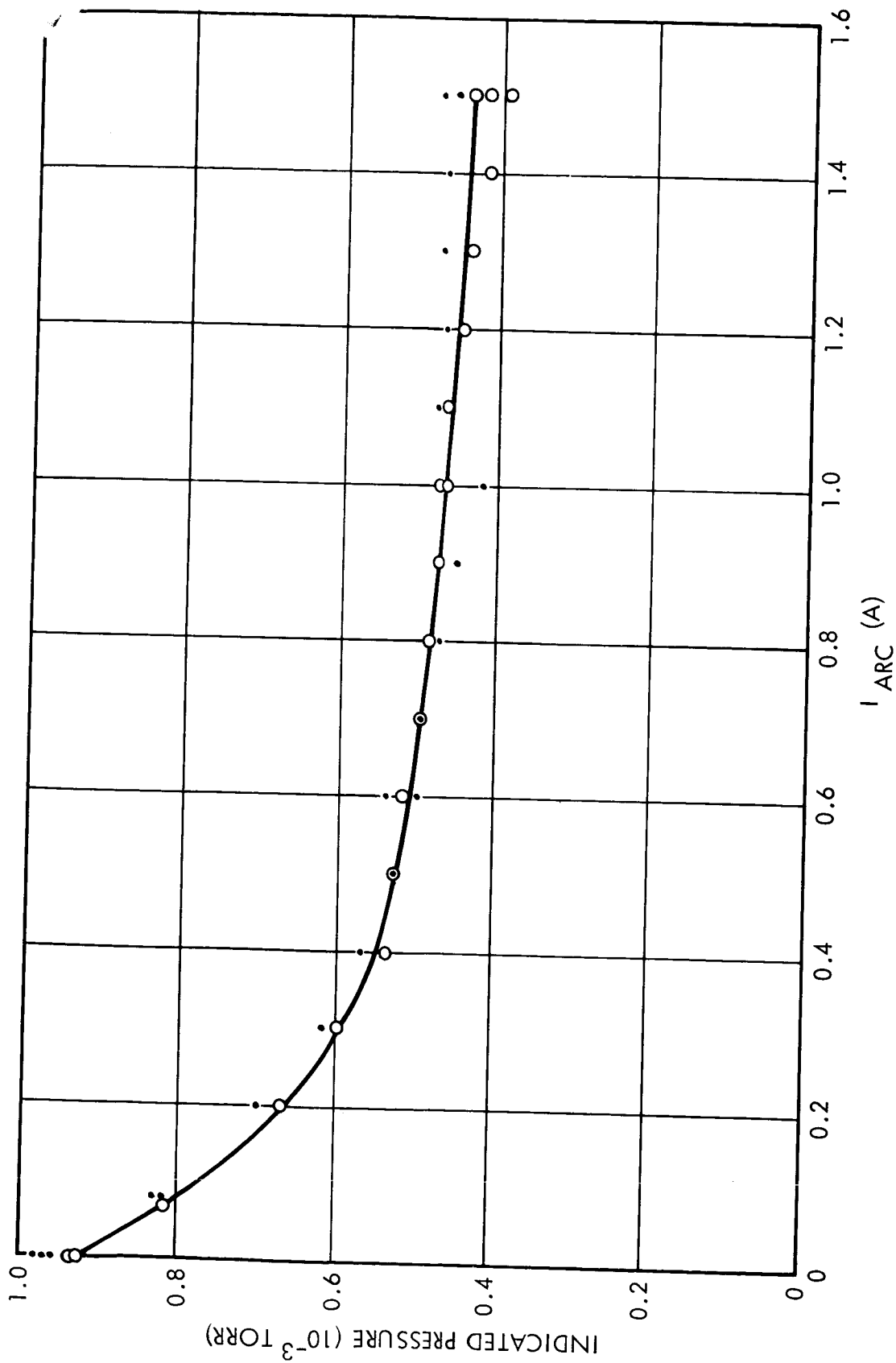


Figure 3.1-6. Chamber Pressure (hence, Mercury Efflux) as a Function of Discharge Current.

obtained in a pair of gravimetric runs in a 4-inch vacuum system. For these two runs, the boiler and tip were carefully controlled in temperature for 5.33 hours -- the same temperatures being used for both runs. One run was made with the neutralizer operating at an arc current of 1.0 amperes; the other with no arc. The temperatures ($229 \pm 1^\circ\text{C}$ for the boiler which corresponds to ~ 50 torr, and $1025 \pm 3^\circ\text{C}$ for the tip) were selected so that the arc was produced in its "spot" mode. Keeper current and voltage were 6-8 milliamperes and 8-10 volts, respectively. The resulting values of mercury efflux as determined from boiler weight measurements were:

	<u>gr/hr</u>	<u>I_{equiv} (A)</u>
$I_{\text{arc}} = 0$	.479	.064
$I_{\text{arc}} = 1.0\text{A}$	.299	.040

The effect observed in the above experiments is probably due to the temperature elevation of the plasma in the orifice. Since $\eta_m = I_-/I_{\text{Hg}}$, and I_{Hg} decreases with I_- , it is easily seen that high mass utilization is associated with high current operation.

This reduction in mercury efflux with increased current density led to the supposition that a reduction in orifice cross section might improve the ratio of η_m to I_- . Accordingly, some cathodes were modified by plugging up the 0.005 inch diameter orifice, and then drilling a hole by a focussed laser beam of about 0.002 inch diameter alongside the original one. Figure 3.1-7 is a photograph of one such hole. When these cathodes were operated, a small improvement in η_m vs I_- was noted; however, the major effect was that one had to increase the mercury vapor pressure in the cathode to about that pressure which would give the same flow rate of mercury as with the larger hole in order to strike the discharge. This result indicated that the density of mercury vapor in the region between the cathode orifice and the keeper was of more importance than had been previously appreciated.

The next important thing we learned was that mercury boiler pressure

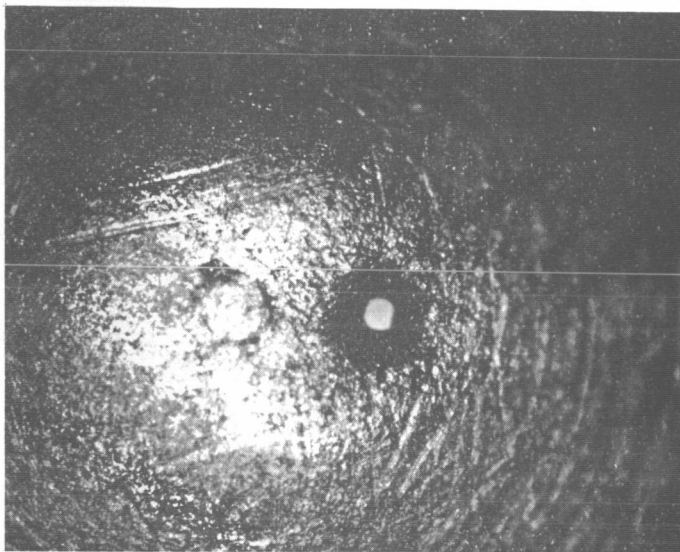


Figure 3.1-7. Photomicrograph of the orifice region of a porous tungsten cathode. The 0.005 inch diameter hole has been plugged with a molybdenum wire, and a 0.002-inch diameter hole has been drilled near by using a focussed laser beam.

and V_c were inversely related at any given x_c . By obtaining data of the sort shown in Figures 3.1-8 and 3.1-9 it was demonstrated that an open keeper configuration had little chance of meeting the design goals.

3.1.4.1 Enclosed Keeper

This data suggested that at reasonable values of x_c , V_c was elevated because of an insufficient number of ions in the keeper to collector space to fully neutralize the electron space charge. This view was supported when argon gas was admitted into the experimental chamber while a neutralizer was in operation: V_c was dramatically reduced, presumably because argon ions were produced in this region.

It was then reasoned that if we could make better use of the neutral mercury atoms escaping from the cathode aperture, an improvement similar to that observed with the argon might result.

To increase mercury ion production in the keeper to collector space without an increase in neutral flow rate, we experimented with several enclosed keeper designs which tended to collimate the neutral flow, thereby increasing the neutral density along the neutralizer axis and hence the ion production rate. It worked.

As Figures 3.1-10 and 3.1-11 show, the characteristic curves became more complicated, but at $x_c = 0.42$ inch and $V_c = 23$ volts, we obtained $\eta_m = 39$ el/atom.

It is interesting to note in Figures 3.1-9 and 3.1-11 that η_m is not linearly dependent on I_c . This results from the reduction in total mercury flow with increasing I_c previously discussed. Again, η_m is virtually independent of x_c .

A qualitative observation made with enclosed keepers was that if, while the neutralizer was operating the spacing between the alumina and cathode body was increased, performance degraded. We therefore concluded that it was desirable to make this joint as leak-tight as possible.

However, following each of several experimental runs with alumina enclosed cathode to keeper spaces it was observed that the alumina surface became metallic in appearance and electrically conducting. It was not difficult to envision an insulator design which incorporated shadowed

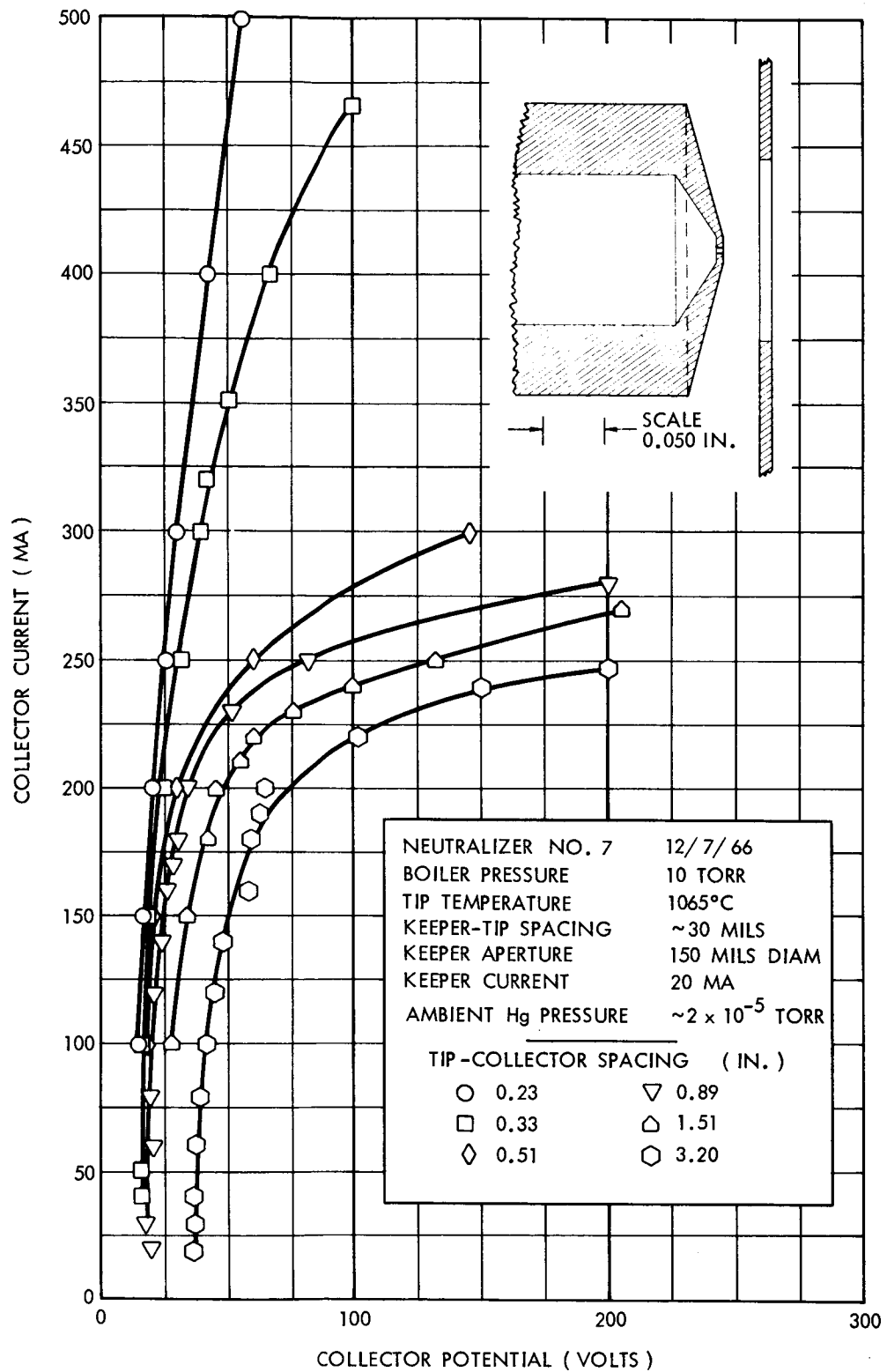


Figure 3.1-8. Electron Collector Current as a Function of Collector Potential for Several Values of Tip to Collector Spacing. The Inset Shows the "Open" Keeper Configuration; the Collector Electrode is Not Shown.

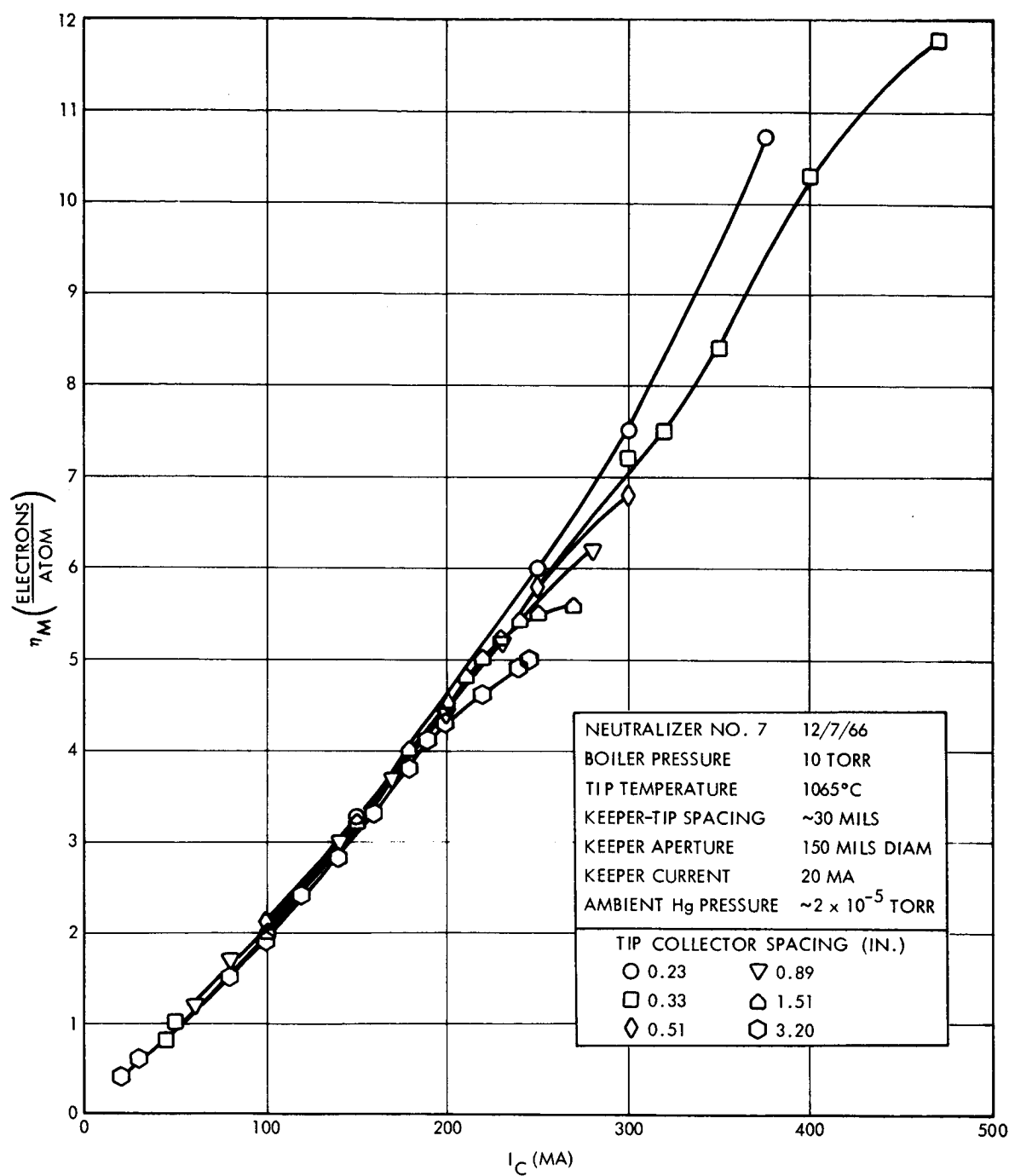


Figure 3.1-9. Mass Utilization Efficiency η_m as a Function of Collector Current I_c for Several Values of Tip to Collector Spacing with the Open Keeper Configuration.

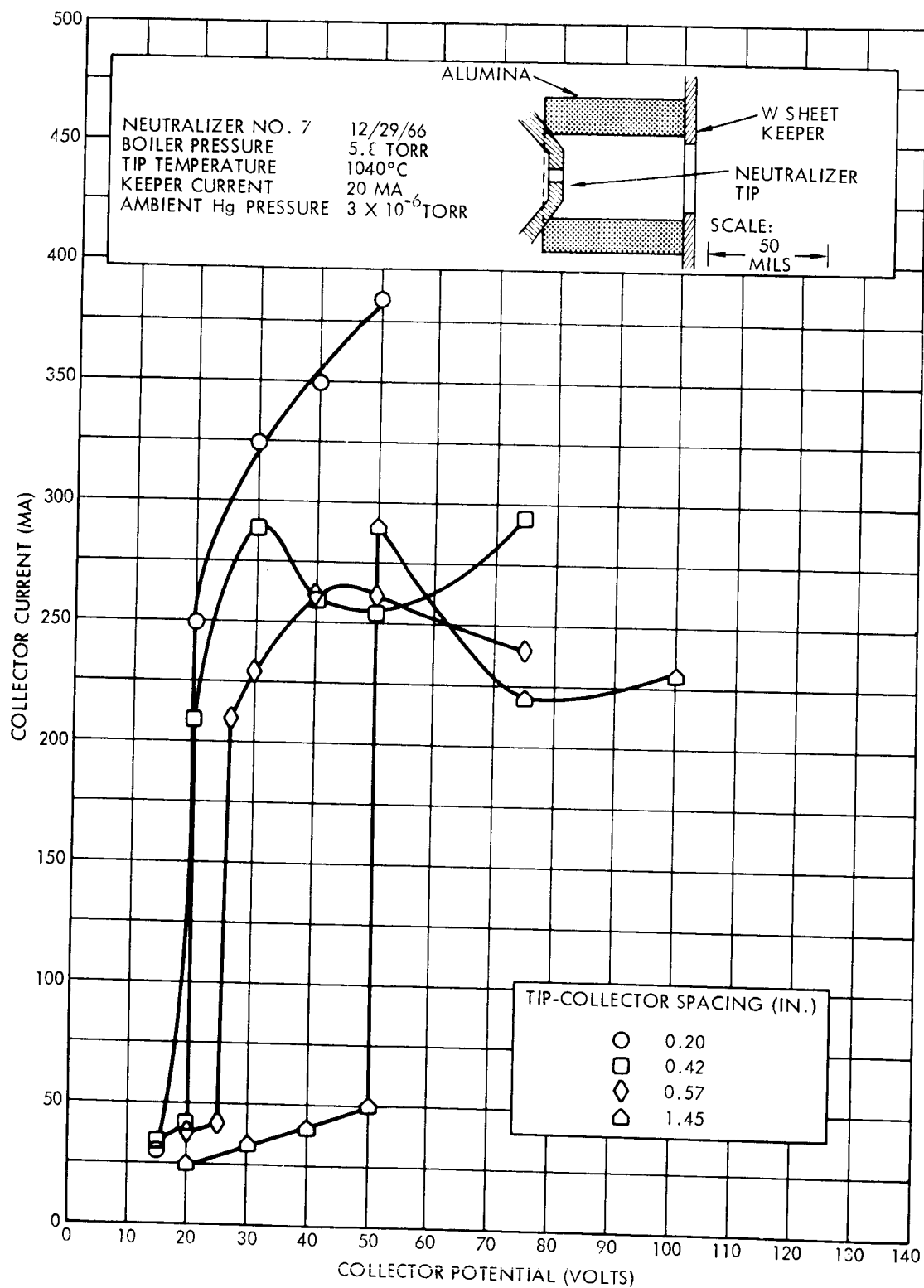


Figure 3.1-10. Collector Current as a Function of Collector Potential for Several Values of Tip to Collector Spacing, Closed Keeper Configuration.

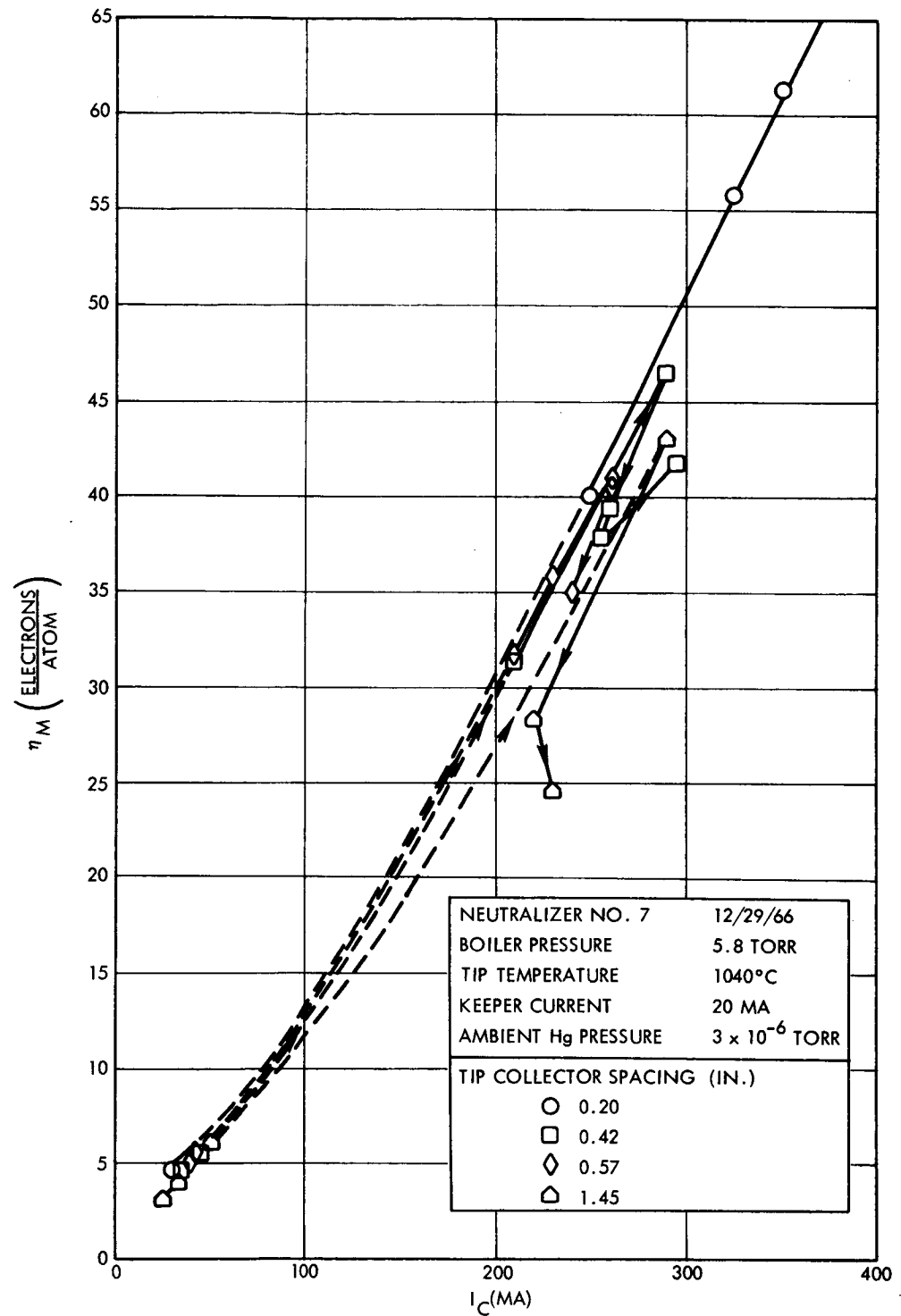


Figure 3.1-11. Mass Utilization Efficiency η_m as a Function of Collector Current for Several Values of Tip to Collector Spacing, Closed Keeper Configuration.

grooves which would prevent eventual shorting of the keeper to the cathode, but the possibility of increased recombination of ions and electrons on these conducting surfaces resulting in degraded performance was disturbing.

We therefore constructed a neutralizer with a keeper in the form of a short molybdenum tube. This tube was spaced off the cathode slightly, which at once allowed some mercury vapor to escape and insulated the keeper from the cathode electrically. As shown in Figures 3.1-12 and 3.1-13, the performance of this neutralizer was only slightly poorer than with the alumina. This reduction can be ascribed to the escape of neutrals through the gap, and at any rate no large degradation results from having the plasma in contact with a relatively large conductive area.

Several other keeper configurations were also tried, but they yielded unimpressive results. One was a 6 inch diameter, 20 mil thick stainless steel disc with a 1/2 inch hole in its center. Spotwelded across this hole was tungsten mesh of 1 mil wires on 10 mil spacing. This keeper plate could be positioned with respect to the cathode. Keeper current was unacceptably high.

Two other attempts to improve performance with the use of grids were made. In both cases the grids were introduced as an additional (movable) electrode in the keeper-collector space and a cylindrical alumina keeper similar to that pictured in Figure 3.1-10 used. Both employed 2 mil tungsten wire spotwelded on a 3 by 3 inch square frame. One used 1/4" wire spacing and the other 1/8" wire spacing. No significant improvements were obtained by applying various potentials at various grid locations in either case.

The nozzle-like keeper in Figure 3.1-14 was tested. It only worked well when the exit plane of the nozzle was within 0.1 inches of the collector, where reuse of mercury evaporating from the collector was certainly possible. Furthermore, after several hours operation, it became quite difficult to restart the discharge.

