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by James F. Morris

Lewis Research Center

Cleveland, Ohio

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SUMMARY

Ordinary electric probes for ionized gases have thermal and edge effects. In the past, these effects were either the source of errors or the cause of enlarged probes.

Now, however, cylindric, spheric, and plane probes with guard rings and thermocouples have been made nearly as small as usual Langmuir probes. Although the primary, guard, and thermocouple elements are effective, these probes are not thermally durable. This deficiency is the result of an absence of microscopic refractory tubing. Because of the lack of proper materials, nickel and ceramic cements were used. Soon, though, small high-temperature probes with guards and thermocouples can be made with tantalum and alumina tubes. These probes will be more resistant to heat and alkali metals and can be used to give more control and knowledge in plasma tests than common probes do.

INTRODUCTION

The ordinary Langmuir probe (ref. 1) is popular because it can be used to measure plasma conditions simply and locally. But these measurements are not accurate. First, since currents to the probe must be passed through sheaths that are dependent on voltage, the plasma is changed by the probe. Furthermore, the insulating support of the probe becomes charged, and electrons and positive ions are separated by the resulting floating potential. Because of this effect, a wall sheath is formed around the base of the probe. Knowledge of these sheaths and end effects is lacking, and therefore, the effective areas of probes cannot be defined. In addition, when films of conducting material are formed on dielectrics in plasma tubes, currents from the surface of the insulating support are received by the probe. Finally, if the contact potential between the probe and the plasma is changed by the probe temperature, which is dependent on probe voltage, the measured effects of properties of the ionized gas are altered (refs. 2 to 10).

Although more problems could be mentioned, the preceding difficulties are basic to the operation of a direct-current probe in a low-energy plasma. In the past, when these malfunctions were corrected, analyses became more complicated, operations were expanded, and the probe was made bigger. Perhaps this dilemma is responsible in a way for the small amount of good probe theory. If some of the experimental problems were removed or lessened, techniques and theories for plasma probes might be generally improved.

A guard ring around and a thermocouple within the primary element can be used to correct usual probe results and to obtain new data. With the thermocouple, changes in contact potential can be adjusted or avoided, and overall coefficients for energy transport can be determined. But with the guard ring wall currents can be removed, the primary can be separated from the floating potential and sheath of the insulating support, and the geometry of the primary can be