In order to quickly determine the approximately optimum length and I.D. of the alumina tubing, a boron nitride block was machined with 6 holes of varying L/D ratio as shown in Figure 3.1.15. The block was then suspended

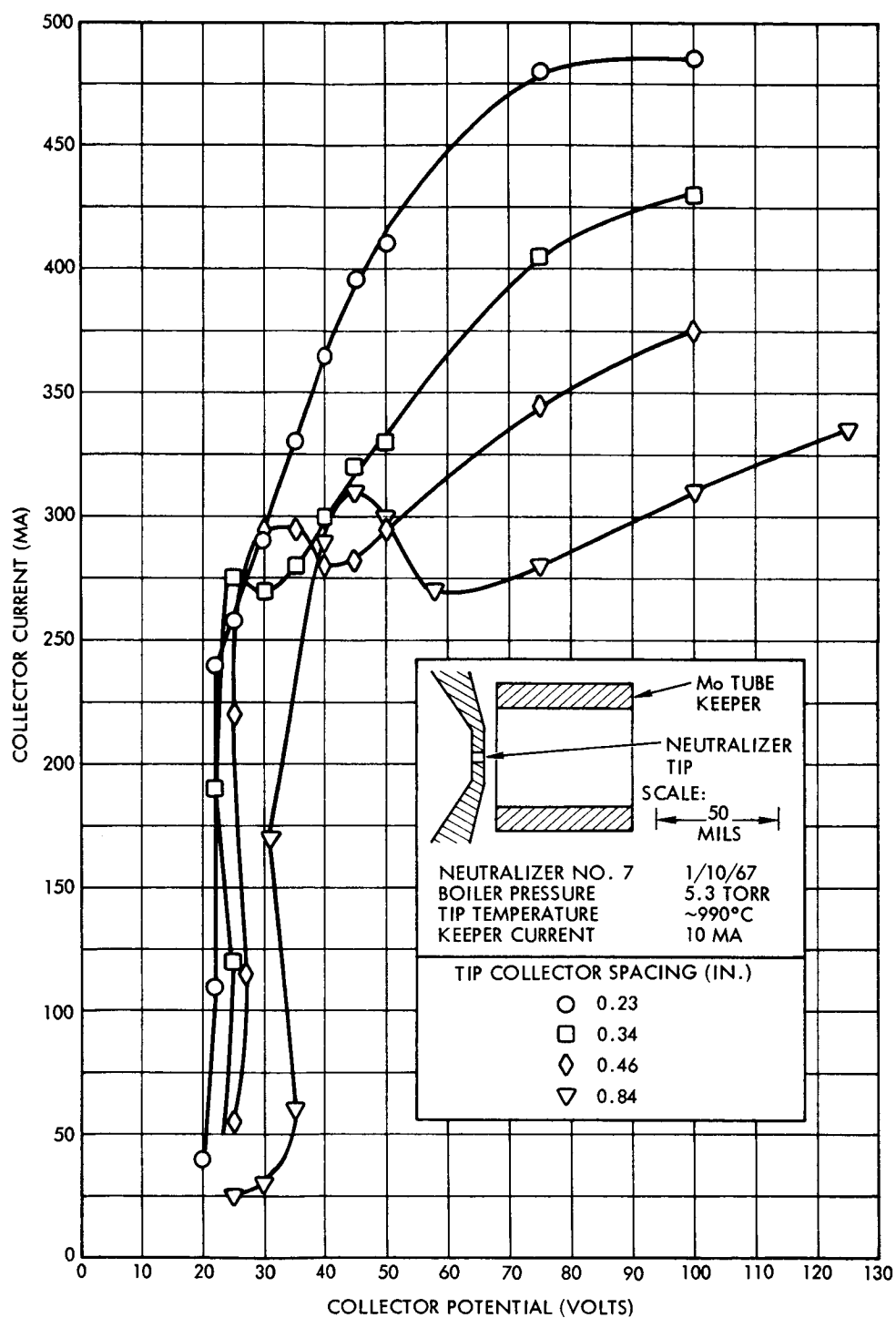


Figure 3.1-12. Collector Current as a Function of Collector Potential for Several Values of Tip to Collector Spacing, Closed Keeper Configuration.

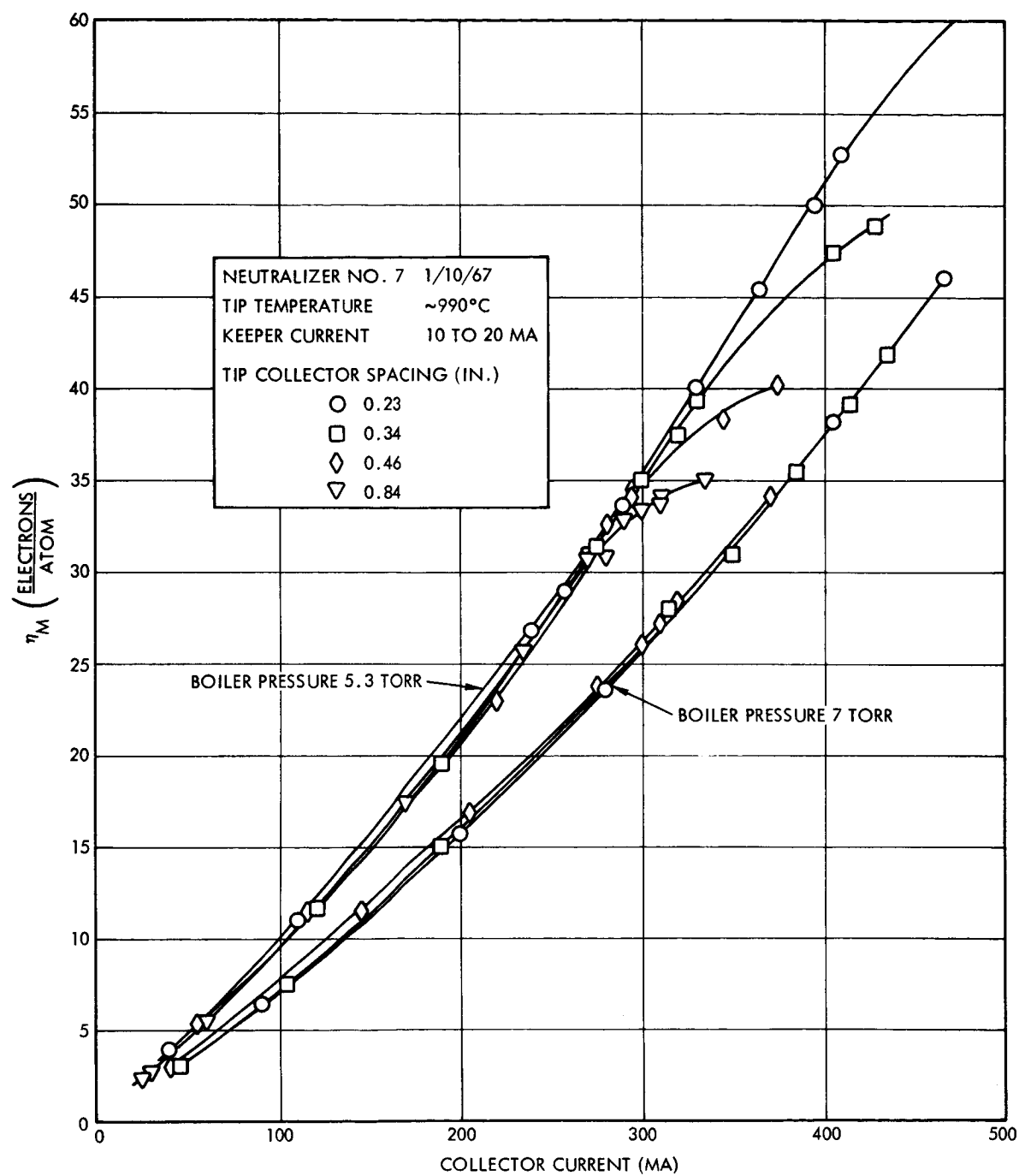


Figure 3.1-13. Mass Utilization Efficiency η_m as a Function of Collector Current for Several Values of Tip to Collector Spacing, Closed Keeper Configuration

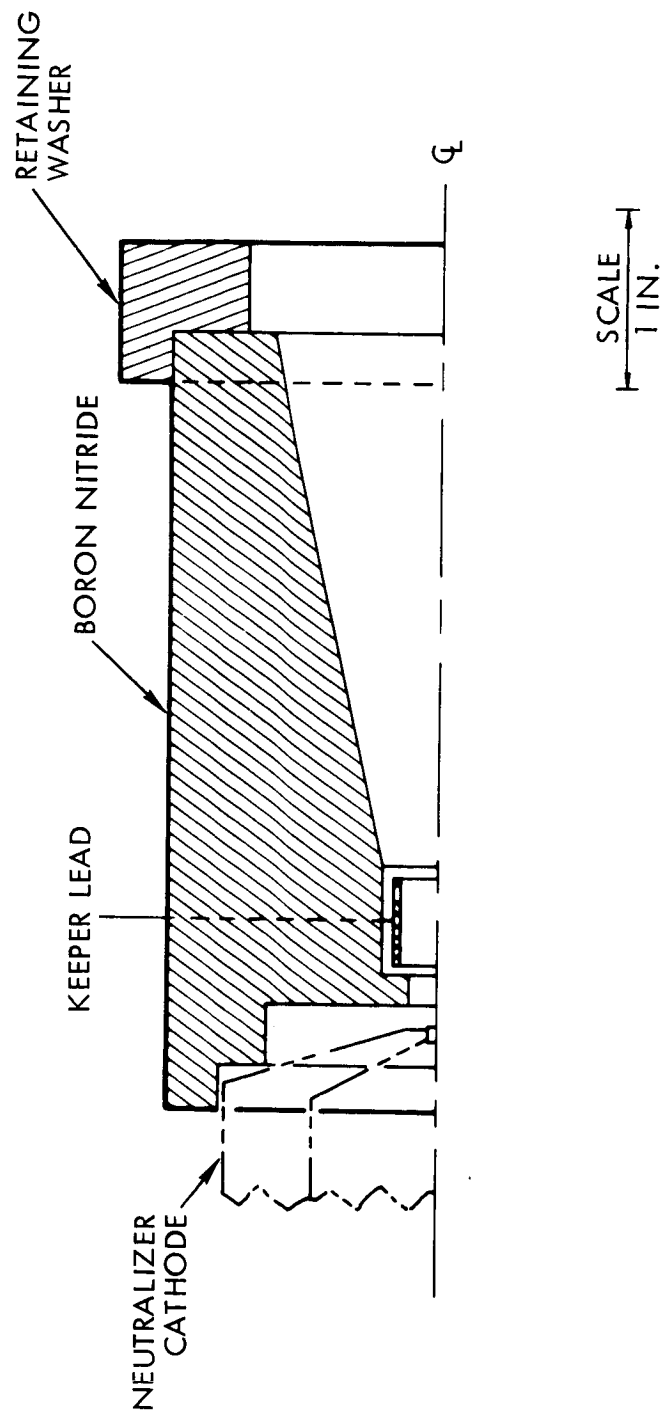


Figure 3.1-14. Section Through Boron Nitride Nozzle and Keeper Configuration

on a rotary-motion feed-through such that each block hole could be positioned on the axis of the keeper assembly shown in Figure 3.1-10. The results of this experiment suggested that .035 inch I D and .100 inch length were near optimum.

This result, as regards the best alumina tubing length for a 0.035 ID, was further substantiated by runs with 0.200 and 0.100 inch lengths of tubing. The 0.200 inch length proved difficult to restart and provided η_m 's around 23 at $x_c = 0.4$ inch and $V_c = 40$ volts.

The 0.100 inch length was tried with a heater power-saving, 0.07 inch OD, "miniature" cathode which had previously demonstrated discharge performance similar to the larger cathodes. Some of the data from this experiment is displayed as V_c vs η_m at $I_c = 250$ in Figure 3.1-16. Two values of x_c were used and are indicated. Variations of data point position for a given value of x_c resulted from different values of boiler pressure, cathode temperature, and keeper current. In general, lower boiler pressures were associated with high values of V_c and η_m ; a broad optimum cathode temperature was expressed in low V_c ; and neutralizer performance depended in a complicated way on the value of I_k over the range of 20 to 250 milliamperes with local optima occurring at multiple values. The overall interpretation of this data is that the design goals of the program were met at $x_c \leq 0.4$ inch: operating points with $\eta_m \geq 25$ and $V_c \leq 25$ were obtained.

Table I displays qualitative relationships between the dependent and independent variables as determined from many bell jar experiments with the several versions of enclosed keeper neutralizers.

An interesting, if inconclusive, observation was made of the interior of cathode number 7 during operation. This was possible by use of a right-angle fitting between the cathode and boiler, a small glass window on the cathode axis, and a suitably placed mirror, chamber window, and telescope. During operation of the discharge the interior of the cathode was observed to be very luminous, supporting earlier probe measurements that the plasma is present throughout the cathode interior. Only subtle changes in appearance occurred when the discharge was switched between the spot and plume modes.

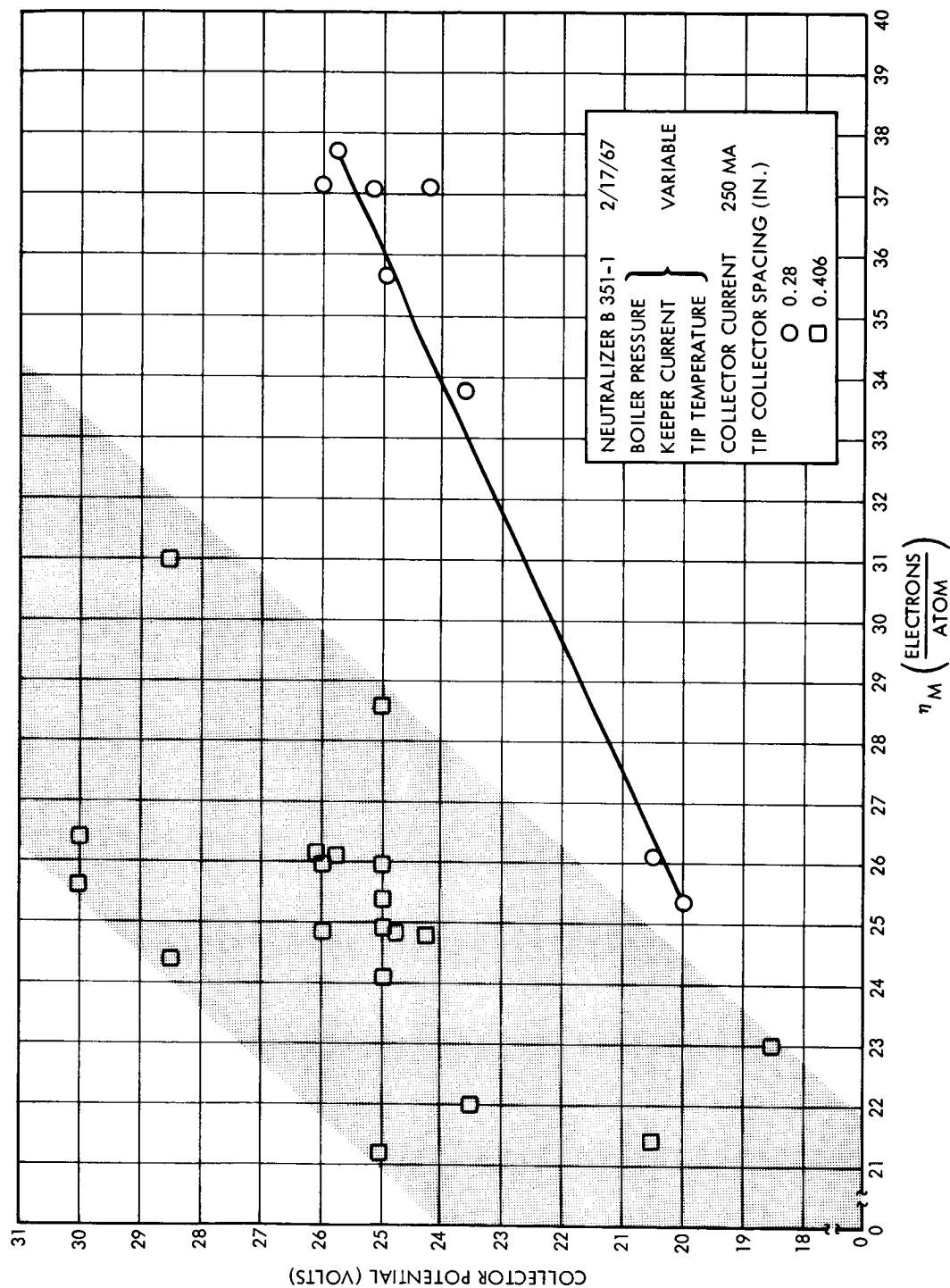


Figure 3.1-16. Collector Potential vs Electrons/Atom Ratio at 250 Milliamperes for Two Values of Collector Spacing. Scatter of Points in Shaded Area is Due to Changes in Boiler Temperature.

TABLE I. Qualitative Relationships Among the Independent and Dependent Neutralizer Variables.

Dependent Variables Independent Variables	η_m	V_c	η_E	V_k
$P_{Hg} \uparrow$	Strong $\downarrow$	Strong $\downarrow$	None	Weak $\downarrow$
$x_c \uparrow$	None	Strong $\uparrow$	$\sim \frac{1}{I_c V_c}$	None
$I_c \uparrow$	Strong $\uparrow$	Strong $\uparrow$ in region of interest	$\sim$ linear $\uparrow$	Weak $\downarrow$
$I_k \uparrow$	Modest $\uparrow$ 2 or more optima	Weak $\uparrow$	$\sim \frac{1}{I_k V_k}$	$\sim$ None
T_c	Optimum exists (sometimes broad)	Optimum exists (sometimes broad)	$\sim \frac{1}{\epsilon \sigma T_c^4}$	Weak $\downarrow$
x_k (open $\uparrow$ Keeper)	Optimum exists	Optimum exists	Weak $\downarrow$	Minimum exists $\uparrow$
$L/D \uparrow$	Small	Small	None	None
Keeper geometry	Important	Important	None	Weak

Throughout the research program data was gathered on erosion of neutralizer parts due to sputtering. It was not uncommon to observe light sputtering damage on metallic keeper parts, particularly near the keeper aperture, but since we believe that these parts may easily be quite massive the major interest was in damage to the cathode proper. Damage, when observed, was heaviest in the most crucial area -- the 5 mil thick region surrounding the aperture -- and always consisted of a chamfering or "dishing out" of this surface. A typical photomicrograph is shown in Figure 3.1-17. We have not observed any evidence of aperture closure as has been observed on Ni, Ma, and Ta cathodes at NASA Lewis Research Center.

3.1.4.2 Platinum Needle Hollow Cathode Experiment

A separate experiment was performed to examine a fundamental question with regard to the operating principles of the discharge neutralizer -- the role of thermionic emission in the operating discharge. If an arc can be made to persist using a high-work-function material, cold tip, then, at least, thermionic emission is not essential to the arc. The experimental apparatus was as shown in the sketch, Figure 3.1-18.

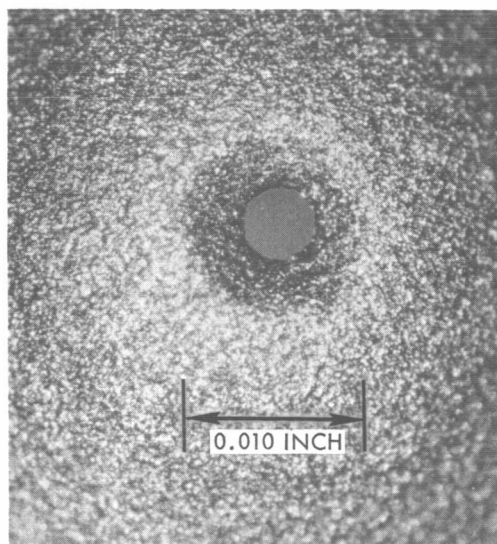


Figure 3.1-17. Photomicrograph of Orifice Region of Porous Tungsten Cathode. Some Chamfering Erosion is Observable

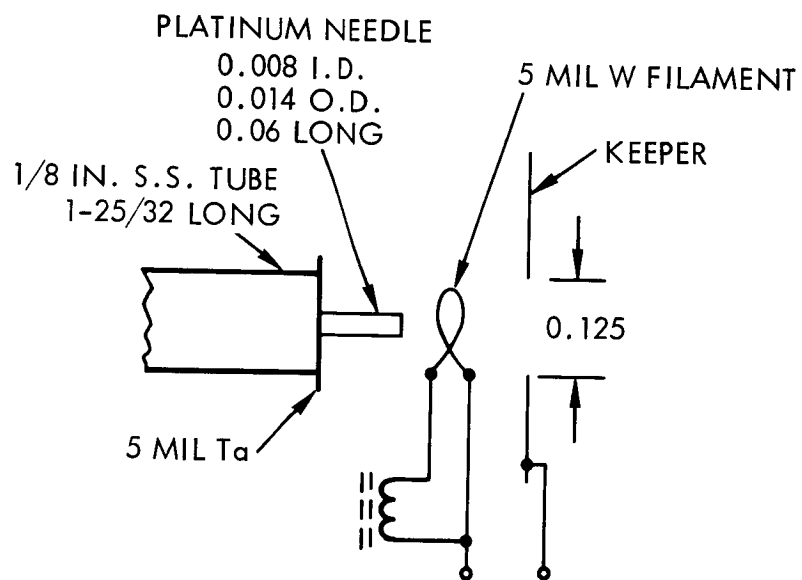


Figure 3.1-18. Platinum Needle Cathode Experiment

A platinum needle 1/16 inch long and of 0.008 inch I.D. was mounted in a 5-mil-thick tantalum plate welded to the end of a stainless steel tube 0.125 inch in diameter and 1-25/32 long, which in turn was attached to the neutralizer boiler. A tungsten filament of 5-mil wire was located near the platinum tip to provide heating for the needle and electrons by thermionic emission to ignite an arc. An electric field was established on the needle tip by a movable keeper in which a 1/8 inch hole was made to allow for transfer of electron current to a collector plate (not shown). It was much more difficult to strike an arc in this device than with an ordinary neutralizer cathode. Nevertheless this was accomplished twice with the boiler at normal starting pressure, and the arc was made to persist after the tungsten filament was turned off. The needle was heated by the discharge to red heat. The discharge extinguished during an attempt to transfer current to the collector, and it was not possible to start it again. At this time, however, there was evidence of mercury leaks around the weld between the end of the stainless tube and the tantalum plate, and it is likely that there was inadequate flow of mercury through the needle.

There is an outside chance that the observed discharge was supported by the presence of trace surface contaminants of an alkali metal, contained in or on the platinum or transported to it by the mercury feed, which sufficiently lowered the work function on parts of the surface to permit thermionic emission. Had contract funds been available for further experiments, further efforts to continuously operate the discharge would have been made, thereby assuring that any such trace contaminants would have thermally desorbed. That would have strengthened our tentative conclusion that thermionic emission in the discharge neutralizer cathode, while it might be helpful, is not essential to the operation of the arc, once struck.

3.1.5 Fabrication and Testing of Deliverable Hardware

During the final phase of the program, 5 neutralizer assemblies were fabricated in accordance with a design approved by the NASA Program Manager. A cross section of the cathode assembly is depicted in Figure 3.1-19.

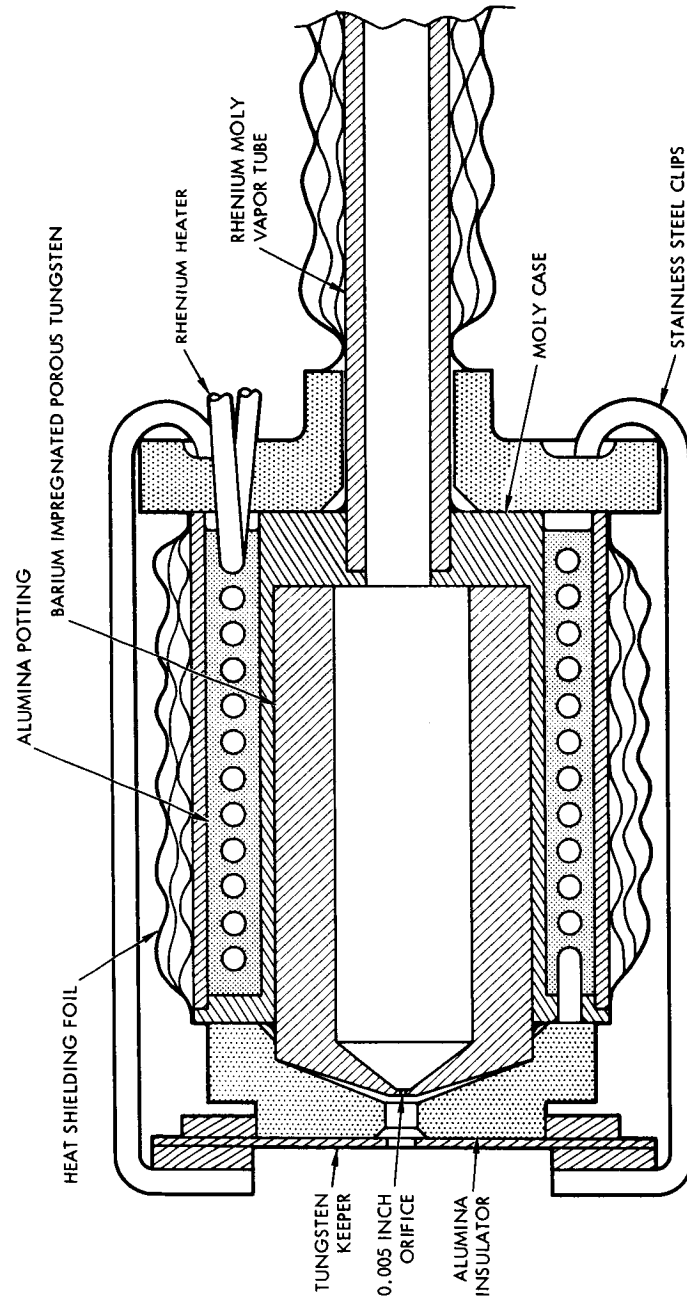


Figure 3.1-19. Closed-Keeper Neutralizer Design Used in 500-Hour Test with the 15 Centimeter Electron Bombardment Thruster.

The impregnated cathode, potted heater, and vapor delivery tube are all included in the sub-assembly, Spectra-Mat Catalog Number B740. The keeper and clip insulators, keeper assembly and heat shielding were added during the fabrication process at TRW. In the order of fabrication, these assemblies were designated serial numbers 1 to 5, inclusive. Numbers 1, 3, and 4 were each tested with a 15-cm electron bombardment thruster supplied by NASA Lewis Research Center and then shipped to NASA Lewis Research Center for further evaluation. The number 5 unit was kept as replacement hardware until the end of the program, at which time it and the number 2 unit were sectioned for microscopic examination of the orifice region. The number 2 unit was subjected to a more extensive series of tests than any other. Its history is described in Section 3.1.5.4.

3.1.5.1 Electrical Connections in the Testing Facility

Certain aspects of the test facility are of importance to the significance of these test results. The diagram of Figure 3.1-20 illustrates some of these aspects. The end of the 4 x 8 foot tank is fitted with an electrically isolated, water cooled, 1/4 inch thick copper ion beam collector. Between it and the midpoint of the tank is a separately isolated, water cooled copper cylinder approximately 3 feet in diameter. Another isolated, cryogenically cooled liner of smaller diameter is placed between the engine position and the downstream shroud. Accordingly, the first impact of any ion leaving the thruster in the forward hemisphere will be on one or the other of these isolated surfaces. In normal operation all three are connected together and returned to the collector grounding switch. Not shown in this sketch is the stray capacitance of the collector ensemble and leakage through the water lines to ground (~ 1500 pF and $> 20,000 \Omega$, respectively).

In addition to numerous meters and oscilloscope test points for observation of instantaneous values of operating variables, provision is

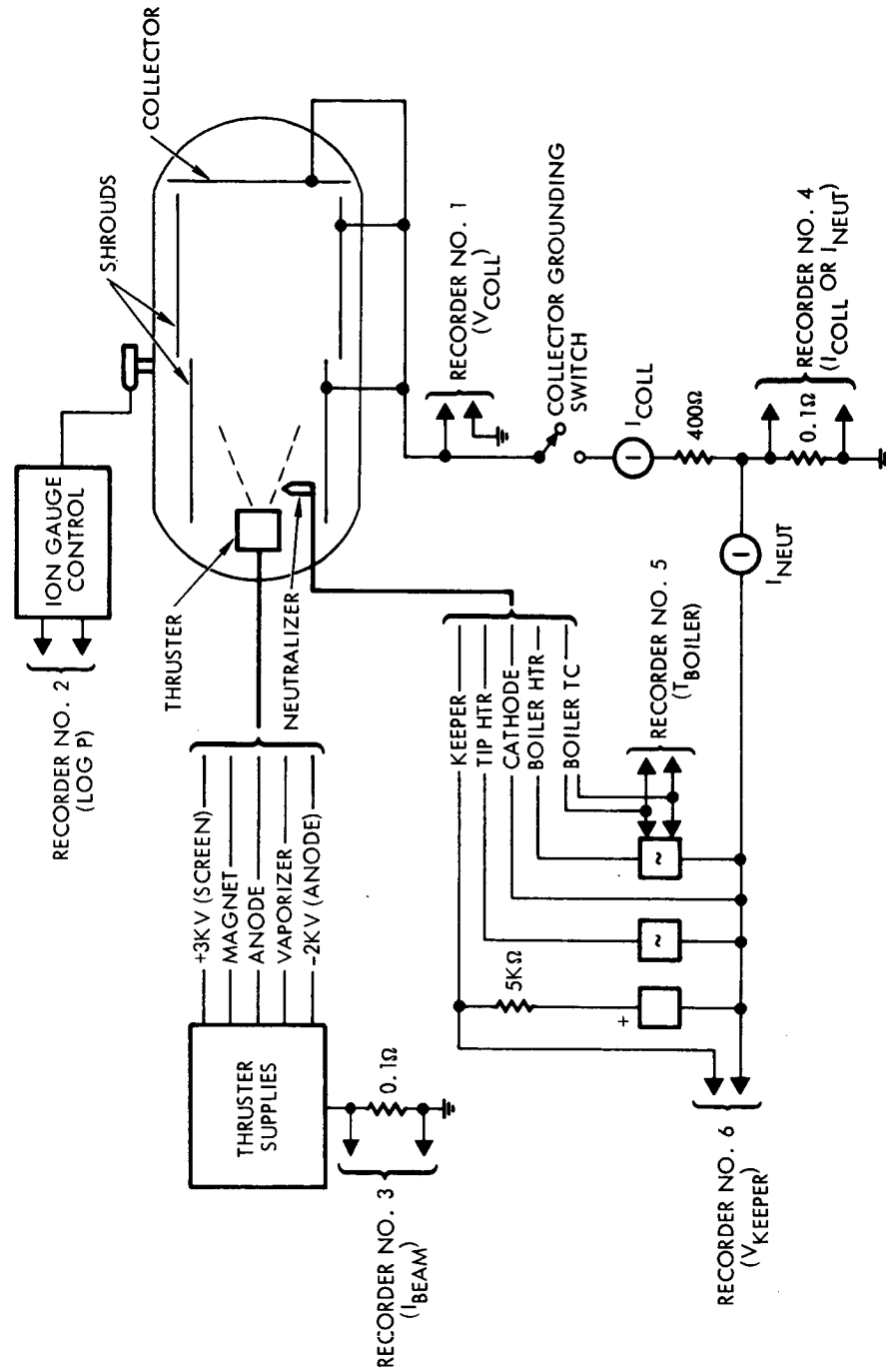


Figure 3.1-20. Instrumentation Circuits for Floating Collector Testing of the Hollow Cathode Discharge Neutralizer with a 15 Centimeter Mercury Electron Bombardment Thruster

made for recording six operating signals on strip-chart recorders. These are:

1.	Collector Voltage	V_{COLL}	100 volts full scale
2.	Log Tank Pressure	P	10^{-10} to 10^{-3} torr
3.	Ion Beam Current	I_{BEAM}	250 mA full scale
4.	Collector or Neutralizer Current	I_{COLL} or I_{NEUT}	250 mA full scale
5.	Neutralizer Boiler Temperature	T_{BOILER}	20 mV full scale (above 22°C) (I-C thermocouple)
6.	Neutralizer Keeper Voltage	V_{KEEPER}	100 volts full scale

When the collector grounding switch is closed, the collector is returned to ground through the recorder shunt and an additional 400 ohms. This latter is an arbitrary value selected to give a full-scale 100 Volt signal on the collector voltage recorder when the ion beam current is 250 milliamperes.

All power supplies in the neutralizer circuit are returned to a common point, which in turn is connected to the same recorder shunt as the collector. Accordingly, as the collector grounding switch is opened no interruption in the neutralizing current chart reading is observed. Also, the common point for the thruster power supplies is returned to ground through the ion beam current recorder shunt. In this way, the anode impingement current is not included in the beam current measurement, although it is indicated separately by a meter. With the connections made in this way, it is possible to maintain accurate accounting of neutralizing electrons as they leave the thruster power supplies and as they return to the beam ions, either through the neutralizer alone or through the sum of neutralizer (if any) and collector currents.

3.1.5.2 Operating Procedure and Typical Performance Data

The objective of the ion beam tests of the deliverable neutralizers was to make measurements which would enable a comparison of the performance of each device with the program design goals. Practically, this meant determining the best operating point, in terms of minimum mercury efflux, minimum power loss, and maximum withdrawal from the ion beam, during a prolonged period of beam neutralization. During these tests the thruster was operated with 250 milliamperes beam current at a net accelerating potential of 3000 volts.

The condition of thruster beam neutralization was specifically interpreted at TRW as requiring that for a 250 milliampere ion beam from the thruster the neutralizer achieve and maintain control of the potential of a floating ion beam collector within 30 volts above neutralizer potential. In most runs it was found that stable operation could only be achieved if the collector potential were held to something between 9 and 13 volts; any attempt to increase this voltage slightly would lead to an abrupt transition to unstable operation with an average collector potential between 50 and 250 volts.

A typical start-up sequence is shown in the strip-chart records of Figure 3.1-21. The total time interval shown is divided into a number of periods as follows: Between (1) and (2) the thruster vaporizer is warming up. After thruster operation has been stabilized at the design level, and the keeper voltage has been applied, (2) to (3), the neutralizer boiler heating is begun at full power. The appearance of a neutralizer arc starts period (4). This event is signalled by a drop in keeper voltage to its operating level and, a simultaneous drop in collector potential to something less than 100 volts. At this point, also, the neutralizer boiler is switched from full heater power to automatic control at the operating temperature, and the collector grounding switch is opened. If the collector voltage drops to less than 30 volts as it should, the run timer clock is started. Some minor adjustments of a number of things are usually required during the subsequent 10 to 30 minutes, after which the run continues with a minimum of attention.

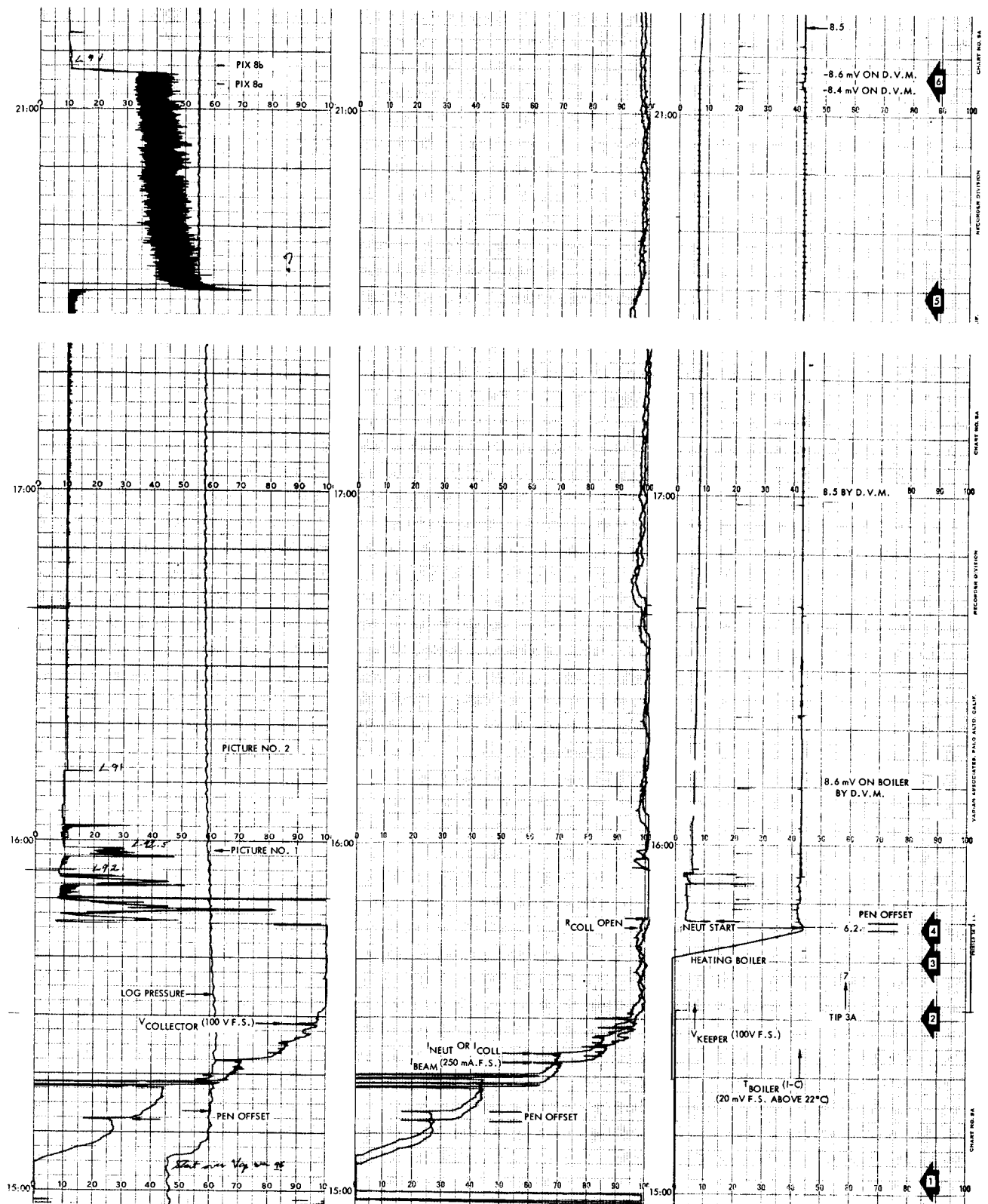


Figure 3.1-21. Samples of Strip-Chart Records from an Ion Beam Neutralization Test. The Lower Portion Shows a Typical Start-Up Sequence, the Upper Portion Shows an Abrupt Increase in Collector Potential which was Corrected by a Slight Adjustment in Neutralizer Boiler Temperature

The chart records (from Run 6, 26 May 1967) show that until the neutralizer arc is struck, the collector current and voltage ($V_{\text{COLL}} = 400 I_{\text{COLL}}$) signals follow the ion beam current signal in detail. After that, the collector potential is determined by neutralizer behavior, and, until the collector grounding switch is opened, the sum of collector and neutralizer currents equals the beam current. No interruption is seen in the neutralizer current trace when the collector circuit is opened, and (except for the pen's hitting a stop) detailed matching of the two current traces continues.

Some interesting observations can be made concerning the short chart records taken later in the run. After a period of slowly increasing noise level, the collector potential suddenly rose to an average of 750 volts with marked increase in noise. When this condition was discovered, and before corrective action was taken, a photograph of the collector voltage oscillogram showed the disturbance to be in the form of high-frequency bursts with peak amplitudes up to 300 volts. Normal operation was restored by increasing the boiler temperature from 179 to 182 and then back to 178°C. In this, as in many other instances, no hint of the event is noticeable on the keeper voltage recording. Therefore, it seems unlikely that the keeper voltage could be used as a control signal. Perhaps, in some other keeper configuration, the transfer function between beam potential and keeper signal might have a useable amplitude, but this remains to be demonstrated.

3.1.5.3 Environmental Testing of Neutralizer Cathodes

During the research phase of the program two barium impregnated neutralizer cathodes were subjected to the sinusoidal vibration test prescribed for the deliverable units. No failures or detrimental effects could be observed. One of these cathodes was of the same size as the later, deliverable units; the other was a much smaller unit, consisting, essentially, of an impregnated porous tungsten plug inserted in the end of the 0.090 inch O.D. vapor delivery tube.

During the final testing phase of the program, the S/N 2 unit was

subjected to a more complete environmental test program without failure. This series of tests was performed between runs 1 and 2 with the mercury thruster.

3.1.5.4 Summary of Test Results

Testing of the deliverable hardware began with the ion beam test, Run 1, of 16 May 1967, using neutralizer S/N 1. The floating collector voltage was stabilized at 30 volts throughout the run. A short in the boiler thermocouple made automatic control impossible and data reduction difficult; 3.7 hours after start of beam neutralization, the run was terminated by a failure of the ribbon filament in the thruster. An estimate of the mercury efflux rate from the neutralizer during operation is 11.8 mA equivalent. This estimate was based on power supply settings, and observations of neutralizer operation (for comparison with previous operating points for similar operation). For other runs, mercury efflux measurements were from gravimetric data. The S/N 3 and 4 units were tested in runs 5 and 8 on 25 May, respectively. For these runs, an oxide matrix cathode was used in the thruster, and the run times were extended to 9.0 and 8.6 hours. Mercury efflux rates were between 9.85 and 8.97 mA equivalent with collector potentials held between 10 and 12 volts.

The history of S/N 2 was more extensive and is summarized in Table II. It was first operated with the ion engine for 8.6 hours, Run 2, then subjected to environmental tests including at least 24 hours exposure to atmosphere, then four more cycles of over 8 hours thruster operation and 24 hours or more in atmosphere (Runs 3, 6, 7, and 9). At this point, in a test of another neutralizer on another program, it became apparent that a significant current of charge-exchange ions was being drawn from the neutralizer discharge to a shield around the edge of the thruster accel grid, and had completely sputtered through the shield. Accordingly, the shield in the thruster used in this program was changed from -2000 volts to ground potential, with the result that the neutralizer could now be withdrawn an additional 3/4 inch from the beam edge with equivalent performance. At the closer position, erosion of the keeper electrode was quite obvious but not measured. Following this change, no further erosion was seen; on the contrary, the keeper began to be coated with copper sputtered from the ion beam collector surfaces. Run 10 was used to verify these changes and to determine the operating point for the 500-hour test which followed.

TABLE II. History of S/N 2 Neutralizer Cathode

DATE 1967	RUN	mA/Torr (typ)	mA (equiv)	% of .3A	el/ Atom	V _{coll}	Hrs this run	Clock	Total
Keeper to beam axis: 3.3 in.									
18 May	2	0.93	8.85	2.95	28.3	25	8.6	8.6	8.6
23	3	1.06	10.56	3.5	23.6	10	9.0	9.0	17.6
26	6	1.29	12.26	4.08	20.6	11	8.3	8.3	25.9
29	7	1.26	12.55	4.16	19.9	10	9.0	9.0	34.9
1 June	9	1.28	10.54	3.5	23.7	9.2	9.0	9.0	43.9

Keeper to beam axis: 4.06 in.

8	10	2.02	10.11	3.37	24.7	10±2	3.2	3.2	47.1
- - - START 500 HOUR TEST - - -									
13-15	11	2.204	13.89	4.63	18.	12	47.1	47.1	94.2
16-19	12	2.72	12.52	4.17	19.9	13	66.5	113.6	160.7
19-20	13	2.6	11.71	3.90	21.3	12	14.3	127.9	175.0
21-23	14	2.42	10.9	3.63	22.9	12	47.3	175.2	222.3
23-24	15	2.45	11.51	3.84	21.7	12.5	22.6	197.8	244.9
27-30	16	2.51	11.78	3.93	21.2	13	78.4	276.2	323.3
8-9 July	17 ⁺	3.2	20.2	6.7	12.4	10	7.2	283.4	330.5
16-18	18*	1.51	9.07	3.02	27.6	13	33.4	316.8	363.9
19-21	19*	4.7	22.1	7.4	11.3	12	19.2	336.0	383.1
21-23	20	2.62	14.4	4.8	17.4	13	40.7	376.7	423.8
24-26	21	2.69	14.8	4.9	16.9	13	42.4	419.0	466.1
27-29	22	2.98	14.	4.7	17.8	12	53.9	472.9	520.0
30-2 Aug	23,24	2.56	11.5	3.8	21.7	13	29.3	502.2	549.3

For the 500 hour test as a whole, the values are

- -	11-24	2.76	11.00	4.33	19.23	12.5	-	502.2	549.3
-----	-------	------	-------	------	-------	------	---	-------	-------

⁺ See text

* Note: There is a possibility of error in weight measurement between runs 18 and 19. Values for the two runs taken as a whole are:

16-21	18,19	2.98	14	4.7	17.8	12.5	52.6	336.0	383.1
-------	-------	------	----	-----	------	------	------	-------	-------

An experiment was performed during Run 6 to determine a relationship between mercury efflux and neutralizer withdrawal. The thruster beam current was held at 250 to 260 milliamperes. Then for each of several boiler temperatures, the maximum stable value of collector current and maximum withdrawal distance of the neutralizer for stable coupling were noted. The results are shown in Figure 3.1-22 in which mercury efflux is plotted against the radial distance from the neutralizer keeper to the beam axis with corresponding collector potential at each point. Note that mercury efflux is given in three sets of units: equivalent milliamperes of Hg^+ , as a percentage of the estimated total mercury efflux of the thruster (300 milliamperes equivalent), and as the ratio of 250 milliamperes of electrons to the actual efflux rate. Values of mercury efflux were computed from boiler temperature measurements using the assumption that efflux is directly proportional to internal vapor pressure when neutralizer current is constant. For Run 10, et seq., with the accelerator at ground instead of -2000 volts, this function should be considerably different, but was not re-examined. The minimum change to be expected would be a shift of the curve to the right by $3/4$ inch in radial distance.

The 500-hour test was broken into a number of runs because of a variety of difficulties, mostly connected with the filament-type cathode used in the thruster but including liquid nitrogen flow failure and others. One vacuum failure allowed the neutralizer to be exposed to air pressure in excess of 200 microns while at operating temperature. When restarted, both the neutralizer performance and thruster cathode performance were poor; at this point Run 16 was terminated. During the first 4 hours of Run 17, the neutralizer was operated at higher than normal boiler pressure and rapid improvement to near normal neutralizer performance was observed, with full recovery by the end of the run. No run was terminated by failure of the neutralizer.

An enlargement of the cathode orifice over the 500-hour test from 0.0055 inch to 0.0065 was noted. In view of the low potentials involved, this is difficult to explain on the basis of ion bombardment, but it might

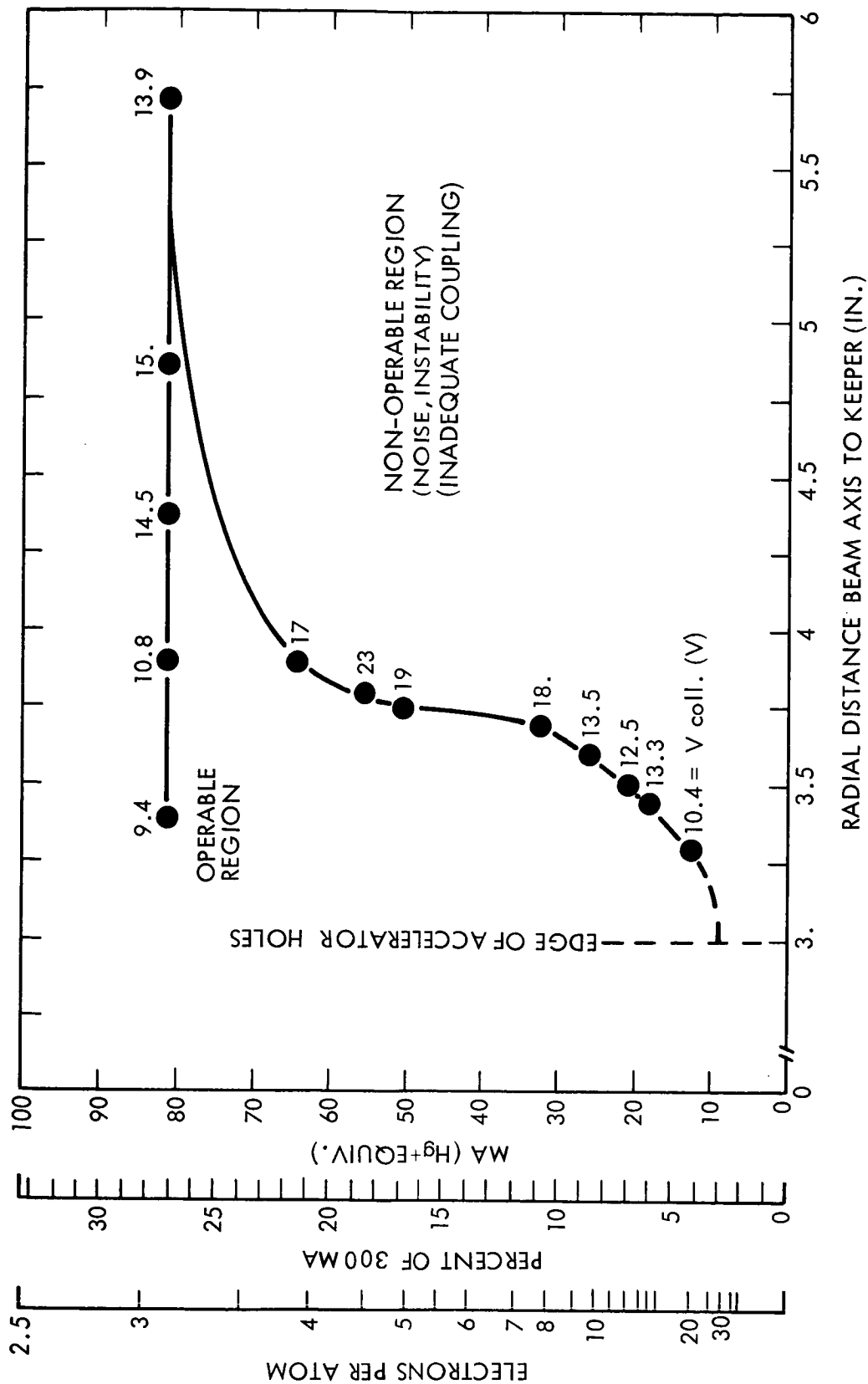


Figure 3.1-22. Mass Utilization Required for Stable Coupling Between the Neutralizer and the Beam as a Function of Neutralizer Withdrawal Distance. Values of the Maximum Stable Floating Collector Potential are Shown at Each Data Point. Neutralizer Axial Position is 7/8 Inch From the Accelerator Grid

be the result of evaporation of tungsten oxide from repeated exposures to air.

Overall performance for the 500-hour tests can be summarized as follows:

Neutralizer electron current	250 milliamps
Cathode heater power	25 watts
Keeper power	0.7 watts
Mercury efflux	13 milliamps (equiv.) 4.3% of .3 amperes 19.2 electrons/atom
Typical collector potential	13 volts
Milliamperes/watt	10

Following the 500-hour test, the S/N 2 and 5 cathode assemblies were encapsulated and sectioned for photomicrographic study. No results are available for the S/N 5 unit, inasmuch as the orifice region of the cathode was broken out during the sectioning process. Good pictures were made of the number 2 unit, however, and one of these is shown in Figure 3.1-23. The section through the cathode orifice is centered near the bottom of the figure. At the upper right and left one sees the keeper insulator (at middle right and left, a portion of one of the two shadow grooves is evident). Elsewhere in the picture the material is the alumina-powder-filled epoxy encapsulating compound or voids. The internal diameter of the keeper insulator is 0.035 inch. On this scale, the minimum orifice diameter at the end of all tests is 0.0065 inch; the thickness of the porous tungsten in the orifice region is 0.004 to 0.0045 inch. What appears to be a 45-degree chamfer on the right side of the orifice is known to have been chipped out during the polishing process. In the original photograph some light erosion on the outer face of the cathode is noticeable. The principal "wear" mechanism seems to have been rounding and slight enlargement of the edge of the orifice during the operating life of the device.

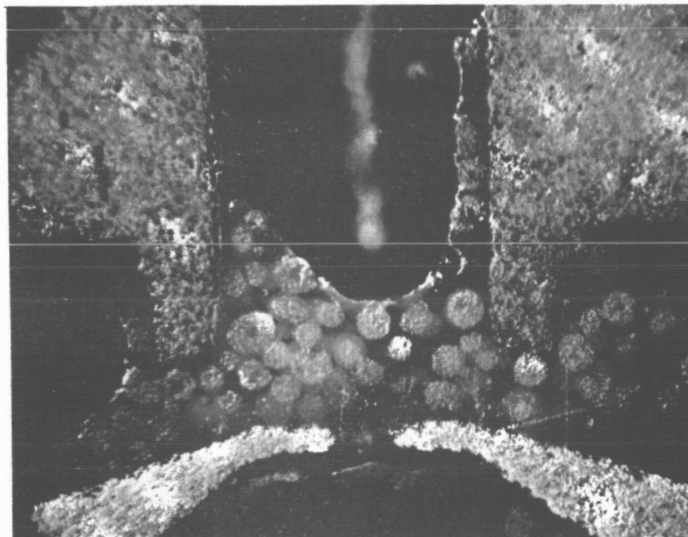


Figure 3.1-23. Photomicrograph of Section of the S/N 2 Cathode Showing Orifice Region and Portion of the Keeper Insulator.

3.1.6 Current Understanding of Discharge Neutralizer Physics

3.1.6.1 The Cathode Region

There are some notable similarities between the mercury discharge neutralizer and the liquid mercury cathode. Both can produce an arc discharge characterized by extremely high current densities, electrode potentials near or even below the ionization potential of mercury, and a bright spot associated with the seat of emission. Controversy among many eminent scientists about the physics of the mercury arc has persisted over the last 60 years, and many basic issues remain unresolved today.

A central point of controversy has been the electron emission mechanisms of the mercury cathode. Every known emission process has been seriously proposed: thermionic emission due to local heating, field emission due to intense space charge electric fields, Auger emission due to cathode bombardment by low energy ions or excited neutrals, and photo-emission due to the intensity of the spot illumination. Each theory has been proved and disproved owing to the paucity of fundamental and trustworthy data. Nonetheless, useful devices, including the mercury rectifier, have been made using this mysterious cathode.

It will therefore not surprise the reader to learn that we cannot conclusively identify the important emission mechanisms of the discharge neutralizer as a result of this device oriented program, however, two observations may be made: first, field emission would seem somewhat more favorable for a solid cathode than for a liquid because of the ever present possibilities of microscopic surface roughness and the attendant enhancement of electric field strength. Second, each of the possible emission mechanisms becomes more favorable with lowered surface work functions.

From a scientific viewpoint, the similarity of the discharge neutralizer and the mercury cathode has a very encouraging aspect. If the similarity is more than superficial, information and understanding gained on the neutralizer may be relevant to this historic problem. The neutralizer is experimentally much more tractable than the mercury cathode arc in that the spot location is fixed and mercury feed rates may be controlled

and measured. Plasma probing is easier than with the moving spot.

3.1.6.2 Bridge Region

The need for space charge neutralizing ions in the coupling region between the neutralizer and the ion beam has been previously discussed. In fact, the principal performance limitations of the device which have been encountered seem to result from an inadequate number of ions in the bridge.

Prior to operating the discharge neutralizers with an ion engine, it was expected that they would exhibit more favorable performance operating into the thrust beam than with a solid collector. This expectation was based on the knowledge that the engine was a source of charge exchange ions and neutral atoms, both of which ought to contribute to formation of the plasma bridge. These contributions were thought to exceed that of mercury atoms returning from a solid collector except when the keeper to collector spacings were so small that mercury was "bottled up" between these two planar surfaces.

Up until the final tests of the program -- the deliverable hardware tests -- neutralizer performance was somewhat poorer with a thrust beam than with a solid collector. However, when the -2 kV accelerator grid of the engine was partially electrostatically shielded from the neutralizer cathode and bridge region, a notable increase in the allowable value of x_c resulted. This increase, plus the previously observed erosion pattern on negative electrodes near the neutralizer seems conclusive evidence that during previous engine runs a significant number of bridge ions were robbed by these electrodes.

Although this shielding has lowered the necessary ion production rate, ion production is still a fundamental essential of the device operation. We are therefore interested in both the mechanism and the location of this production. Two mechanisms are possible: one-step ionization by collisions between neutral atoms and electrons with energies in excess of the ionization potential, and two-step cumulative ionization by collisions between excited atoms and lower energy electrons. The latter process is

believed to be important in some mercury pool cathode arcs, and could be associated with the low keeper potentials (~ 7 volts) occasionally observed.

Ionization by the two-step mechanism would only be expected in the luminous volume near the cathode since excited atoms do radiate photons. For ions produced near the cathode to proceed to the dark bridge space they must be subjected to a force in that direction. Their thermal energy, if it consists only of that gained from the $\sim 1000^\circ\text{C}$ cathode, is minute. Depending on the concentrations of neutrals and ions in the near vicinity of the cathode, a significant diffusion force could exist, abetted by the directedness of the atomic flow out of the orifice. Another possibility is a maximum in the plasma potential at the location where ions are produced such as has been observed with probes in the thermionic arc.⁶ Then ions could diffuse through the bridge under an electric field. Ionizing electrons which have given up some of their energy, and the new electrons which are the product of ionization and have little energy regain sufficient energy to diffuse against this field by interacting with energetic primary electrons.

If the bridge ions are produced in the bridge itself, then one pictures at least a slight axial electric field accelerating these ions toward the cathode. In the absence of plasma oscillations, the gradients in the bridge plasma potential would necessarily be slight indeed. Consequently, to account for the cathode to beam potential, V_c , a sheath would be required at one or both ends of this virtually unipotential column. Electrons traversing such sheaths would gain energy and become more efficient ionizers.

3.1.7 Conclusions

During the course of this program, experimental evidence has been gathered in support of the following conclusions:

- Barium impregnated porous tungsten dispenser cathodes are suitable for use as neutralizer cathodes. In particular, the low work function surface which they provide is not damaged by ion bombardment in normal operating conditions, and is easily recovered if damaged by exposure to air.

- A significant improvement in mass utilization efficiency was achieved by enclosing the region between the cathode and keeper with an insulating sleeve. Operation of the device is not impaired if the interior of the sleeve becomes a conducting surface so long as a direct short is not formed between the cathode and keeper (shadow grooves are able to prevent this from happening).
- Although an optimum size for the cathode aperture was not established in this program, reduction in orifice diameter from 0.005 inch to 0.002 inch resulted more in an increase in required vapor pressure than in an improvement in mass utilization.
- Operation of the neutralizer with a 15 cm electron bombardment ion engine was successfully accomplished for a cumulative period of over 500 hours. At the end of this test a small increase was noted in orifice diameter. The cause of this enlargement is not known -- it cannot be explained on the basis of ion bombardment erosion. A suggested explanation is that it is due to evaporation of tungsten oxide formed during repeated air exposures.
- Electrical coupling between the neutralizer and the thrust beam plasma from the ion engine was found to give low (9 to 15 volts) injection potentials with stable and relatively quiet operation when the following conditions simultaneously exist: minimum adequate mercury vapor efflux, minimum adequate keeper current, maximum allowable withdrawal from the beam, maximum allowable magnetic field, optimum cathode temperature, and maximum allowable extraneous electric field. Near a critical operating point, the neutralizer operation could be switched from stable operation to an unstable, noisy condition with high (50 to 300 volt) injection potentials. Suitable and unsuitable operating regions are readily observed if the entire engine thrust beam is collected on an electrically isolated surface having low capacitance to the thruster power supply common point.

- The final performance can be compared to the design goals as follows:
 1. The electron emission requirement of 250 mA was more of a constraint than a challenge.
 2. Electron production efficiency of 10 mA/watt is less than the goal of 15 mA/watt, principally because of the high (25 watt) heater power requirement of the large size cathode. Unfortunately, the time and contractual constraints of the program did not enable us to test the smaller type extensively.
 3. The goal of 9 mA equivalent mercury efflux (maximum) was occasionally achieved, but not consistently exceeded by a significant safety margin. In order to produce realistically meaningful results with respect to the eventual neutralization task, constraints not actually called for in the contract were imposed. These related to the maximum value and noise quality of the floating collector potential and to withdrawal of the neutralizer from the beam edge. Our experience, together with that at NASA Lewis Research Center, suggests that this goal is a realistic one, and potentially achievable.
 4. The potential life of the device is not easily predictable from our results, inasmuch as the maximum hole size at the "failure point" is not known. From the knowledge that such discharges have been obtained from cathode orifices larger than 0.010 inch, the operating life may well be over 3000 hours.
 5. No significant permanent effect of air exposure has been seen, unless the erosion is related to these events as discussed above.
 6. The type of neutralizer developed in this program is potentially capable of flight-hardware development. A first step in that direction would be the design of an enclosed keeper assembly for the smaller size cathode.

3.2 RESEARCH AND DEVELOPMENT OF AN ELECTRIC FIELD STRENGTH METER

A program of research and development has been conducted on an electric field strength meter (E-meter) of the linear strip variety. This basic design, shown conceptually in figure 3.2-1, is based on the use of a single hot wire filament as an electron emitter. The electrons are accelerated by the hood-grid structure and deflected in the space between the grid and the collecting plates by the externally applied electric field which is to be measured. Work done in development of this instrument was expended in several areas:

- Investigation of tungsten-rhenium alloy as a filament material
- Design and fabrication of breadboard power and signal conditioning circuitry
- Calculation of electron trajectories and development of design equations
- Fabrication of an E-meter and comparison of its performance with that predicted by the design equations
- Investigation of the effects of environmental factors such as magnetic fields and plasma particle currents on performance.

The first two of these items is discussed in 3.2.1 and 3.2.2. The remaining items are covered in the paper, "Electron Emissive Surface Electric Field Meters," by H. S. Ogawa, R. K. Cole, and J. M. Sellen, Jr. which has been published in The Review of Scientific Instruments. A reprint of this paper is included in Appendix A.

Some additional work, performed under a separate program, is reviewed in 3.2.3. It is included in this report because of its relevance to the problem of measuring the surface electric field strength on a spacecraft.

3.2.1 Investigation of Tungsten-Rhenium as a Filament Material

An obvious choice for filament material in an E-meter is, of course, pure tungsten wire. However, this material becomes notoriously brittle when operated above its recrystallization temperature, and this necessarily occurs when tungsten wire is used as an electron emitter. An anticipated requirement for any space flight instrument is that it be thoroughly tested prior to launch.

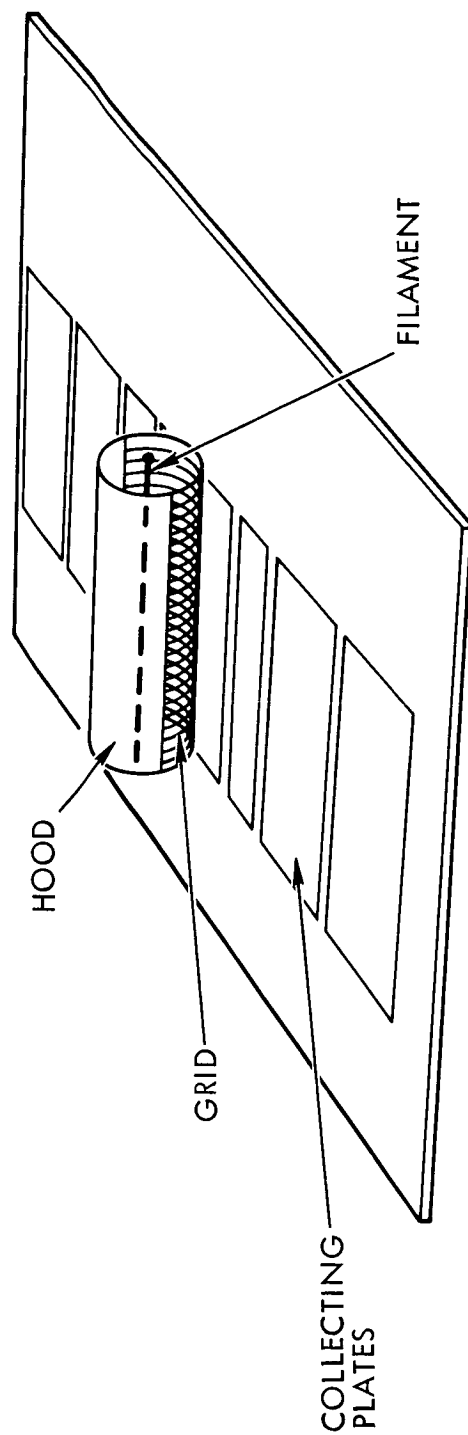


Figure 3.2-1. Linear Strip Electric Field Meter.

Hence, one is obliged to launch either an untested or an embrittled filament if tungsten is the filament material. This dilemma motivated the examination of the properties of tungsten-rhenium alloy.

Samples of 0.002-inch-diameter wire of tungsten-25% rhenium material were mounted in a developmental model E-meter and operated for various lengths of time. Certain conclusive results were readily obtained:

- The tungsten-rhenium wires remained ductile (could be bent without breaking) after having been heated to electron-emission temperatures.
- Because of higher work function and thermal emissivity, heating power requirement for the same size wire was roughly twice that of pure tungsten.
- Subtle changes were noted in wire performance over periods of hours.

In order to pinpoint the nature and causes of slow variations in filament performance, a series of diode experiments was run. A diagram of the apparatus is shown in figure 3.2-2. The filament is supported in a spring clamp held in synthetic mica mounted on a lava base. The central anode and the two guard electrodes are made of stainless steel; each is 1 cm in diameter and 1 cm long. Filament power is supported in the form of half-sine-wave pulses at 300 Hz; readings of diode currents are made during the intervals in which the longitudinal voltage drop in the filament is zero. Measureable quantities, as shown, are

V	anode to filament potential	V
V_f	filament heating voltage	V
i_f	filament heating current	mA
i_e	filament emission	mA
i_b	anode current	mA
i_g	guard electrode current	mA

The data shown in figure 3.2-3 were taken at one point during a 4-day accelerated aging test. During this period, the heating power to the filament was on continuously with the filament at a relatively high temperature ($\sim 2700^\circ\text{K}$). At intervals, the filament temperature was reduced to obtain three definite values of emission-limited current, and a set of data was taken

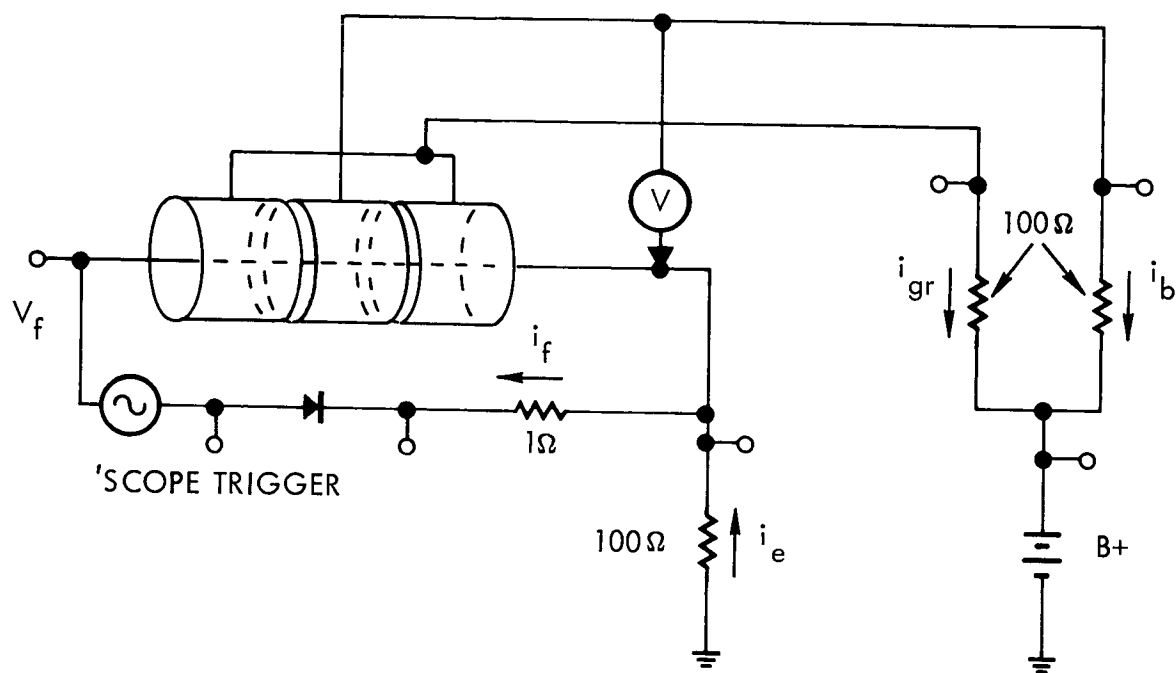


Figure 3.2-2. Diagram of Diode Experiment.

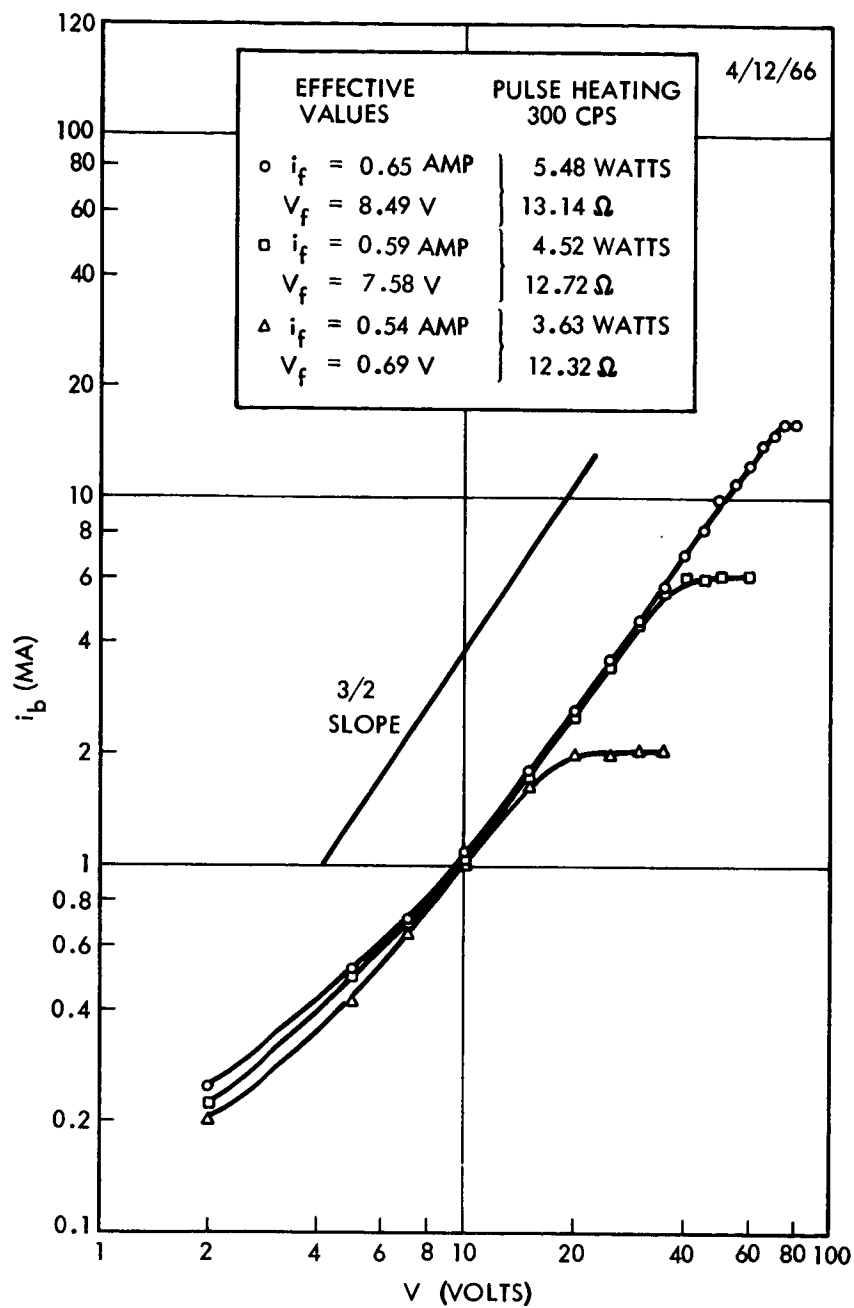


Figure 3.2-3. Diode Characteristics for Three Heating Power Levels.

at each point. One such set of data is shown. During the 4-day interval, although the characteristic curves remained unchanged, the filament operating point required to obtain the specified values of emission-limited current did not. Variations in filament heater power and filament resistance for three emission levels during the test are shown in the following tabulation. The heater power was seen to decrease for a given emission, although the filament resistance continuously increased. These results indicate either a decrease in work function, a decrease in emissivity, or an increase in resistivity of the filament material, or some combination of these factors.

Power Input (Watts)

<u>4/11</u>	<u>4/12</u>	<u>4/13</u>	<u>4/14</u>
5.87	5.48	5.088	5.070
4.89	4.52	4.192	4.127
4.056	3.63	3.351	3.350

Resistance (Ohms)

<u>4/11</u>	<u>4/12</u>	<u>4/13</u>	<u>4/14</u>
11.98	13.14	14.13	14.52
11.57	12.72	13.63	14.00
11.27	12.32	13.04	13.40

Examination was made of the filament after test. The most obvious effect was a change in diameter of the central portion of the wire from an initial value of 0.00225 to 0.00200 inch, a 20% reduction in cross section. The change in total resistance was from 11.98 to 14.5 ohms — an 18% change.

This test does not attempt to predict the aging rate for normal operation of filaments of this material. Inasmuch as the cold trap of the oil-pumped vacuum system was not in continuous operation, it is conceivable that some carbiding of the filament could have occurred. However, an increase in either the emissivity or the work function as a result of carbiding would have led to results opposite to those observed. During the test, the gas pressure

might have increased to the point where ion bombardment of the filament occurred. But for a pressure p of 10^{-5} torr, and electron path length $r = 0.5$ cm, the ratio of ions to electrons is given by

$$\frac{n_+}{n_-} = \sigma r p \approx 5 \times 10^{-5}$$

where σ is the electron-bombardment ionization cross section = 10 ions/torr-cm. It seems likely, therefore, that the observed effects were due to evaporation of rhenium from the filament.

The prediction of unacceptably short life (albeit inexact), together with the indicated instability of material composition and the heating power penalty, make tungsten-rhenium alloy a poor choice for the E-meter filament.

The diode characteristic as shown in figure 3.2-2 only approximates the $2/3$ power dependence expected from the perveance equation

$$i_b = KV^{3/2}.$$

If, however, the total interelectrode voltage

$$V = V_E + V_C$$

where V_B = applied voltage as read from a meter, and

V_C = contact potential and virtual source potential,

one may derive

$$i_b^{2/3} = K^{2/3}(V_B + V_C).$$

Hence, $i_b^{2/3}$ is a linear function of V_B provided V_C holds constant. Plotted in this way the diode characteristic indicates a V_C contribution of -2.5 volts. When this is added to the measured potentials, the experimental points as shown in figure 3.2-4, compare well with space-charge limited current values predicted by the Child-Langmuir equation

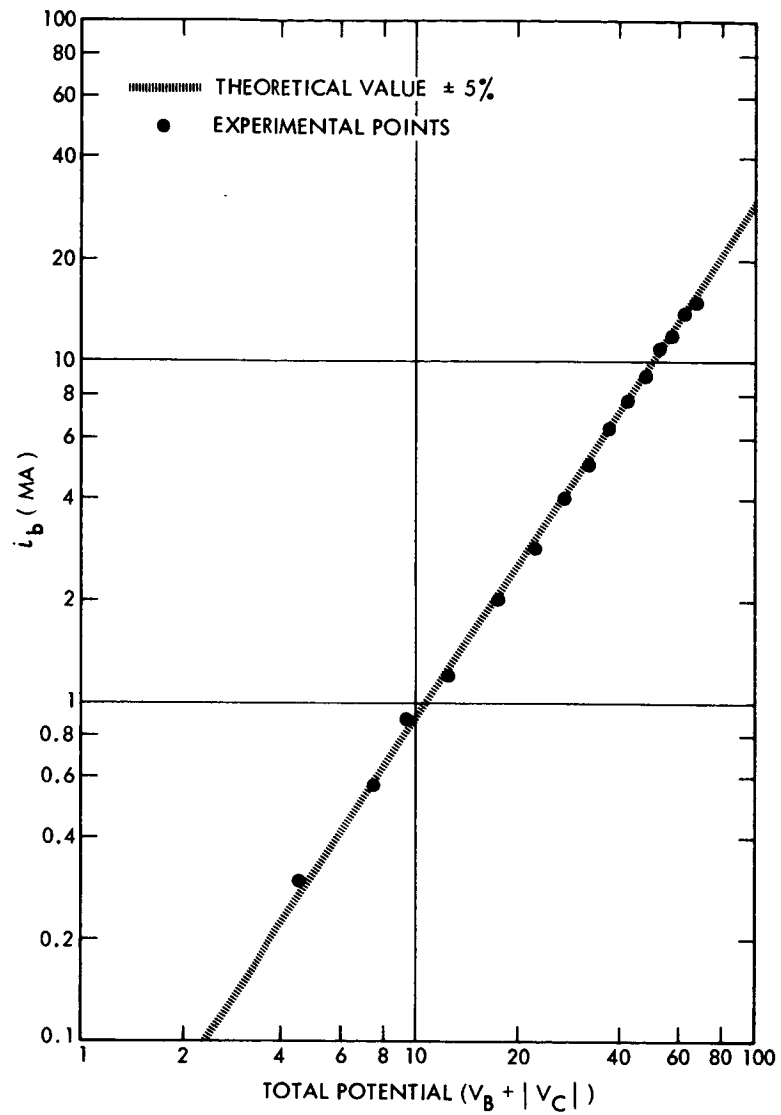


Figure 3.2-4. Diode Characteristic Corrected for Contact and Virtual Source Potential Contributions.

$$i_b = 2.34 \times 10^{-6} \frac{V^{3/2}}{r^2 \beta^2} A \quad (\text{amperes})$$

where

r = anode radius (cm)

β = Langmuir-Blodgett function for cylinders
(= $1 \pm .046$)

A = anode area (cm^2).

3.2.2 Development of E-Meter Power and Signal Conditioning Electronics

The goal of the electronic circuit design phase of the E-meter task was to develop an electronic package which would obtain all required power from the spacecraft power supply, provide for power and control requirements for the E-meter transducer of the generic type shown in figure 3.2-1, and supply appropriate analog signals to the spacecraft telemetry system. Specific requirements and constraints placed on the circuit design are:

- Spacecraft power is assumed to be 28 volts, nominal, dc.
- Filament heating power is dc, regulated on filament emission. Power is interrupted during measurement interval.
- Filament bias potential is -20 volts, dc.
- Signals from up to three sets of electron collecting plates are to be telemetered.

In order to check out the design of the system, a complete breadboard package was built. This was tested, first alone, then with vacuum tube diodes, and finally with an operating E-meter. A block diagram of the system, less power supply, is shown in figure 3.2-5. A clock and gate driver was included in the breadboard design, although it is expected that suitable signals for gating of the filament power and sample and hold circuits could be obtained from the spacecraft telemetry circuits or on-board computer. With timing pulses suitably synchronized to the commutator reading the amplifier outputs, it would likely be possible to eliminate the sample and hold also.

3.2.2.1 Filament Power Supply

It is important with this instrument to stabilize the filament emission. Accordingly, an emission regulator circuit has been incorporated in the filament power supply. Part of this circuit is a special control anode, a half cylinder 1 mm in diameter and 2 mm long located at one end of the electron-

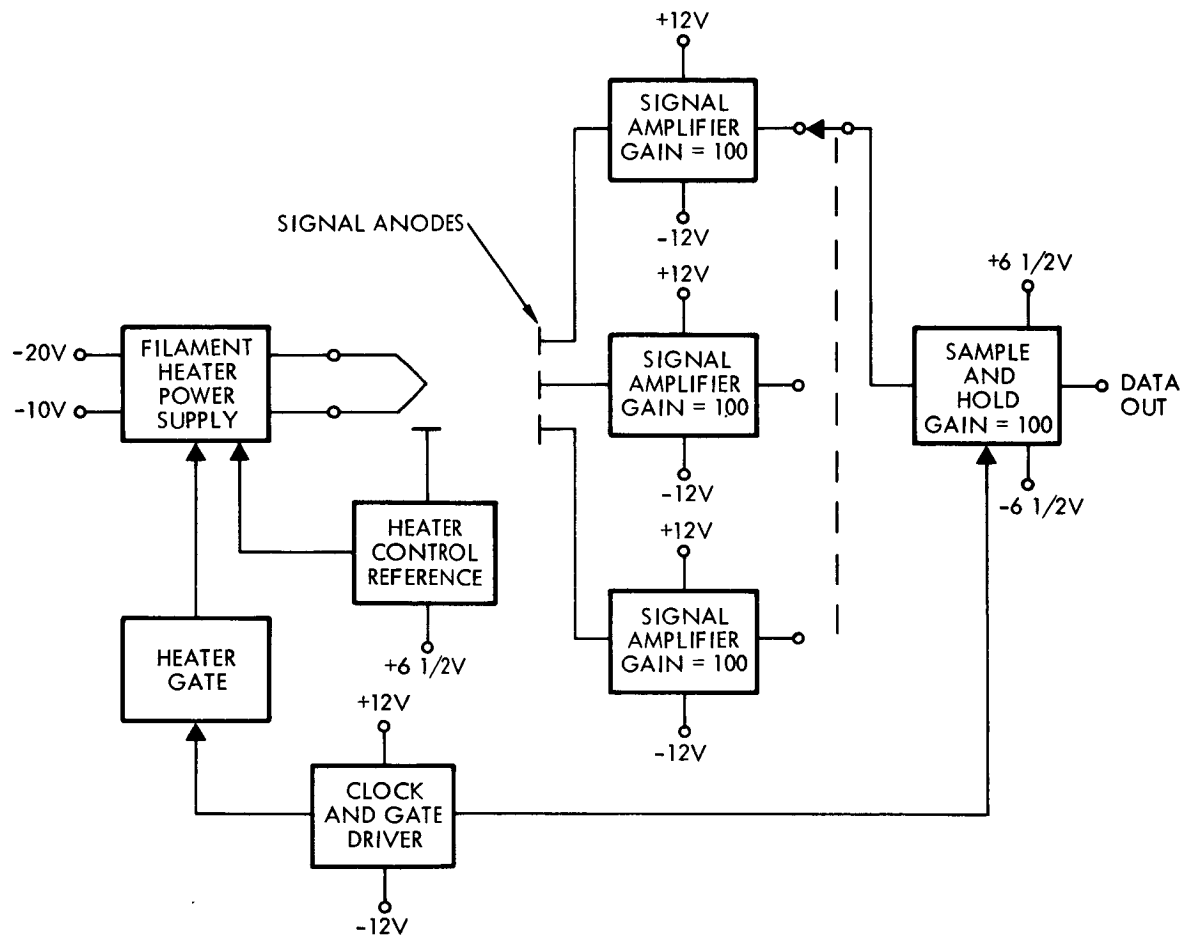


Figure 3.2-5. Block Diagram of Signal Conditioning Circuits for the Linear Strip Electric Field Meter

emissive portion of the filament. The spacing between the filament and this anode is much smaller than that between the filament and the accelerating grid. Thus it is possible to operate the filament at the minimum power level which causes it to run emission limited in the region of the small anode, and space charge limited elsewhere. This circuit is designed not only to provide additional stabilization against power supply voltage variations but also to adjust filament power appropriately to compensate for filament aging over its useful life. A schematic diagram of the filament power conditioner is shown in figure 3.2-6.

3.2.2.2 Amplifiers, Sample-hold, and Clock Circuits

A schematic diagram of the signal amplifiers, the sample and hold, and clock circuits is shown in figure 3.2-7. The amplifiers chosen for this breadboard circuit are integrated-circuit modules, Type SN 525A. The requirements of the circuits are sufficiently modest that any of several similar devices could be used. The timing of the filament blanking gate and measurement interval is a compromise among three factors: high filament power duty cycle, minimum sample and hold error between samples, and frequency response of the input amplifiers. As designed, the clock provides a 12V, 1 msec pulse to the filament power switch to turn it off. Between 80 and 100 microseconds after the filament is turned off, the sample-hold accepts a signal from the selected amplifier. The delay is necessary to permit settling of the input amplifiers following the transient caused by returning the filament bias to the -20 V level. During the remaining 900 microseconds, the sample-hold is permitted to settle. At the termination of 1 msec pulse, the filament resumes heating and the sample-hold retains the last level seen. Nine msec later the cycle repeats. Maximum data rate of the present design is about 25 Hz before aliasing becomes a problem.

3.2.2.3 Power Supply

The power supply schematic diagram is shown in figure 3.2-8. The design is conventional other than the short circuit protection provided for at the input series regulator. This feature is considered necessary to permit current limiting during cold starts of the filament. Peak power with a cold

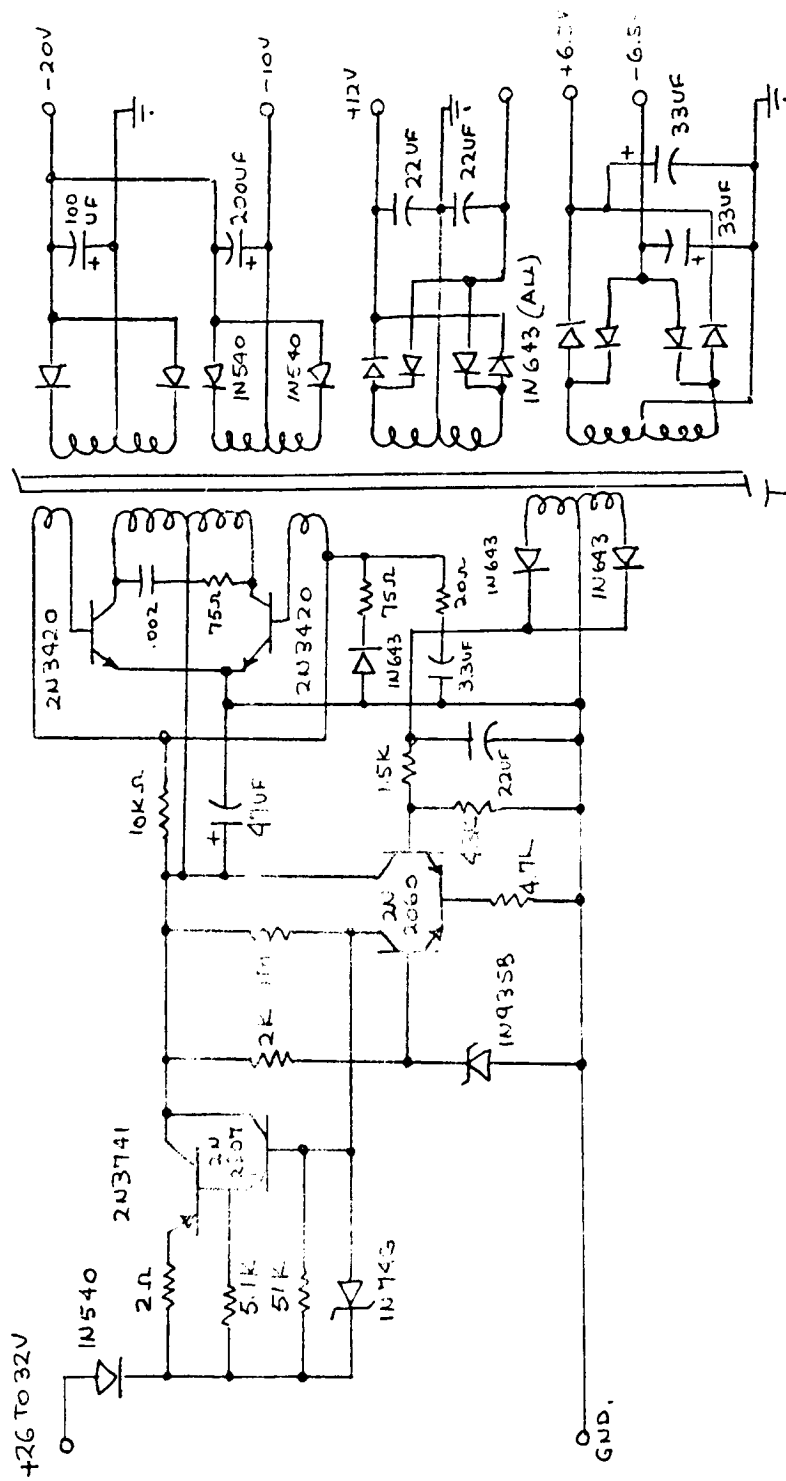


Figure 3.2-8. Power Supply.

filament at full voltage is 5 to 6 times the average operating power, and is inclined to induce premature failure of the filament through the development of a hot spot.

3.2.2.4 Breadboard Testing

The filament control portions of the circuit were tested with a standard radio type vacuum tube. Initial problems were encountered because of the long thermal time constant of the indirectly heated cathode. This was overcome in a special vacuum diode fabricated for the purpose which used a wire filament and an anode similar to the control anode in the E-meter. The breadboard circuit was also tested with an operating E-meter, but only to the extent of verifying that all circuits were operating as they had been designed to do.

3.2.3 Review of Recent E-Meter Development

The potential of an ion engine-propelled spacecraft may be driven negatively with respect to the ambient plasma if beam current neutralization is not adequate; it is unlikely that the spacecraft potential will shift very far in a positive direction. Hence, the useful range of E-meter sensitivity should coincide with a wide range of negative spacecraft potentials.

When the linear-strip E-meter was reviewed as a candidate for a particular spacecraft application, it became apparent that the range of sensitivity of this instrument for negative spacecraft potentials was inadequate. (In Appendix A, figure 3 of the Rev. Sci. Instr. reprint shows the negative values of E for $I_i/I_e = 0$ are much less than the corresponding positive values.) In other words, the electron beams within the instrument could be quickly swept away from the craft by this polarity of surface field.

A type of E-meter is currently under development at TRW Systems for use on a particular electrically propelled space vehicle, which retains the advantages of the linear strip instrument and also provides uniform sensitivity over the interesting range of spacecraft potentials. This work is being sponsored by the Aero Propulsion Laboratory of Wright-Patterson Air Force Base under Contract No. F33615-67-C-1141. The device can be described with reference to figure 3.2-9. A slab beam of electrons is generated by the negatively

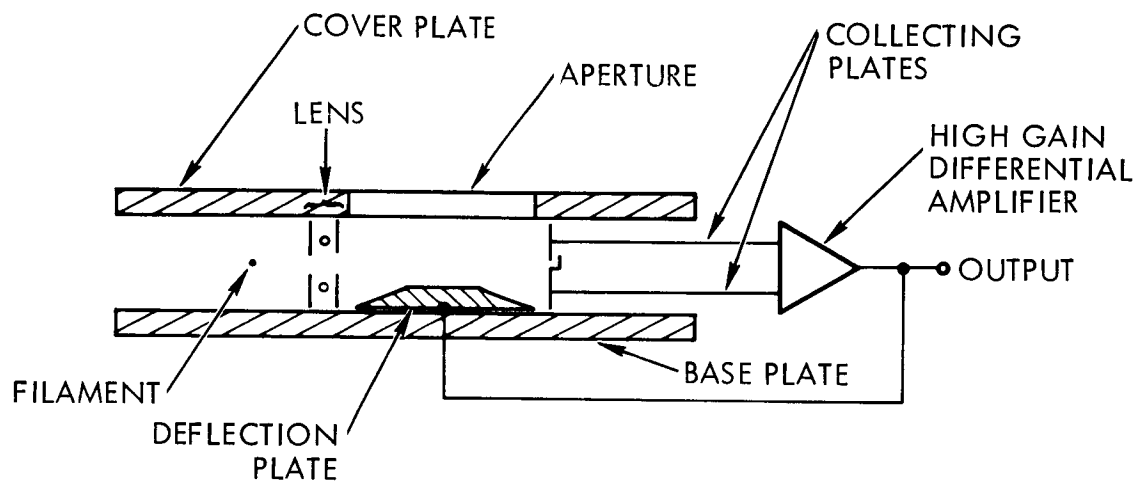


Figure 3.2-9. Electron-Beam, Null Deflection Electric Field Meter Developed Under Air Force Contract.

biased tungsten filament and the focusing electrodes. In the drift space between the grounded exit slit and the collecting anodes, the beam is subjected to the electric field which penetrates the aperture in the cover plate and to the counteracting field of the deflecting plate on the bottom. The potential of the deflection plate is controlled by a high-gain differential amplifier so that actual electron beam deflection is made very small. The deflection plate potential is thus almost directly proportional to the surface electric field to be measured, making data reduction very simple.

The present design of the instrument is such that a full-scale ± 10 volts on the deflection plate corresponds to -10 kV/m to $+15$ kV/m. The upper and lower plates and the sides of the instrument are made of annealed high-permeability iron alloy so that the transducer has a sensitivity to magnetic fields of about 0.1% of full scale per gauss. The instrument is, to first order, insensitive to variations in filament emission and electron beam drift velocity, and hence, no longer requires a tightly regulated power supply.

Transducer weight is 4 ounces; its volume is 1.3 cubic inches exclusive of connectors. The power and signal conditioning electronics are of nearly the same size and weight, exclusive of cabling. An entire system should be fully flight qualified by mid-1968.

3.3 BEAM NEUTRALIZATION TESTS AND SPACECRAFT DIAGNOSTICS

3.3.1 Ground Testing of Neutralizer Systems

The concept of testing spacecraft systems prior to launch is generally accepted in principle and widely applied in practice. At the present time, however, the proper method for ground testing the neutralizer system of an electric propulsion engine is not universally agreed upon and the test procedures used prior to space flights have varied widely. So also have the degrees of success achieved. In one instance, the SERT-I flight test of July 1964, a consistent sequence of research into ion beam diagnostics and the neutralization problem led to the design of neutralizer tests with a flight model engine. These tests verified the neutralizer design for the flight mission and accurately predicted the success obtained on the flight.² Perhaps similar tests would have revealed the problems on other flight systems when something could have been done to correct them.

3.3.1.1 Test Criteria

The fundamental principle of prelaunch testing is to simulate as nearly as possible the conditions of space flight operation and to require the given system to perform within design specifications under the simulated conditions. Therefore, in the simulation it is necessary to remove factors which could interfere with normal operation or mask an abnormal mode of behavior.

What then, is the situation to be simulated in ground testing of a thruster and its neutralizer system? A spacecraft in orbit is an electrically isolated body, immersed in a very dilute plasma. It has a definable capacitance to its environment.

The thruster ejects a current of ions into the ambient plasma which were created within the engine by stripping propellant atoms of electrons. The resulting electron current loop is closed through the accelerating voltage supply with the electrons returned to the beam by the neutralizer. Recombination takes place at some indefinite distance far removed electrically from the thruster. Considerations of thrust efficiency and of compatibility

with on-board experiments require that the potential of the spacecraft not depart markedly from that of the ambient plasma. This, in turn, makes the well-recognized requirement for current neutralization of the thrust beam a very stringent one, for it demands that the match between the neutralizer current and the ion beam current be held within one part in 10^6 for periods on the order of 1 millisecond, and closer than that for longer periods of time.

Any real ion beam source has a current $I_B = f(t)$ which is not simply pure dc. Typically, it has an average value which differs from its design value and an alternating component comprising frequencies from near zero up to hundreds of kHz. Depending on the type of thruster and its operating condition at a given moment, the noise amplitudes in the beam current can be significant fractions of the nominal dc value. In space flight operation some mechanism within the neutralizer system must act with sufficient gain and rapidity to assure that the neutralizer current function of time is the same as the beam current function within the above criteria. Hence, a meaningful test of a neutralizer system should both allow and require that such an emission control mechanism be operative.

In all neutralizer systems that have been devised, the one mechanism that ultimately must be relied on to match the neutralizer current to the beam current is the space-charge-limited emission of electrons from either a real or virtual electron source. Accordingly, the task of other control loops is to assure that the maximum emission capability of the neutralizer is sufficient (but, for economy, not much more than sufficient) to match the peak demands of the ion beam current.

In the context of the previous remarks, the various types of thruster test facilities in current use may be discussed.

3.3.1.2 Grounded Collector - No Neutralizer

The simplest of these facilities is, of course, a solid metallic vacuum enclosure, at "ground" potential, into which the beam is discharged. Operation of a thruster in such a facility is sometimes spoken of as operation without beam neutralization. A more accurate description would be operation with "collector neutralization", inasmuch as the electron current loop

is closed by returning the ionizing electron current to ground through the high-voltage supply and by recombination at the collector surface. Space charge neutralization in such a situation is achieved by a trapped colony of relatively "cool" electrons maintained by secondary emission. This method of testing, represented in figure 3.3-1a, is not a neutralization test in any sense, of course, but in many cases successful thruster operation can be achieved in this way and many aspects of the thruster, other than the neutralizer, can be tested.

3.3.1.3 Grounded Collector - Biased Neutralizer

Figure 3.3-1a has identified the closed current path for neutralizing electrons in a facility which does not include an electron emitter. It is now conceivable to superimpose another independent closed current path in the same facility by placing an electron emitter somewhere within the enclosure and biasing it negatively so that it emits electrons capable of reaching any grounded surface within the chamber. This situation is represented in figure 3.3-1b. By adjusting the neutralizer bias supply, the neutralizer emission I_N may be made approximately equal to the beam current I_B , although in any case it will not contain the full amplitude of the oscillating components. If the electron emitter is placed much closer to the ion beam than it is to any surface at ground potential its superimposed current will be less "independent" than it might be otherwise. Nevertheless, it is readily observed from oscillographic records of neutralizing and beam current functions that the intimate correspondence of waveform which will eventually be required in the space environment is not obtained in this mode of testing.

The reasons why the grounded collector-biased neutralizer configuration does not provide a meaningful neutralizer test may be stated in several ways. The most obvious is to point out that the neutralizer emission is not under control of the beam but of the knob on the low-impedance bias supply. If the neutralizer emission is or becomes inadequate, engine operation goes on as before and the system falls back on collector neutralization. On the other hand, it is inconceivable that neutralizer emission current away

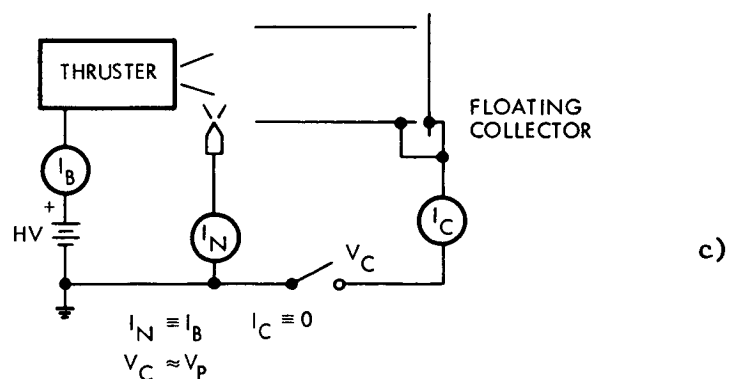
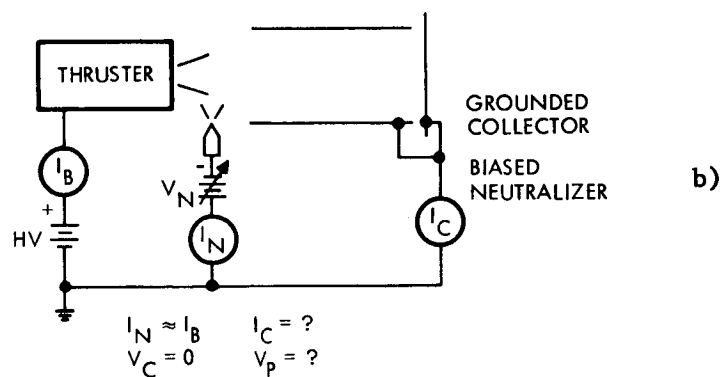
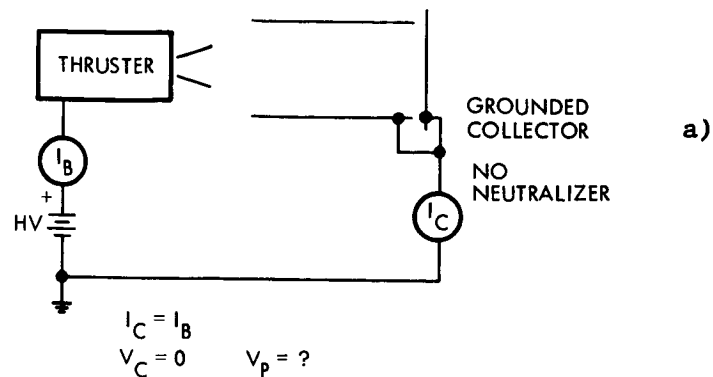


Figure 3.3-1. Schematic Representation of Three Types of Electrostatic Thruster Tests. a) Current Neutralization by Recombination at the Collector b) Superimposed Current Loops Leave Degree of Collector Neutralization Undetermined c) A Stringent Simulation of Spacecraft Operation.

from a spacecraft could exceed ion beam current for any appreciable length of time. But by turning up the knob on a biased neutralizer with grounded collector the neutralizer current can be made greater than the beam current continuously. Another way of stating the case is that with a neutralizer biased negatively with respect to the tank walls as well as to grounded parts of the thruster system, there is no way of knowing how many electrons from the neutralizer go directly to the nearest grounded surface without contributing to the space-charge neutralization of the beam. In other words, in the superimposed-current-loop situation it is impossible to do accurate "bookkeeping" on the neutralizer electrons, and I_C is undetermined. Ordinarily, in such a facility one cannot place a meter as shown in the figure for measuring the total current to all the grounded surfaces exposed to the ion beam. This measurement was made on the SERT-II life test facility at TRW, instrumented as in figure 3.1- . When $I_N \approx I_B = 250$ mA it was found that 175 mA more ions than electrons were going to ground through the collector with an equivalent excess of electrons collecting on two tank liners. In yet other words, with the grounded collector - biased neutralizer mode of testing, there is no accurate way of determining under what conditions the neutralizer emission and coupling to the beam are adequate and when they are not, i.e., a measurement of V_p is not provided.

Preferable methods are available for thruster testing, and the launching of an electrically propelled spacecraft which relies only on this kind of test for qualification of its neutralizer system involves a risk much greater than necessary.

3.3.1.4 Floating Collector

In the floating collector mode of thruster testing, the thruster power supplies, neutralizer supplies, and laboratory instrumentation all have a common "ground" at the potential of the vacuum chamber walls. The testing chamber is fitted with a thrust beam collector at the far end of the tank, and, usually also, the walls of the tank are shielded from the beam by one or more cylindrical liners (which may also be used for cryogenic pumping). The collector and liners are insulated from the tank ground and may be used either

for current measurement or floating potential measurements. When electrically isolated, the floating elements assume a potential at which the net current from all sources is zero. This situation is depicted in figure 3.3-1c. Although the collector and shrouds are shown tied together for the purpose of measuring one value of V_C , the test criterion is not changed if these elements are separately isolated. Because the collector neutralization current loop has been broken and the only source of electrons in the facility is the neutralizer, the collector potential will have a constant value near the neutralizer potential only when the neutralizer current continuously matches the beam current as it will be required to do in space.

The floating collector potential was identified as a close approximation to the neutralized plasma potential during a series of pulsed beam experiments on ion beam neutralization in 1961.⁷ Later, using the SERT-I thruster, in another series of pulsed beam experiments,⁴ it was shown that ion trajectories were almost identical before and after the first ions in the beam had reached the floating collector. In all these experiments, an automatic correspondence between neutralizer and beam current correlates with stable, quiet values of collector potential near the neutralizer potential. As discussed below, as the neutralizer is withdrawn from the edge of the beam or the vaporizer is cooled the transition between adequate and inadequate coupling is not smooth and continuous as with hot wire neutralizers but switches abruptly from one condition to another and hence clearly defines useable and non-useable regions. The floating collector potential is a sensitive (often spectacular) indicator of the occurrence of these transitions. The kinds of data that can be obtained with a floating collector: stable, low-voltage plasma potential, automatic correspondence between beam current and neutralizer emission, definite indications of when these conditions obtain and when not, are the kinds of data on which confident predictions of the space behavior of neutralizer systems can be based.

3.3.1.5 Floating Thruster System — Grounded Collector

An alternative to testing a thruster with a floating collector is to discharge the thrust beam into a grounded enclosure from a thruster-neutralizer-power supply system, all of which is isolated from ground.

Now "payload" potential is the significant measured variable. In this case, if the beam were well neutralized the thruster common node would float near ground potential; if not, the potential of this node would drop negative by as much as the value of the high-voltage supply. This method is equivalent to the floating collector method in that only one current path for the neutralizing electrons exists namely, through the neutralizer and recombination at the (electrically isolated) physical boundary. Indeed, this configuration is a direct analog of the isolated spacecraft.

Certain special requirements must be met in testing an isolated thruster. For one, the power derived from the laboratory mains must be coupled to the thruster system and floating instrumentation by a transformer insulated for more than the ion acceleration voltage. High voltage protection is required for personnel operating the floating instruments. Perhaps the most difficult requirement is that the total capacitance to ground of the entire floating system must not exceed a few thousand picofarads. There are two reasons for this requirement: first, the capacitance to space of the isolated spacecraft will be in this range, and second, experience with the floating collector method of testing the 250 mA thruster indicates that the neutralizer coupling problem is made very difficult if the capacitance of the floating collector to ground exceeds about 4000 picofarads. Inasmuch as the thrust beam plasma is intimately connected to the collector potential, an excessive capacitive coupling back to the thruster common node introduces a time lag in the response of the plasma potential to minute discrepancies between beam and neutralizer currents and causes the system to become unstable.

The problem of isolating a thruster system from the laboratory electrical supplies is much less difficult in the case of a flight package. Accordingly, the floating payload method, used in as large a facility as possible, is the logical choice for thermal-vacuum preflight testing of a complete thruster-neutralizer system.

3.3.2 Spacecraft Diagnostics

3.3.2.1 Electrical Equilibrium Conditions for an Isolated Spacecraft

The conditions which affect the magnitude and character of the electrical equilibrium which may be established between an isolated spacecraft and its environment have been examined by Sellen.⁸ That discussion considers two classes of spacecraft — active and passive. Of the active class, i.e., those which can actively influence the equilibration process, electrically propelled spacecraft are the most prominent. This is because the level of the particle beams which they discharge into the space plasma may range many orders of magnitude above the normal level of charged particle exchange between a passive spacecraft and the ambient plasma. Measureable quantities of the equilibrium conditions are the potential differences, electric fields, and the stability of these quantities. These aspects of the electrical equilibrium are of crucial importance in the context of future applications of electric propulsion to vehicles engaged in the collection and interpretation of scientific data.

During the period of development of electric thrusters, in only two instances have measurements been obtained of the electrical equilibrium between the craft and its beam or its environment. One was a ballistic shot in which, because of neutralizer inadequacy, the spacecraft to plasma potential was shown by an E-meter on board to be over 1000 volts negative. In the other instance, the SERT-I flight test, also a ballistic shot, measurements of spacecraft dynamics and electrical measurements on the thruster system establish that the spacecraft potential was equal to the plasma potential within about 250 volts (see Reference 9, Section C). A rotating-vane E-meter on this craft was shown to be strongly affected by the presence of dilute plasmas of the densities encountered in the space flight. Nevertheless, an interpretation of data from this instrument suggests (but does not confirm) that the potential may have been between 20 and 40 volts positive (Reference 9, Section D). This degree of uncertainty is sufficient to compromise in whole, or in part, many of the particle detection experiments which are of interest in current scientific missions.

A possibility of reducing this uncertainty exists in the forthcoming SERT-II flight. While the principle emphasis of this test flight will be the demonstration of long term operation of electric thrusters in space, it remains that this vehicle will provide the only direct precise measurements of vehicle equilibrium conditions for a period of several years. Hence, future scientific missions contemplating the use of electric thrusting units must rely heavily upon this flight test for information on the in-flight compatibility between electric propulsion and a scientific payload. The only other projected measurement of any similarity is the possible measurement of the floating potential of isolated booms (cold probes) on an ATS-series spacecraft.

3.3.2.2 Spacecraft Diagnostic Instrumentation

There are two principal instruments which have evolved for diagnostic measurements of the electrical interaction of a spacecraft with its environment. These are the electron-beam deflection electric field meter discussed in Section 3.2 and the hot-wire electron emissive probe which is discussed below. Following that discussion, a comparison is made of the range of applicability of the two instruments.

During the early portion of this program, a breadboard circuit was built and tested for operating a floating hot wire emissive probe over a voltage excursion greater than 200 volts. The objective in designing this circuit was to develop an instrument for measuring the plasma potential within the thrust beam of an electric thruster, or the potential of the ambient space plasma, with respect to the spacecraft surface. In this circuit, the emissive filament was connected to the secondary winding of a filament transformer and heated by square-wave ac current to an electron emissive temperature. The single other connection to the secondary winding was made to one input of a high-input-impedance differential amplifier. The other amplifier input was connected to the output of a voltage-controlled dc inverter circuit, and the output of the amplifier was used as the controlling voltage. Thus, the output of the dc inverter was made to follow the probe potential within the design range of the circuit, and in principle,

could be scaled with passive circuitry to match the input requirements of a spacecraft telemetry system. The input impedance of the breadboard circuit was about 7000 megohms; its voltage range extended from below zero to over +200 volts. This range was specifically selected to provide a resolution of the ambiguity remaining from the SERT-I experiment.

Each of these instruments — the electron-emissive probe and the electric field meter — has its own region of applicability, the critical parameter being ambient plasma density. In Reference 4, it is shown that for plasma densities between 10^6 and 10^{10} cm^{-3} the hot wire probe sheath is small compared to typical probe dimensions, and Langmuir probe currents are small compared to ion currents (in streaming plasmas); with some difficulty, measurements can be made one or two orders of magnitude in density outside of this range. On the other hand, it can be shown that, depending on vehicle size and potential, and to some extent on plasma electron temperature, a significant enhancement in surface electric field¹⁰ for a given potential will occur in plasma densities over about 10^4 cm^{-3} because of the nearness of the plasma sheath boundary to the spacecraft surface. Accordingly, the emissive probe would seem to be best suited to measurements of plasma potential in the ion thrust beam or in the ambient plasma of a spacecraft orbit within relatively dense regions of the ionosphere. The E-meter appears to be particularly well suited to measurements of surface fields in deeper regions of space (e.g., synchronous altitudes and beyond). For highly elliptical orbits, a spacecraft might suitably be equipped with both kinds of instrument.

Inevitably, the calibration of an E-meter for a particular spacecraft use will involve in situ measurements of E-meter response as the spacecraft potential is varied with respect to that of some other surface in a vacuum enclosure. Such testing can, at best, only approximate the eventual flight geometry, and the desirability of having both kinds of diagnostic probe on a given spacecraft is obvious, for the purpose of cross-checking between the two instruments and of checking the calculated field enhancement factors against flight conditions.

3.4 CONSIDERATIONS IN LONG LIFE THRUST BEAM COLLECTOR DESIGN

This section discusses some of the design considerations involved in the provision within a ground testing facility for the capture and disposal of the propellant mass ejected in the thrust beam of an electric propulsion engine. For the sake of continuity and clarity as to the aspects of the problem which are being considered, this discussion is set in the context of a fairly specific example. The type of test in mind is one in which an ion thruster using either cesium or mercury as propellant is to be operated for a period of something like ten thousand hours at a specific impulse of 5000 to 8000 seconds and a thrust level in the neighborhood of 10 to 100 millipounds. During the course of such a test, many thousands of ampere-hours of charged particles will be delivered to the collector at energies of several thousand eV per charge.

Several primary considerations in the design of a thrust beam collector for ground testing of medium to high power electric thrusters may be enumerated:

- Collector durability for extended life tests
- Contamination of the thruster or of the facility by erosion products
- Dissipation of incident beam power
- Fabrication and operating cost

These factors interact to a considerable degree, and all are related to the basic problem of sputtering erosion of the collector surface material by the high-energy thrust beam ions.

3.4.1 Collector Durability

Sputtering erosion is the dominant mechanism for collector deterioration for high velocity exhaust streams (specific impulse of 600 sec and above). An appreciation of the magnitude of the problem can be gained by the following calculation.

The mass of material removed from the target is given by

$$\Delta M_2 = n_1 Y_{1,2} m_2$$

where,

ΔM_2 = mass of target eroded by sputtering

n_1 = number of impinging particles

$Y_{1,2}$ = sputtering yield of target per impinging particle

m_2 = mass of target atom

If the impinging particles are electrically charged, the number of incident particles has the electrical equivalent

$$n_1 = \frac{I_B \tau}{dq_e}$$

where,

I_B = beam current

τ = test duration

d = degree of ionization, i.e., electronic charge per particle

q_e = electronic charge

Then

$$\Delta M_2 = \frac{I_B \tau}{d q_e} Y_{1,2} m_2$$

For singly charged ions $d = 1$ and for colloidal particles, d is of the order of 10^{-3} . The remainder of the discussion relates to ions and d is dropped.

The volume of material removed from the target is

$$\Delta V_2 = \frac{I_B \tau}{q_e} Y_{1,2} \frac{m_2}{\rho_2}$$

where

ρ_2 = density of the target material.

One may also define the atom density in the target as

$$n_2 = \frac{\rho_2}{m_2} \quad (\text{atoms/cm}^3)$$

from which

$$\Delta V_2 = \frac{I_B \tau}{n_2 q_e} Y_{1,2}$$

Inasmuch as all common structural materials have the same number of atoms/cm³ (within about a factor of 2), and sputtering yields in the range of interest are roughly 5 atoms/ion, an estimate can be made of the volume of target material eroded by the integrated incident beam as follows:

For 10⁴ ampere hours

$$\Delta V \approx \frac{5 \times 3.6 \times 10^7}{1.6 \times 10^{-19} \times 5 \times 10^{22}} \approx 2 \times 10^4 \quad (\text{cm}^3)$$

Stated in another way, the target erosion depth is of the order of 2 cm for an exposure of 1 ampere hour/cm².

The mass removal for the same 10⁴ Ah exposure is

$$\Delta M_2 \approx 20 \times 10^3 \rho_2 \quad (\text{grams})$$

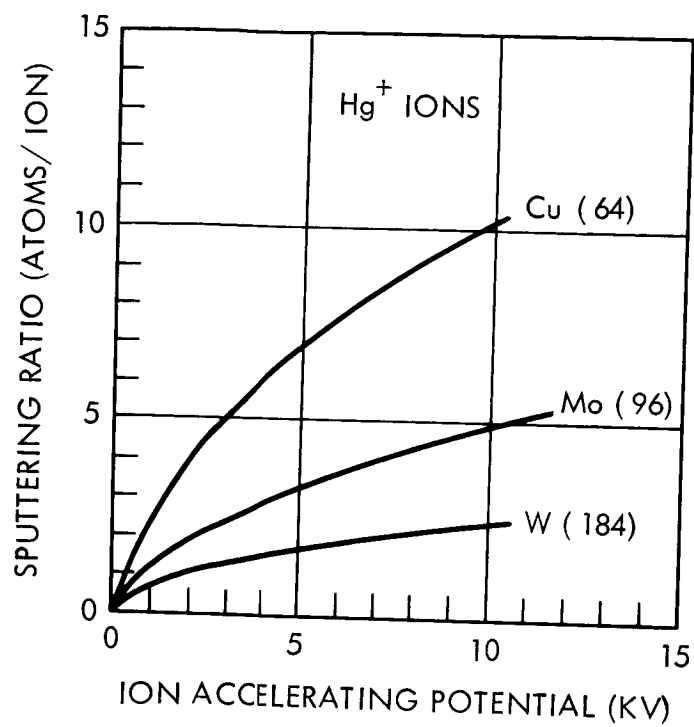
While these results will vary considerably with target material and particle velocity they show that durability is not a critical factor for engine tests of several kilowatt years integrated beam power. Calculations for representative target materials are given in Table III, and figure 3.4-1.

Granted that ion beam collectors may be made sufficiently durable for extended tests, the problem remains of the arrival of collector material at the thruster location. The next few paragraphs consider the phenomenon of back sputtering and means that have been suggested for minimizing its effect.

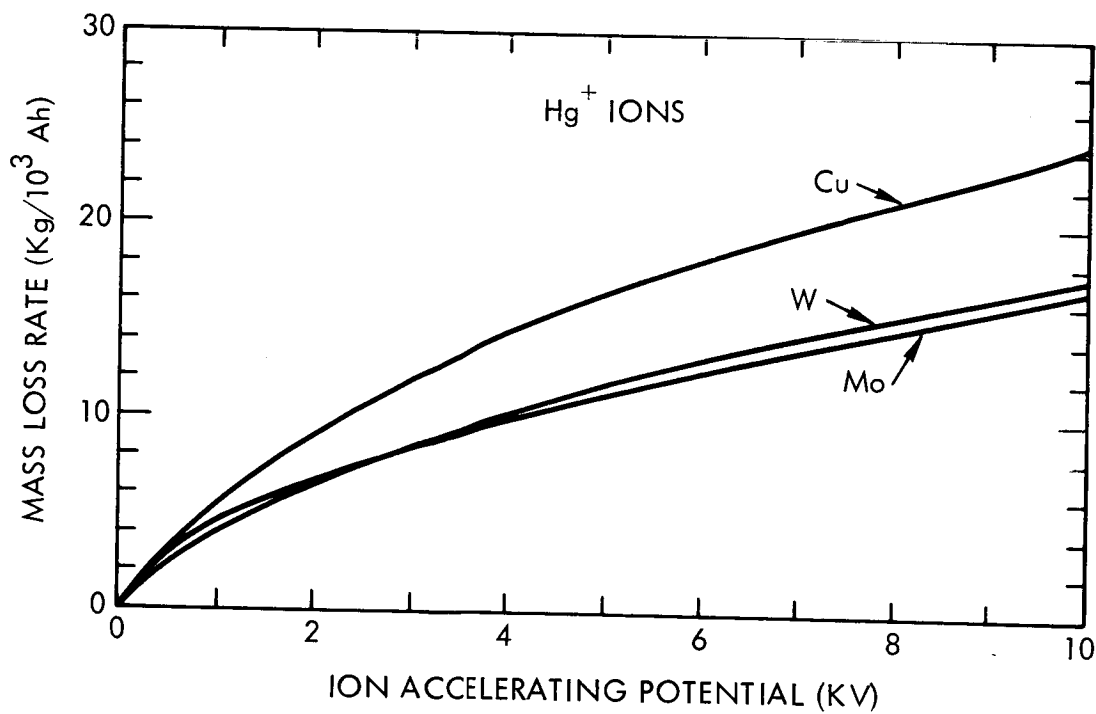
TABLE III. Weight and cost of possible target materials. Weights are estimated for a plate 1" x 48" x 48".

<u>MATERIAL</u>	<u>TARGET WEIGHT (kg)</u>	<u>APPROX. COST (\$/kilogram)</u>
Copper (OFHC)	337.3	2.55
Aluminum (6061T6)	102.3	2.01
Nickel (200)	343.2	4.07
Lead	409.1	0.88
Beryllium	70.5	605.00
Titanium (6AL4V)	170.9	11.55
Tin	204.5	5.50
Molybdenum	424.1	105.60

Note: Costs based on prevailing price per pound and do not include cutting charges or minimum mill run quantities. Some materials not ordinarily available in indicated size. Beryllium is listed because of its known low sputtering yield, but is ruled out on cost and health hazard considerations.



a)



b)

Figure 3.4-1. Sputtering Ratio (a) and Mass Loss Rate (b) for Three Target Materials as Functions of Accelerating Potential of Bombarding Mercury Ions.

3.4.2 Back Sputtering and Its Attenuation

The material sputtered back toward the engine is determined by the sputtering yield, the angular distribution of ejected material, and the distance from the target to the engine.

The amount of material deposited on the engine by back sputtering from a flat collector can be found from the geometry. Since the maximum-to-average ratio for a cosine distribution is 2:1, and the volume-to-area ratio of back-sputtered material gives the thickness of material deposited, this thickness at the thruster location is given by

$$S = \frac{V}{A} = \frac{2 \Delta V_2}{2 \pi r^2}$$

Using our previous result, this is

$$S = \frac{I_B \tau Y_{1,2}}{\pi r^2 n_2 q_e}$$

The previous estimate of $2 \times 10^4 \text{ cm}^3$ of sputtered material per 10^4 amp hour of beam results in a layer thickness of

$$S \approx \frac{7 \times 10^3}{r^2} \quad (\text{cm})$$

Taking, as an example, $r = 200 \text{ cm}$, one has $S \approx 0.2 \text{ cm}$ for 10^4 amp hours.

This is clearly a serious problem in terms of engine fouling and at least an order of magnitude reduction is desired.

The simplest approach to limiting back sputtering is to place the collector at some distance from the engine and to depend on separation for the needed attenuation of back-sputtered material at the engine. In a long test, the required distance becomes appreciable and possible alternatives to distance attenuation need to be considered. One such alternative is the louvered collector, in which the collecting surfaces are presented at other than normal incidence in an attempt to reduce the flux of sputtered material directed toward the engine. The honeycomb collector is an example of this approach. Another possible alternative is the decel-collector, in which

energy is removed electrically from the ions in order to reduce their sputtering yields at impact.

The relationship between sputtering yield and incidence angle is the crucial factor in the evaluation of these alternatives. Simple scattering theory^{11,12} predicts that at kilovolt energies the absolute sputtering yield should behave approximately as

$$Y_{1,2} = \alpha \frac{E_m}{\lambda(E) \cos \theta}$$

where,

α = a proportionality constant chosen to fit the experimental data

$$E_m = \frac{4 E_1 (m_1 m_2)}{(m_1 + m_2)^2} = \text{Maximum energy transfer by collision between the incoming and target particles}$$

$$\lambda(E) = \frac{1}{\sigma(E) n_2} = \text{Mean free path in the target for incoming particle}$$

θ = angle between incoming trajectory and the normal to the target

Both experimental data and theory indicate that the collision cross section $\sigma(E)$ tends to follow an inverse relationship to particle velocity, i.e., the probability of interaction is proportional to the time spent near the target atom. Since incident ion velocity v_1 is proportional to $E_1^{1/2}$ the resultant equation is

$$Y_{1,2} = \frac{\alpha E_m n_2 \sigma_0 (E_1/E_0)^{1/2}}{\cos \theta} = c \frac{v_1}{\cos \theta}$$

That is, for a given combination of propellant and collector the sputtering yield is proportional to the particle velocity and varies inversely with the cosine of the incident angle. One interesting consequence of these relationships is that the collector erosion is proportional to the total impulse delivered by the engine and independent of I_{sp} , thrust level, or engine-to-target distance. Further consequences are that the collector erosion increases rapidly with θ and that the amount of material sputtered back along the incoming path is independent of angle. This is illustrated in figure 3.4-2 which shows the situation for normal incidence (0 degrees) and for some

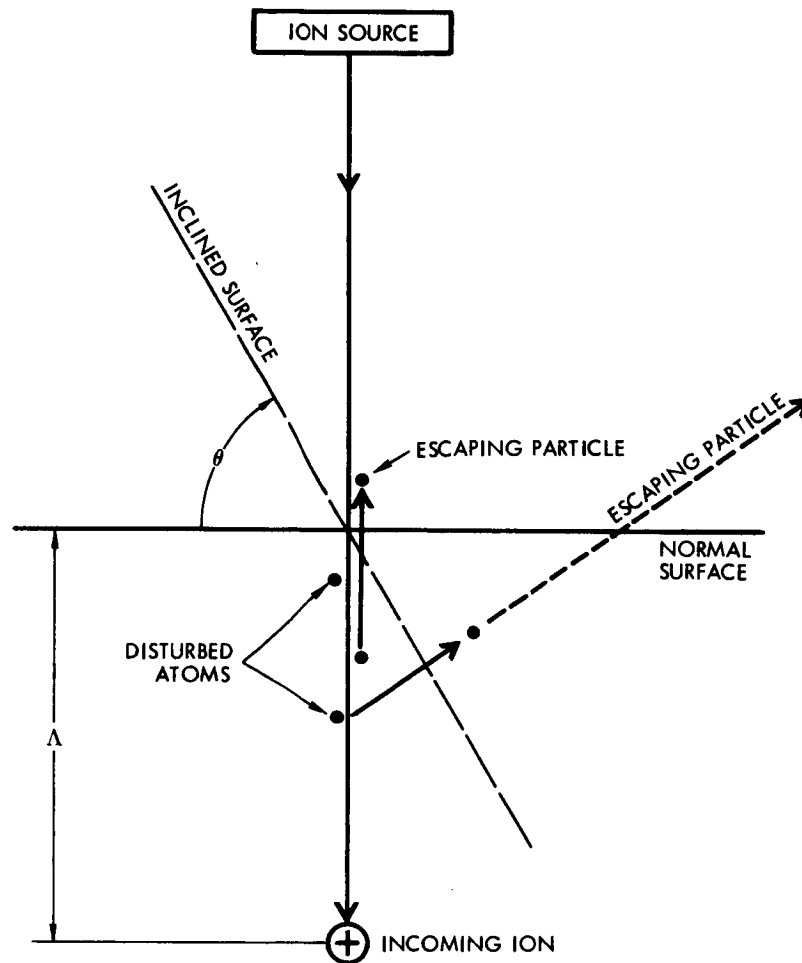


Figure 3.4-2. Simple Sputtering Model Schematic.

angle θ . The incoming ion is assumed to penetrate some distance Λ (which is independent of θ) and to disturb a number of atoms which, after other collisions, escape from the surface. When the plane is inclined at an angle θ those atoms moving to the right in the figure have an enhanced probability of escape, while those leaving toward the left are inhibited. At angles approaching grazing incidence ($\theta \sim 90$ degrees) at least half of the disturbed atoms escape, and when multiple scattering is taken into account, it is clear that more than half will escape. A detailed analysis of this simple picture is inappropriate, but if the escaping fraction is less than half at normal incidence, a sputtering yield increasing with θ would be expected. It is noteworthy that the distance a disturbed atom must go to escape in the direction of the incoming ion is independent of θ , and hence the sputtering yield in this particular direction should remain unaffected even for large values of θ .

Conclusions from this simple picture are supported by experimental evidence. The sputtered material is found to leave in approximately a cosine distribution about the normal to the collector. The material leaving along the original line of incidence is then proportional to $Y(\theta) \cos \theta$, and the back-sputtering rate relative to that for normal incidence is

$$R(\theta) = \frac{Y(\theta) \cos \theta}{Y(0^\circ) \cos 0^\circ}$$

This function is plotted in figure 3.4-3 for 2-keV Hg ions incident on Cu and Mo targets.¹³ These data show that for copper, the sputtering yield increases approximately as the inverse of the cosine of θ , with the result that the back-sputtered material flux is essentially independent of the angle of the target. For molybdenum, the increase with angle is even greater, and the back-sputtered material flux is seen to increase up to 45 degrees and then return to the normal value at 60 degrees. Hence, a 45-degree chevron target would return 30-percent more material to the engine than a collector normal to the beam. Many other materials show either no change or increased back-sputtering with angle; for example, Cs on copper shows a significant increase out to 45 degrees and beyond.

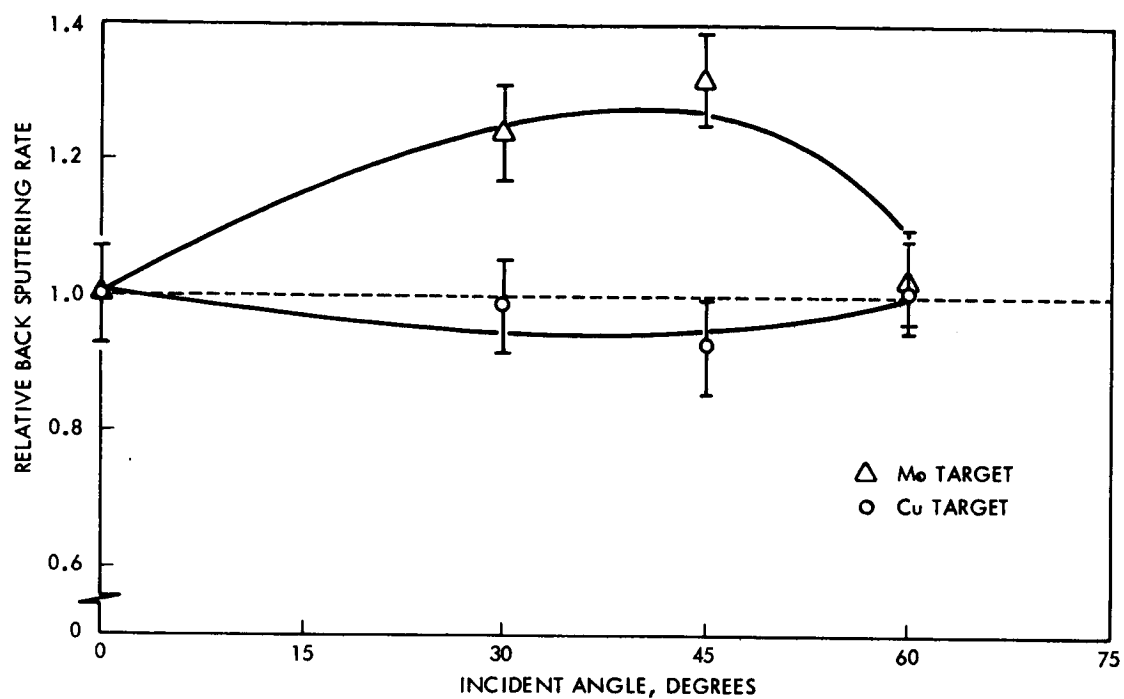


Figure 3.4-3. Back Sputtering vs Incident Angle for 2 Kv Hg ions.

The recent work of Chaney and Pitkin¹⁴ shows that for 1.5-keV xenon ions on copper, the absolute sputtering yield is a maximum at $\theta = 75$ degrees. At this angle the total material removal rate is more than seven times that for normal incidence. The back-sputtered flux directed toward the ion source is 1.8 times that for normal incidence. Beyond 75 degrees there is a rapid decrease in sputtering yield, so that at 80 degrees the back-sputtering rate is again equal to that at normal incidence. To account for this drop as 90 degrees is approached the authors speculate that the ion has not imparted much of its energy to the target before being deflected out of it. If this is correct, the incident ion has not been stopped and further sputtering collisions have yet to occur.

Experimental evidence in support of this hypothesis has been obtained in this laboratory during an extended ion engine test. The result is shown in Figure 3.4-4. This is a profile of a Cu sample originally 0.05 inch thick. (The bright line is the edge of a Ni film deposited after the run to preserve the surface boundary against smearing during sample preparation. Copper was then deposited on the Ni.) The ion beam was incident from the top of the page. The region at the left is the original surface which was protected by a Cu clamp 0.05 inch thick. Figure 3.4-3b shows the salient features of this sample. The protective cover and the sample develop a steep edge which concentrates incoming ions at the bottom of this edge. The sputtering yield from the nearly vertical surface is low. However, a deep trough is eroded at the bottom by ions scattered from the steep edge. Most of the sputtered material from the trough cannot reach other parts of the sample while the small amount of material sputtered from the vertical faces falls off rapidly with distance through geometric dilution.

Since sputtering data generally show that the increase in yield is nearly proportional to the increase in $1/\cos \theta$ out to large angles, it follows that a collector plate inserted in an ion beam at any angle will have its thickness (normal to the plate, not the beam) reduced by the same amount in a given time, regardless of the incident angle. This is true despite the fact that it may intercept a lower flux density of beam ions. This is illustrated in Figure 3.4-5 which is a schematic of the hypothetical target which follows the $1/\cos \theta$ sputtering law. Conditions are shown for normal incidence and 60° incidence. At 60° incidence the flux returned along the beam vector is unchanged and the erosion depth is also unchanged. The total amount of eroded target material is doubled at 60° incidence.

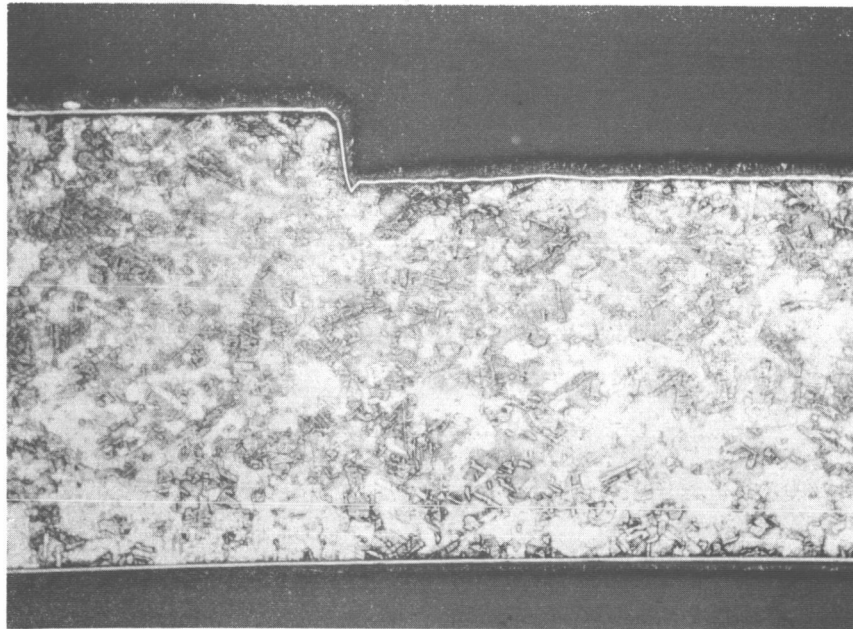


Figure 3.4-4a. Cross Section of Copper Sample Sputtered at 2 Kev with TRW Cesium Thrustor. Un-eroded Area (left) was Protected by 50 Mil Ca Clamp. 50X.

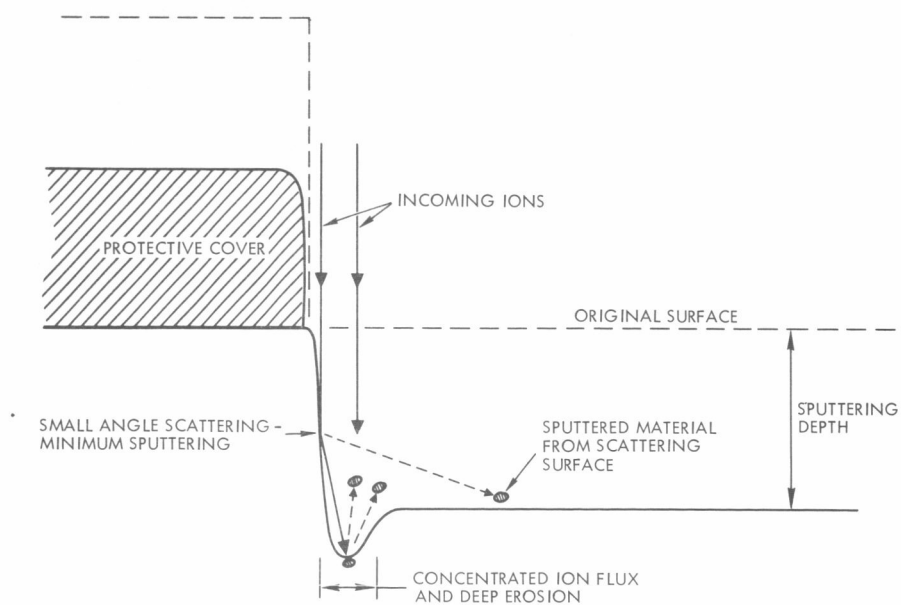
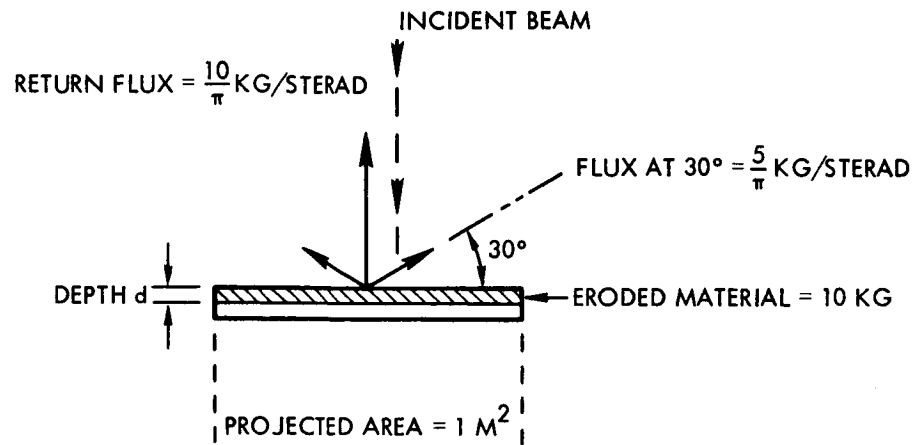
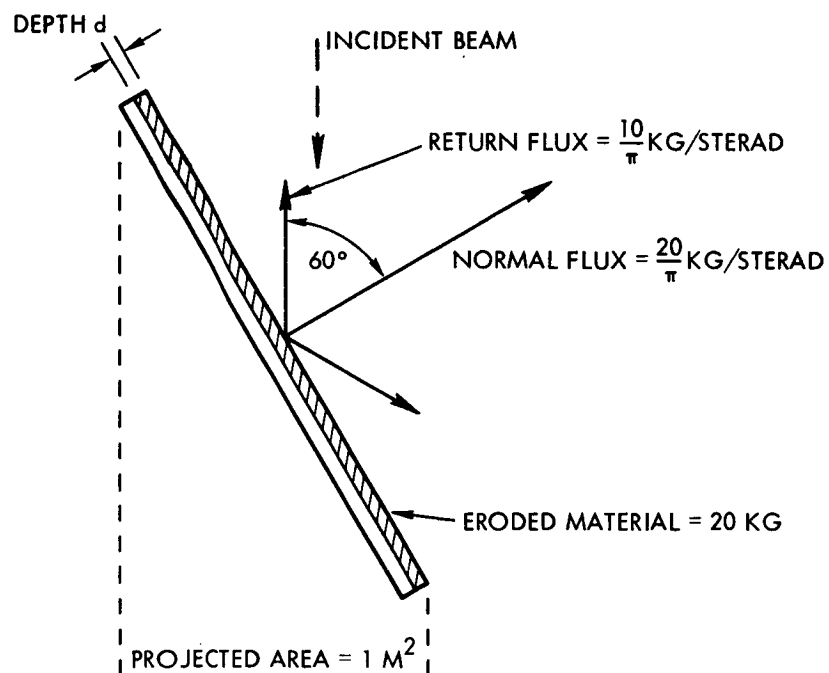


Figure 3.4-4b. Schematic Diagram Explaining Development of Trough seen in Figure 3.4-4a.



A. NORMAL INCIDENCE



B. 60° INCIDENCE

Figure 3.4-5. Implications of the $1/\cos$ Sputtering Law. The Eroded Thickness and Return Flux are Independent of Incidence Angle; Normal Flux and Mass Loss Rate Increase for Off-Normal Incidence

Therefore, if a 1/4-inch thick plate is needed for a flat collector, then a chevron collector must also be constructed of 1/4-inch thick plates. Similarly, the webs in a honeycomb would need to be 1/4-inch thick. This rather startling result has been confirmed in sputtering experiments with 2-keV cesium ions on copper. A section of copper pipe was placed transverse to an ion beam for several hundred hours. The reduction in pipe wall thickness at 80 degrees from the beam normal was found to be as great as that at normal incidence.

3.4.2.1 Louvered Collector

The question then arises whether any louvered collector can reduce the amount of material sputtered back toward the engine. For copper and similar materials, the answer for incident angles of 80 degrees or less is clearly no. Between 80 and 90 degrees there may be some advantage.

A possibly useful configuration which takes advantage of the effect described above is shown in Figure 3.4-6. A number of plates may be inclined at a 20:1 slope from the normal ($\theta \approx 87^\circ$). Incoming particles will be deflected with low sputtering yields and will impact at a point hidden from the thruster so there will be no further contribution to the return flux and contamination of the thruster will be reduced.

To achieve any significant gain -- say a factor of two -- angles must be held between 84 and 90 degrees, and this introduces practical limitations inasmuch as source width, beam spreading, and electric fields in sheaths can easily introduce variations in ion trajectories of this magnitude. Our conclusion from the data at hand is that the louvered or honeycomb configuration is of questionable merit and even in a well-designed collector can easily do more harm than good because of uncontrollable ion trajectories.

3.4.2.2 Decel Collector

In the decel-collector the objective is to slow the ions before impact. Ideally the collector would simply be operated at ion source potential, and the ions would strike it at zero velocity. Here again the variation of ion trajectories from normal incidence introduces problems if the collector is at the full accelerating potential since ions approaching at other angles will be deflected and will return to some point which is at ground potential. Furthermore, no matter where the collector is placed if it is not electrically isolated from the beam, the beam plasma will assume a high potential, unreasonable demands will be made on the thrust beam neutralizer system, and the decel region will be

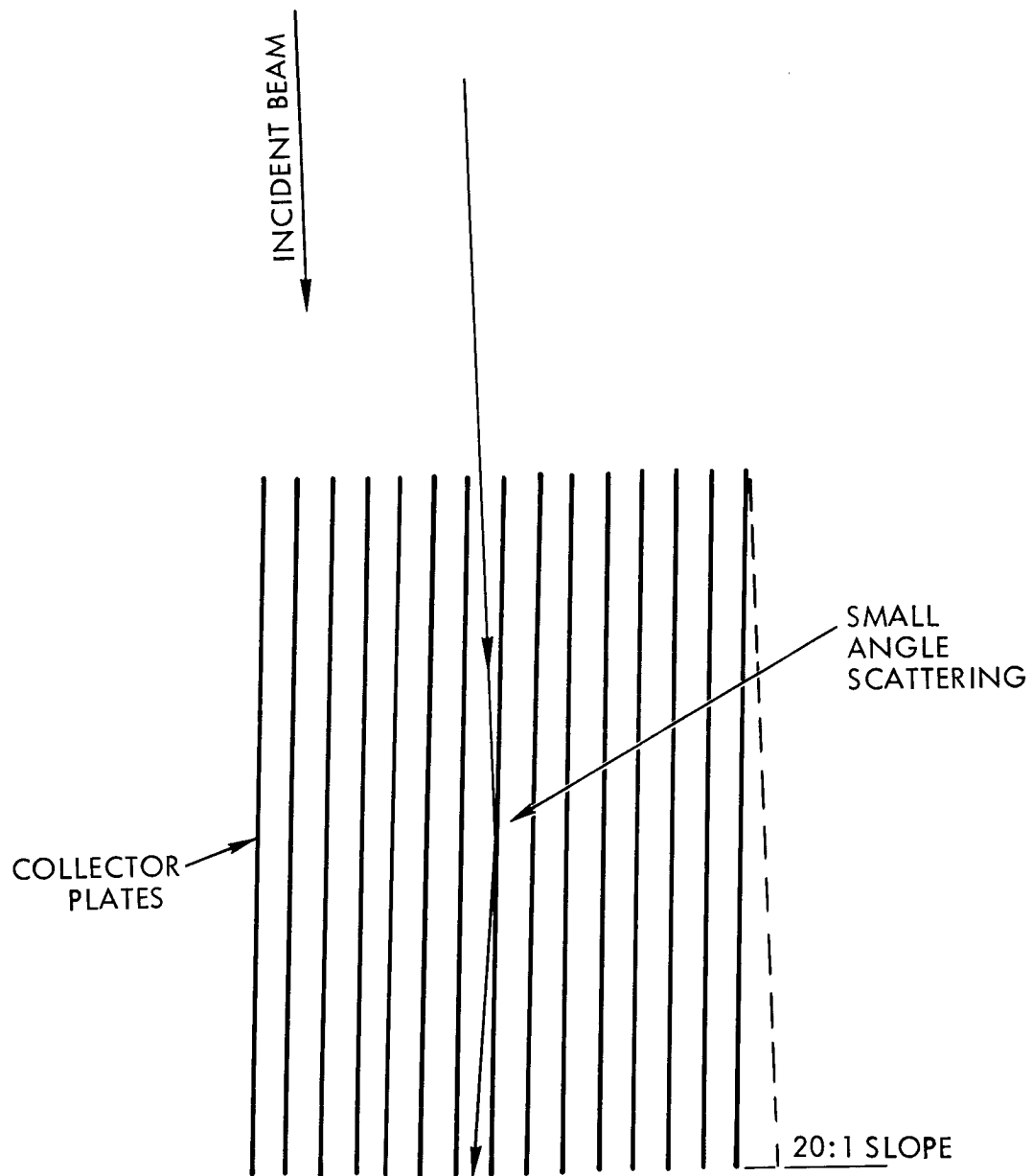


Figure 3.4-6. Geometrical Consideration for a Louvered Collector Which has a Potential for Reducing Net Return Flux.

confined to a stalling region in front of the engine. This produces undesirable effects on the ion optics in the engine and will return many primary ions and charge-exchange ions to the engine accel grid at high velocity. It therefore becomes necessary to provide the collector with a grid that separates the decel region from the beam plasma. The grid then is subjected to the same sputtering rate as any collector, and the grid thickness must be adequate to withstand this erosion. Again, the problem of enhanced sputtering at grazing angles arises, for not only must the front of the grids withstand the frontal ions, but the sides must provide enough material for the enhanced sputtering at low angles. For example, if a 1/4 inch flat plate is required at normal incidence, the grid must be at least 1/4 inch thick in the direction transverse to the beam unless the surfaces can be kept within a few degrees of parallel to the beam. This is practically impossible because of ion deflections produced by penetration of the decel field into the grid interstices. We therefore conclude that in order to be conservative, the grid would have to consist of bars about 3/8 inch thick. The next problem is what grid spacing and decel distance are required? For a current density at the collector of 0.1 ma/cm^2 , Child's law will require a decel distance of no greater than 1 inch for a 3-Kv decel potential. The grid bars will also have to be placed on centers of about 1 inch to prevent field penetration, and therefore the grid occupies three-eighths of the frontal area. Actually the full 3-Kv decel cannot be used because the ions would acquire some transverse velocity components in the decel field and fail to reach the collector. A potential of 2700 volts (90 percent of beam accelerating potential) permits trajectories inclined 15 degrees from normal to impinge on the collector and is considered as a practical limit. At this potential the ions strike with 300 eV of energy (per charge) and, on aluminum, the sputtering yield would be reduced to about one-fifth of its value at 3 keV.

The back-sputtering from this array consists of material from the grid that intercepts three-eighths of the incident beam and sputters at the normal, or 100-percent rate, plus five-eighths of the beam, which sputters at the reduced rate of 20 percent. The result is no more than a factor of two reduction in material back-sputtered onto the engine.

The decel collector thus has two practical problems, the presence of massive grids which will be eroded in the usual way, and the inability to reduce the sputtering of the ions that are decelerated by at least a factor of 3 to 5. This latter difficulty occurs because of the $E_1^{1/2}$ dependence of the sputtering yield.

Fundamentally, the decel collector can be dismissed as a practical device by the following argument which, in effect, invokes the second law of thermodynamics. In principle, if the individual particle stream tubes from each of the engine apertures were to remain separated over the entire engine to collector distance, it would be possible to direct the beams through a grid structure without interception. The particles could then be brought to rest by a decel arrangement symmetrical to the accelerator structure. In the actual situation, once the beams have travelled one or two centimeters from the accel region, the beams have merged. Beyond that point, the original order and separation is lost, and it is no longer possible to channel the flow of individual stream tubes through separate apertures.

Finally, the decel collector violates the principles of ion engine testing described in Section 3.3 in that it either makes unreasonable demands on the thruster neutralizer (as mentioned) or, if isolated by a grid, gives rise to a condition in which the ion charge density in the beam is neutralized by a static trapped colony of electrons, and the neutralizer is not required to work at all. In neither case is a valid test made of the thruster performance, relative to its behavior in the space environment.

3.4.2.3 Beam Deflector

Another possibility that has been considered is a beam deflector system, which would dispose of the beam ions in areas that are shielded from the engine.

As in the decel case the beam must be held at a low potential by grids placed between the deflection region and the engine, otherwise the beam potential will rise to that of the most positive electrode in the plasma. The problem once again is that even if the transmitted portion of the beam can be disposed of completely, interception by the grids constitutes a substantial fraction of the beam and backsputtering will not be reduced as much as an order of magnitude. Once again a valid thruster test is not made possible.

3.4.3 Cooling

A significant consideration in the design of a thrust beam collector is disposal of the heat load of the thrust beam power. This section discusses several aspects of the problem of cooling the thrust beam collector itself. It is assumed that elsewhere within the testing chamber, usually near the thruster, other large surfaces will be used for cryogenic pumping of propellant material or other condensable vapors.

Several means of cooling the collector have been suggested:

- Radiation cooling
- Water cooling
- Cryo cooling
- Freon cooling

Each of these is discussed in the following paragraphs.

A nominal ion beam power of 1 KW can be dissipated by radiation cooling from a 1 m^2 collector (two surfaces) at a temperature of about 400°C . Use of such an arrangement would keep the collector free of all condensables and, after initial clean-up, would minimize outgassing or vaporization of material during fluctuations in beam location occasioned by arcing or other variations in engine behavior. The principal disadvantage of this approach is that about one-third of the power is radiated into the cryo wall by the hot collector. Cryo cooling is one of the major costs of life tests, and consumption of coolants should be minimized. One of the objections to a deep thin-walled honeycomb collector is that conductive cooling of the front is poor and much of the beam power is radiated back to the cryo system.

The most convenient approach from both technical and cost standpoints is a simple water-cooled collector at about room temperature. This approach has been used for many years in our cesium ion engine testing program, in which up to 3 KW of beam power is used. The water temperature rise is easily monitored for calorimeter purposes. Water temperatures from 20°C to 80°C have been used. (The higher temperatures are helpful in initial clean-up of the target.) Leakage currents through the water stream are less than 1 mA at ordinary collector potentials and do not perturb the electrical measurements in either the grounded or floating collector mode.

There appears to be no advantage in cryo cooling the collector; in fact, it appears to be inadvisable from two counts. First, the use of cryo coolants in the collector is a costly approach, inasmuch as the collector dissipates more than half of all the power input to the system, including radiation into the cryo system. Second, the condensation of propellant and other materials on the collector surface could result in an unstable situation in the event of changes in ion beam distribution over the collector. Such changes could lead to rapid volatilization or decomposition of condensed material and a consequent rise in system pressure.

Cryo cooling costs can be estimated from liquid nitrogen costs and heat content. The enthalpy change for LN_2 including phase change and temperature rise to 200°K is 140 BTU/lb of which about 120 BTU/lb can be realized in a cryo panel heat exchanger. One kilowatt hour is 3413 BTU and would require 28.5 lb or about 16 liters. At bulk rates LN_2 costs will be about \$1.50/KW hour. The power input will consist of beam power plus radiation of about 100 watts/m^2 of cold surface. The cost of cryo cooling a 10^4 ampere hour test at 3 kV beam potential with a 4 m^2 (two sides) collector is of the order of \$50K for the collector alone. Increasing the collector area to 20 m^2 to reduce current density at the collector could almost double this cost.

In a test of a thruster using mercury as propellant, a conceivable advantage of a cryo cooled collector would be the protection provided by the frozen propellant on the collector against sputtering of the substrate. The conditions needed for this approach can be found by calculating the partial pressure of Hg vapor required to maintain a coating on the collector. The incident flux of Hg from the vapor phase in the vessel is given by

$$\Gamma = \frac{P}{\sqrt{2\pi m k T}}$$

or for mercury at 300°C ,

$$\Gamma = (1.4 \times 10^{20}) P$$

where

Γ = flux in particles/cm² sec

P = Hg partial pressure in torr

To maintain coverage the incoming flux must equal the flux of material sputtered off the target by the incoming beam. This is given by

$$\Gamma = \frac{I_B}{qA} Y$$

where

I = ion beam current

q = charge on the ion (coulomb)

Y = sputtering yield (atoms/ion)

A = area of the beam at the target

The assumption of a 1 ampere beam spread over 1 m² gives the sputtered removal flux as

$$\Gamma = 6.2 \times 10^{14} Y \quad (\text{sec}^{-1} \text{ cm}^{-2})$$

Accordingly the mercury vapor pressure required in the vessel to maintain mercury coverage on the collector is

$$P(\text{torr}) = 4.4 \times 10^{-6} Y$$

The sputtering yield of 3-Kev mercury ions on mercury is probably not less than two atoms/ion, so that a pressure of $\sim 1 \times 10^{-5}$ torr would be required in the vessel to supply Hg ions at the collector as fast as they are sputtered off. A collector current density of less than 0.1 amp/m² would be required to operate at pressures of 1×10^{-6} torr. The required collector dimensions are mechanically feasible, but the large area adds an additional heat load to the cryo system which is already burdened with the full beam power in this approach. It is therefore concluded that the self replenishing cryo cooled collector is unattractive from the standpoint of fabrication and operating costs.

3.4.3.1 Frozen Mercury Collector

If the operating temperature of the collector is higher than cryogenic temperatures, e.g., in the range of a freon refrigeration system, a very attractive solution presents itself, at least for mercury engines. In this scheme, which has seen use in the life testing of a 15-cm SERT II electron-bombardment thruster, the ion beam is directed vertically downward onto a horizontal pan preloaded with mercury. The temperature of the mercury slab is maintained below -50°C at which temperature the vapor pressure is about 1×10^{-6} torr not just to keep the surface frozen, but to keep the evaporation rate well below the sputtering rate. As in other chamber designs, the pressure is controlled by cryogenic liners near the thruster position, and is below the replenishment level (see 3.4.3). Accordingly there is a continuous loss of mercury from the frozen collector, most of which goes to the cryoliner. In 10^4 Ah of beam operation at a sputtering yield of 3, this loss could amount to about 2.25×10^5 grams (515 lb) of mercury. The cost of at least this much mercury ($\sim \$4,000$) would be part of the initial fabrication costs of the facility.

For the SERT II thruster facility a 2-ton (7 kW) refrigeration system was selected at a cost of roughly \$4700.00, including the unit, collector pan plumbing, etc. In addition to the collector, the tank liner at the collector end of the facility was also cooled by the refrigeration system.

Our experience with the frozen mercury collector during a run of about 700 hours indicates that a refrigerator of this size was more than adequate to maintain the frozen pool at the desired temperature. The removal of mercury to the cryoliner and to those frozen surfaces not sputtered by the beam was seen to proceed as predicted. Although it was not possible to weigh the mercury thus transferred, one could observe the rate at which liquid dripped back into the pan from both sides of the cryoliner and from the outside of the downstream shroud when these surfaces were warmed up. The calculated value of about 9 lbs is believable.

3.5 PRODUCT ASSURANCE SUPPORT

The objective of the product assurance support to this program was to insure that materials, processes, drawings, and deliverable units conform to applicable standards or specifications. Accordingly all purchase orders for materials or parts to be included in deliverable hardware were screened by cognizant Quality Assurance personnel, and material and conformance certifications were required of each vendor. Where uncertified raw stock materials were used, samples were given chemical analysis to verify the identify of each such material.

Cancellation of the electric field meter task early in the program significantly reduced the magnitude of the product assurance task inasmuch as both numbers and kinds of deliverable items were reduced. Furthermore, considerations of reliability relating to the development of the E-meter breadboard electronics were dropped from consideration.

During fabrication of the deliverable neutralizer cathode assemblies, each component part and fabrication process was monitored by a Quality Assurance inspector, and serialized inspection and test logs were kept for each assembly. Any discrepancies between the dimensions of actual parts and those indicated on original drawings were noted on an "Assembly Squawk Sheet." Approval for use of such parts was given by the TRW project engineer under the following conditions: (1) The discrepancies bore no relationship to the functional operation of the device, and (2) no time was available for modifying the drawings to match the parts (which would have required another approval cycle) nor were techniques for machining parts to exactly match the original drawings.

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APPENDIX A.

ELECTRON EMISSIVE SURFACE ELECTRIC FIELD METER
(Reprint from R. S. I.)

Electron Emissive Surface Electric Field Meter

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The performance of a surface electric field strength meter, utilizing a broad unfocused beam of electrons, has been evaluated analytically and experimentally. The meter is capable of measuring E fields up to 100 V/cm and possesses a sensitivity of ~ 0.1 V/cm in the field regime near $E=0$. The meter response to time varying electric fields is limited by the finite transit time ($<10^{-7}$ sec) of the electrons from the source to the detector plates. Simple formulae for the errors introduced in the measurement of time dependent electric fields by finite transit time effects and by displacement currents are presented and indicate errors of ~ 0.1 V/cm for E fields rising at 10^6 V/cm sec. Sensitivity of the meter to magnetic field perturbations along three mutually perpendicular directions has been evaluated. The meter response has been examined in a plasma flow simulating spacecraft through the ionosphere.

I. INTRODUCTION

THE electric field strength on the surface of an isolated system is determined by the difference in potential between the system and its immediate environment. Such electric fields are usually measured by means of an electrostatic flux meter, the "field mill,"¹⁻³ or by the deflection of charged particles, usually an electron beam.^{4,5}

This paper describes an instrument which uses the deflection of a free electron current to determine the electric field. An unfocused electron beam consisting of electrons traversing many possible trajectories is produced by an extended hot filament. Surrounding the filament is an accelerating grid structure which affords physical protection to the filament and which effectively shields it from external electric fields. The anode assembly which consists of several collecting plates is positioned symmetrically about the cathode grid structure. A functional relationship exists between the electron current to any collecting plate and the average electric field in the region traversed by the electrons. The current to one plate or to a pair of symmetric plates may exhibit a double valued relationship to the electric field. When this occurs, it is necessary to measure the current to more than one collecting element.

This particle deflection electric field meter offers several advantages over other electric field meters. It is simple in construction and employs no moving parts. In general, the currents to the collecting plates are large compared to the induced currents of the field mill meter so it can be used in the presence of stronger ambient plasmas. Both power and electronic requirements are modest. The bandwidth

capability is related to the transit time of the electrons, which is typically 10^{-7} sec for 20 eV electrons. The instrument can be used either as a dc or pulsed device, and is capable of measuring electric fields between 0.1 and 100 V/cm.

II. THEORY

The response of a surface field meter to electric fields may be determined, within first order effects, by comparatively simple analysis. A two dimensional model which represents the meter described in this article is shown in Fig. 1. Electrons emitted from an extended filament at the axis of the cylinder are accelerated through the potential difference V between the filament and the grid hood structure and emerge from the grid with a velocity $v_0 = (2eV/m)^{1/2}$. Any variations in the electron energy produced by the dc heating potential gradient are ignored. This effect may be circumvented by pulsed heating, or made small by choosing $V \gg \Delta V_f$ where ΔV_f is the voltage drop across the filament. When the grid and collecting elements are at the same potential, and if magnetic field and space charge effects are

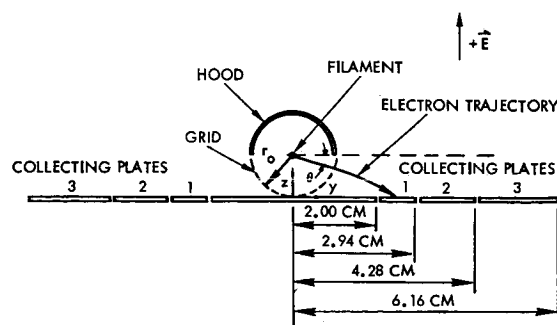


FIG. 1. Schematic diagram of electron emissive surface electric field meter. Electron trajectory indicated for positive E field. Values of y at plate edges determined from Eq. (3) to provide current cutoff at negative E fields of 2, 4, 8, and 16 V/cm.

¹ R. C. Waddell, Rev. Sci. Instr. **19**, 31 (1948).

² P. J. L. Wildman, J. Atmospheric Terrest. Phys. **27**, 417 (1965).

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⁴ S. G. Forbes, R. F. Kemp, J. M. Sellen, Jr., H. Shelton, and J. C. Slattery, "Ion Engine Testing Techniques," ARS Space Flight Report to the Nation, New York, ARS 2183-61 (October 1961).

⁵ J. Lucas, J. Sci. Instr. **40**, 481 (1963).

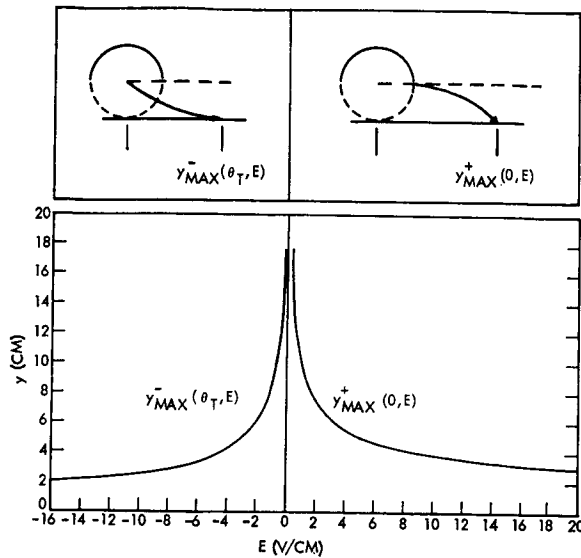


FIG. 2. Maximum impact distance of 20 eV electrons as a function of electric field for the meter shown in Fig. 1.

ignored, the only force acting on the electrons outside the grid is the external electric field.

The currents to a pair of collecting elements which are placed symmetrically about the filament are summed. Later it will be demonstrated that this symmetry property may be utilized in minimizing the effects of magnetic fields. The collecting elements are assumed to be clean surfaces which collect all incident electrons and emit no secondaries.⁶⁻⁹ The proper choice of the accelerating potential minimizes the effects of scattering and secondary emission. Similarly, the effects of magnetic fields, space charge, and variations of electron energy can be minimized by a proper choice of V .

The electric field E acting on the particles is assumed to be uniform and normal to the collecting plates and any distortion of E caused by the grid structure is ignored. Then the equations of motion for the electrons external to the grid become $m\ddot{z} = -eE$ and $\ddot{y} = 0$. E is defined by

$E > 0$, meter is above environmental potential,

$E < 0$, meter is below environmental potential;

e is the magnitude of the electron charge. These equations

⁶ Not all of the electrons incident on a surface are simply absorbed. Incident electrons can be scattered elastically and inelastically and, even for low energy primary electrons, the production of secondaries can occur. The net current to a collecting surface is reduced by scattering and secondary electron emission and is enhanced by these effects on other surfaces. A comparison of the measured currents with the currents predicted theoretically shows diminution of approximately 30% in the weak field region ($E \approx 0$). Since several possible factors may contribute to this diminution, the possible influence of scattering and secondary emission is most likely less than indicated.

⁷ V. Evtuhov, G. F. Smith, and L. S. Yaggy, Rev. Sci. Instr. 32, 1362 (1961).

⁸ Kenneth G. McKay, Advances in Electronics 1, 65 (1948).

⁹ O. Hackenberg and W. Braver, Advances in Electronics and Electron Physics 11, 413 (1959).

together with the initial conditions

$$y(t=0) = r_0 \cos \theta$$

$$z(t=0) = r_0(1 - \sin \theta)$$

$$\dot{y}(t=0) = v_0 \cos \theta$$

$$\dot{z}(t=0) = -v_0 \sin \theta$$

determine the trajectories of the electrons emerging from the grid at angle θ with respect to the reference plane. The position of impact is determined when $z=0$ and may be expressed as

$$y(\theta, E) = r_0 \cos \theta \left(1 - \frac{2V}{Er_0} \sin \theta \right) + \frac{2V}{E} \cos \theta \left[\sin^2 \theta + \frac{Er_0}{V} (1 - \sin \theta) \right]^{\frac{1}{2}}, \quad (1)$$

where the coordinates are shown in Fig. 1 and the geometry of the meter limits $0 \leq \theta \leq 90^\circ$. V is the magnitude of the filament potential which is negative with respect to the grid hood electrode.

In describing the electron trajectories, the change in potential in the immediate region external to the grid which is produced by replacing the actual electric field by a uniform field has been neglected. This assumption is justified if $|Ez_0| \ll V$, a condition which holds over most of the range of E for which the meter is utilized.

Equation (1) may be used to design an E meter and to predict its current response. It provides a mapping of the y plane into the θ coordinate, and, from the known electron current contained within an increment in θ , the current to a collecting plate may be determined as a function of E . Two special cases of Eq. (1) provide the design characteristics for the E meter. For $E > 0$, the emitted electrons are accelerated towards the collecting plane. As E increases, more electrons are collected by a plate until the maximum position of impact, obtained by electrons with trajectories at $\theta=0$, equals the outer edge of that plate. For stronger E fields, the current collected by that plate decreases. The maximum range is given by

$$y_{\max}^+(0, E) = r_0 [1 + (4V/Er_0)^{\frac{1}{2}}]. \quad (2)$$

The current to a collecting plate goes to zero as the maximum range goes to the inner edge of the plate.

For $E < 0$, the electrons are accelerated away from the collecting plane. In this case, the current to a plate always decreases with increasing field strength (E becomes more negative). The maximum position of impact now corresponds to that trajectory which is tangent to the collecting plane. The tangency condition, $\dot{z}=0$ at $z=0$, is satisfied by that particle emerging at θ_T where $\sin^2 \theta_T + (Er_0/V) \times (1 - \sin \theta_T) = 0$. Utilizing this condition and Eq. (1), the

maximum position of tangency impact is given by

$$y_{\max}^-(\theta_T, E) = r_0 \cos \theta_T \left(1 - \frac{2V}{Er_0} \sin \theta_T \right). \quad (3)$$

The current to a plate goes to zero as $y_{\max}^-$ approaches the y coordinate of the inner edge of the plate. From this and the preceding paragraph, it may be seen that the current to a plate ranges from zero through a maximum value and returns to zero as the electric field varies through a particular range.

Equations (2) and (3) are shown graphically in Fig. 2 for $V=20$ V and $r_0=1$ cm. These two functions demonstrate the intuitive notion that the outer plates are more sensitive to changes in the field than are the inner plates. They also give a relation between the maximum position of impact and the external field strength, and therefore provide the relation between plate dimensions and the range of electric field which can be measured. Utilizing the $y_{\max}^-(\theta_T, E)$ curve in Fig. 2, the plate dimensions illustrated in Fig. 1 were chosen to provide cutoffs in the current response at 2, 4, 8, and 16 V/cm.

From Eq. (1) and from the stipulated y values for the collecting plates, the increment in θ , $\Delta\theta$, for trajectories intercepting a given plate may be calculated as a function of E . Denoting the filament emission current as i_0 , the current collected by a given set of plates as i , and the normalized current response to the symmetric pair of collecting plates as $i_0 = (i/i_0)$, then i_0 is given by

$$i_0(E) = \Delta\theta/\pi. \quad (4)$$

The quantities of interest in the meter performance are $i_0(E)$, $\partial i_0/\partial E$, $\partial^2 i_0/\partial E^2$, and the sensitivity η defined as $i_0^{-1}(\partial i_0/\partial E)$. For measurements of small electric fields, it is desirable to maximize the value of η . This necessarily limits the field range for a given set of plates, and several sets of collecting plates are then utilized to broaden the field measuring capacity. While the E meter is designed to measure a large range of electric fields, the field range near $E=0$ is of particular interest. The double valued nature of the current response for E such that $y_{\max}^+ \approx$ the outer y value of a pair of collecting plates is to produce a condition $\partial i_0/\partial E \approx 0$. It is essential that this condition should not occur near $E=0$. Furthermore, if the sensitivity is not to change rapidly, then $\partial^2 i_0/\partial E^2 \approx 0$ should be realized over that range of E fields for which a pair of collecting plate signals are to be utilized. Later it will be demonstrated that this condition, along with the symmetry condition, leads to a partial cancellation of the effects of magnetic fields.

A general expression for the normalized current response cannot be directly stated since $y(\theta, E)$ is a transcendental function. However, representative curves can be obtained by numerical analysis of Eq. (1) and the stipulated y

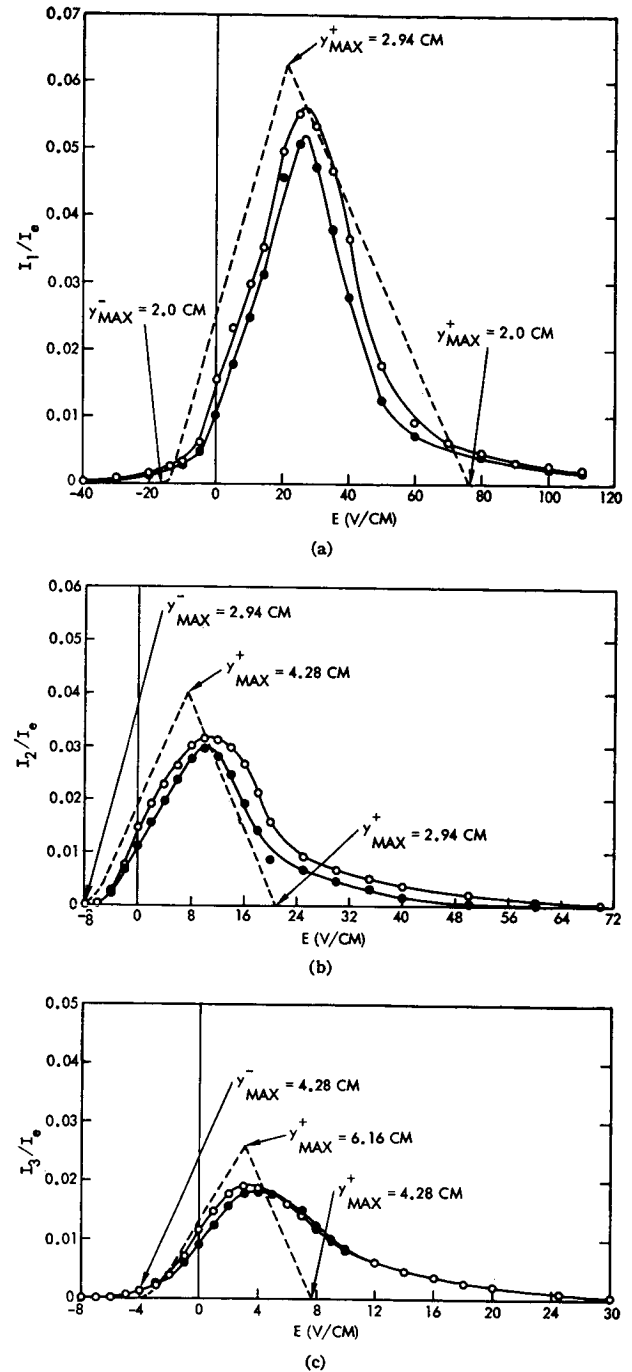
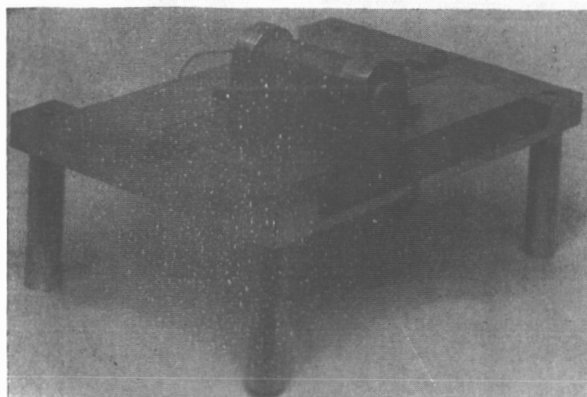


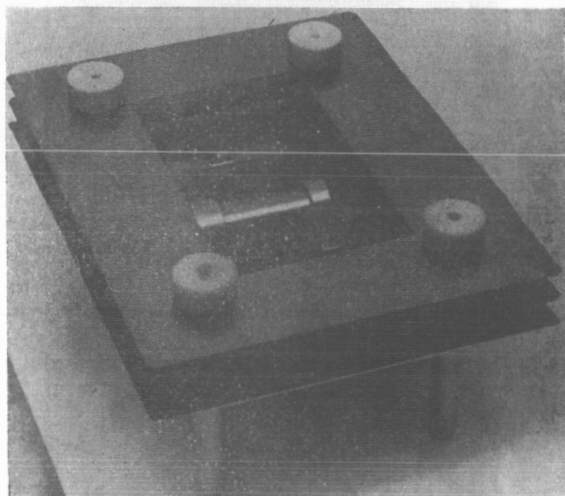
FIG. 3. Response of collecting plates to electric fields. Dashed lines represent the theoretical predictions assuming a grid transmission of 60%. Circles are experimental plate currents normalized to total filament emission. Open circles were obtained shortly after meter was turned on; solid circles were obtained 24 h later. (a)—Response of inner plates (plate no. 1); (b)—response of intermediate plates (plate no. 2); and (c)—response of outer plates (plate no. 3).

values. The results of these calculations are shown by the dashed curves in Figs. 3(a), (b), and (c) for $r_0=1$ cm, $V=20$ V, and a 60% grid transmission factor.

An approximate expression may be obtained for the meter sensitivity, $i_0^{-1}(\partial i_0/\partial E)$, when $E \approx 0$ and $y \gg r_0$. In



(a)



(b)

FIG. 4. (a) Photograph of E meter and test base; and (b) photograph of E meter in calibration assembly with the calibrating plate removed.

order to evaluate $\partial i_0/\partial E$, it is first necessary to evaluate the variation of θ with respect to E for a fixed impact position in y . This may be accomplished in either of two ways; first, by setting $z=0$, and taking the differentials of the equations of motion holding y constant; second, by considering a small perturbing E field which slightly changes the electron trajectories. Both methods lead to

$$\left(\frac{\partial \theta}{\partial E}\right)_y = \frac{-y}{4V \left(\frac{y}{y-r_0 \cos \theta}\right)^2 \left(1 + \frac{v_0 \tau E \sin \theta}{2V}\right)} \approx -\frac{y}{4V} \left(1 - \frac{r_0}{y}\right)^2, \quad (5)$$

where τ is the time of flight of the electron from the grid to a plate, and under the stated conditions θ is nearly zero. Equations (4) and (5) yield

$$\partial i_0/\partial E \approx \Delta y/4\pi V, \quad (6)$$

where Δy is the increment in y coordinate between the inner and outer edges of a plate. In Eq. (6) the conditions

$(\partial i_0/\partial E)|_{E=0} \neq 0$, and $(\partial^2 i_0/\partial E^2)|_{E=0} \approx 0$ are satisfied. Since the normalized current at $E=0$ is

$$i_0 \approx -\frac{1}{\pi} \frac{\Delta y \sin \theta}{(r_0^2 + y^2)^{3/2}} = -\frac{1}{\pi} \frac{\Delta y r_0}{r_0^2 + y^2} \quad (7)$$

where the y value to be utilized should be intermediate between the inner and outer edges of the plate, the sensitivity may be written

$$\eta = (r_0^2 + y^2)/4r_0 V. \quad (8)$$

From Eq. (8) it is evident that the meter sensitivity may be increased by increased distances to the outer plates and by reductions of r_0 and V . A simple calculation of Eq. (8) with $r_0=1$ cm, $V=20$ V, and $y=5$ cm (corresponding to plate no. 3) gives $\eta=0.32$ cm/V. Thus, a variation of 0.1 V/cm in the electric field intensity produces a variation of 3% in the normalized current. This calculated sensitivity from Eq. (8) is in good agreement with both the numerical result presented in Fig. 3(c) and the experimental result of $\eta=0.31$ cm/V to be presented later for plate no. 3.

III. EXPERIMENTAL RESULTS

The surface electric field strength meter shown in Fig. 4(a) was constructed with the same geometry and dimensions used in the calculations. All conducting parts were stainless steel. The tungsten filament, 3 cm long, 0.005 cm in diameter, was supported by a spring clamp mechanism on the symmetry axis. The width of the collecting plates was 3 cm. The filament was negatively biased 20 V with respect to both the grid hood structure and the collecting plane, and was operated space charge limited at approximately 3 mA. The filament power was 3.5 W. The grid was fabricated by eloxing 1.5 mm square holes to leave 0.5 mm webbing. This provided an average electron transmission of 60%.

A uniform electric field was established by placing a large copper plate above and parallel to the base of the meter. Figure 4(b) shows the E meter and the support structure of this plate. The three guard plates were maintained at intermediate potentials to reduce edge effects.

Measurements were made in an oil diffusion pumped vacuum system at $\sim 10^{-6}$ mm Hg and a turbomolecular pumped vacuum system at $\sim 3 \times 10^{-7}$ mm Hg. Condensable vapors were trapped by liquid nitrogen cooled baffles. An investigation in which the geomagnetic field was cancelled by applied magnetic fields showed that it had no appreciable effect on the performance of the meter for the orientations utilized in the experimental work.

The measured normalized currents of the three pairs of collecting plates are shown in Figs. 3(a), (b), and (c). All curves show a diminution of normalized current from the theoretical predictions, a shift in the maxima, and for large E a greater current than expected.

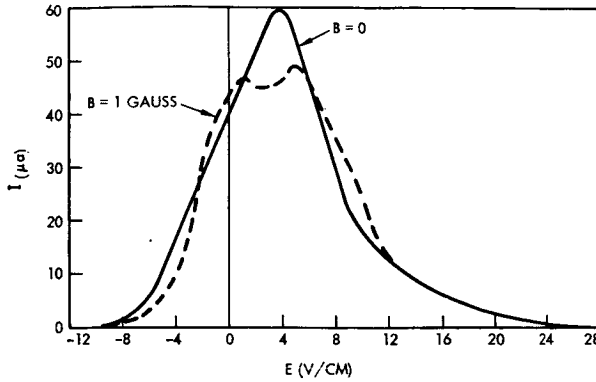


FIG. 5. Current signal of outer collecting plates with B field orientation to produce maximum perturbation effects. Solid line is collector current as a function of E field with no magnetic field present. Dashed curve is collector current response with magnetic field of 1 G parallel to filament.

Small deviations from the predictions of the model are expected, since the theory does not include the field distortion at the grid, space charge effects, current losses from scattered or secondary electrons, and electron energy variations. Furthermore, a constant transmission coefficient has been assumed, and there is experimental evidence that field penetration into the grid structure, which can alter the transmission as much as 10%, exists for large E fields. However, the over-all agreement between the experimental data and the calculated curves demonstrates that the simple theoretical model can be used to design an E meter. The actual determination of the meter response should be carried out experimentally and this calibration should be accomplished in a configuration which appropriately represents the environmental conditions under which the meter is expected to operate. It is also important that the meter response remain constant. Measurements indicate that there is a long term current diminution which is apparently associated with the formation of a film on the plates. It is believed that this film results from the bombardment of certain residual vapors by the electrons in the beam and is thus associated with the problems of particular vacuum system usage. When the plates were cleaned, the meter exhibited its initial current response. Film formation may pose other problems, such as the charging of surfaces and alterations of the electron scattering and secondary electron emission probabilities. The buildup of such films for operation in the space environment is not anticipated.

IV. MAGNETIC FIELD EFFECTS

An electron moving with velocity v in the presence of an electric field E and a magnetic field B will be acted on by a force $F = e(E + v \times B)$. If $|v \times B| \approx |E|$, serious deviations from the calculated trajectories may result. The most troublesome of these B field perturbations is for that con-

dition in which the $v \times B$ force is parallel to the E field which is to be measured. This B field perturbation can be minimized by reducing v . Even for 20 eV electrons, this leads to a $v \times B$ force in a 1 G field which is approximately 1 V/cm. However, by summing the currents to identical collection plates positioned symmetrically with respect to the filament, this B field perturbation, namely that produced by the component of B parallel to the filament, may be greatly minimized. This minimization occurs because the $v \times B$ force is parallel to E on one side of the meter and antiparallel to E on the other side. The cancellation of the B field effects is not total, but does lead to a greatly reduced uncertainty in E given by

$$\Delta E \approx \frac{(\partial^2 i_0 / \partial E^2)|_{E_0} |v \times B|^2}{(\partial i_0 / \partial E)|_{E_0} 2}, \quad (9)$$

where E_0 is the E field being measured. From (9) it can be seen that the desirable properties of the current response which have been mentioned previously (to make $\partial^2 i_0 / \partial E^2$ as small as possible and $\partial i_0 / \partial E$ as large as possible) are also of value in minimizing B field perturbations.

The curves shown in Fig. 5 are representative of the effects of magnetic fields on E field measurements. B fields up to 1 G in any of three orthogonal directions were generated by three mutually perpendicular coil systems. The solid line gives the current response of the outer set of plates for $B = 0$. The dashed curve shows the response to the same plates with a 1 G field parallel to the filament. At $E = 0$ the presence of the magnetic field would be interpreted as an E field of 0.8 V/cm. This error is approximately a factor of 10 larger than that expected from Eq. (9).

The disagreement is attributed to the B field inside the grid hood structure. Such B fields would be expected to exert substantial effects upon the electron trajectories prior to their emergence from the grid. Such effects, moreover, would be enhanced by the space charge conditions prevalent near the filament. However, to treat the complete $v \times B$ interaction from the filament to the grid requires a lengthy numerical analysis which has not been attempted. The magnetic field did not affect the currents to the two inner sets of collectors except where $\partial^2 i / \partial E^2$ was large.

When the magnetic field was perpendicular to the filament, similar observations were obtained; however, the effect of B on the collector currents was only half as large.

The observation of large B field effects at the outer plates does not preclude the use of the device in the presence of magnetic fields. In laboratory conditions, the meter can be calibrated in the presence of whatever magnetic fields exist, provided that such fields are not excessive. In other applications, such as interplanetary flight, the meter would be used at larger distances from the earth where the geomagnetic field is weak. In either case, the two inner sets of

collectors are unaffected by B fields as large as 1 G and will give reliable, although less precise, E field measurements. If operation in a zero B environment is desired, field cancellation may be obtained with Helmholtz coils or use may be made of Mu-metal in the construction of the E meter.

Response to Time Dependent Electric Fields

For 20 eV electrons the time of flight to the outer plates is of the order of 10^{-7} sec. This suggests that the characteristic rise time of the E meter in response to a step function in the electric field would be approximately given by this figure of 10^{-7} sec. In a series of pulsed operational tests, the signals to all collectors along with the pulsed E field (step function) were displayed on an oscilloscope and photographed. The currents to all three pairs of collectors lagged the applied field by the same interval of approximately 2×10^{-7} sec. Since the lag was identical for all sets of plates and was in excess of that predicted from transit time considerations, the time lag is interpreted as resulting primarily from circuit capacitance. Improvements in the output circuitry rise time would improve the over-all meter performance within the basic limitations imposed by the electron time of flight.

A second form of electric field that may be considered is a linearly rising field. Comparatively simple considerations reveal that the error which results because of the finite transit time of the electrons is given by

$$\Delta E \approx \frac{2}{3} \frac{dE}{dt} \tau. \quad (10)$$

For a field linearly rising at 10^6 V/cm sec and for a transit time of 10^{-7} sec, the error introduced because of electron transit time effects is approximately 0.07 V/cm.

A time dependent electric field produces a displacement current

$$j_D = \epsilon_0 \frac{dE}{dt}. \quad (11)$$

With $dE/dt = 10^6$ V/cm sec, the induced current in the collecting elements is $\sim 10^{-7}$ A/cm² which is 3% of the collected signal current. This additional signal would lead to an uncertainty of about 0.1 V/cm in the measured electric field for the stated condition in $\vec{E}$.

Plasma Effects

If a surface electric field strength meter is operated on an isolated body in space, then the collection of charged particles by the detection plates of the meter will create an additional signal. Moreover, the interaction of these space charges with the vehicle itself will form a plasma sheath of thickness characteristically given by the Debye length, λ_D . For an electron temperature T_e in degrees

Kelvin and a plasma density n_e in electrons/cm³,¹⁰

$$\lambda_D = 6.9 (T_e/n_e)^{1/2} \text{ cm}. \quad (12)$$

The operation of the meter is seriously impaired if the space particle current density is comparable to the meter electron current density on the collecting surface. However, for most of the ranges of the ionosphere, the plasma particle current densities are of the order of $0.1 \mu\text{A/cm}^2$ or less and the meter current signal is sufficiently large compared to the background to allow meter operation. A second necessary condition in the operation of an electric field meter in space is that the excursion of the particles relative to the detection plates of the meter should be small compared to the Debye length. This second condition assures that the particles are acted upon by an electric field which is essentially constant as they move along the trajectories, rather than varying from point to point along the trajectory, as would be the case if the particle excursion becomes comparable to the sheath thickness.

A means of simulating in the laboratory the conditions of an isolated body moving through the ambient plasma of space is provided by the plasma wind tunnel.^{11,12} The plasma wind tunnel facility has been used to examine E meter performance in the presence of streaming plasmas. The ion current densities in the plasma wind tunnel were varied in the region of $0.1 \mu\text{A/cm}^2$, which simulated vehicle motion in the ionospheric plasma at ~ 600 km. The configuration in which the meter is at zero potential and the plasma potential V_p is positive can be treated theoretically. For ions of charge density ρ_+ , an electric field strength given by

$$E_s = (2\rho_+ V_p / \epsilon_0)^{1/2} \quad (13)$$

exists at the surface of the meter and a total sheath thickness given by

$$L_{sh} = (2\epsilon_0 V_p / \rho_+)^{1/2} \quad (14)$$

exists from the surface of the meter to the unperturbed plasma flow. It should be noted for that condition in which the potential difference between the plasma flow and the material surface may be arbitrarily specified, as in a plasma wind tunnel, and may be considerably in excess of kT_e/e , if desired, that the sheath thickness is not limited to the Debye length given earlier, but is given by Eq. (14). Measurements obtained from the E field meter under the conditions specified above verified the calculated electric field strength given in Eq. (13).

For that configuration in which the meter surface is positive with respect to the plasma flow, the theoretical

¹⁰ L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1962), 2nd ed., p. 22.

¹¹ David F. Hall, Robert F. Kemp, and J. M. Sellen, Jr., *AIAA J.* 2, 1032 (1964).

¹² David F. Hall, Robert F. Kemp, and J. M. Sellen, Jr., *AIAA J.* 3, 1490 (1965).

treatment of the sheath region is complicated, and no simple theory exists for the surface electric field and the sheath thickness. It should be emphasized here that this present difficulty is created by the fact that the energy of the ions in the plasma flow is large compared to the potential increment across the plasma sheath from the plasma to the meter surface. For this regime, the electric field meter performance was complicated. Investigation of these data, however, leads one to conclude that the complications in the data are created by the plasma flow configura-

tion, and do not reflect upon the ability of the surface electric field meter to determine electric field strengths.

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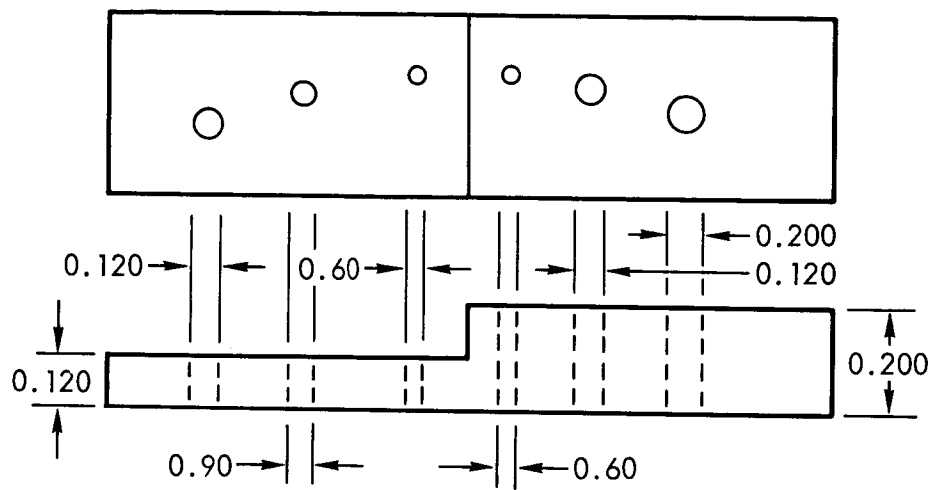


Figure 3.1-15. Details of Boron Nitride Block Used to Determine Optimum Keeper Insulator Design.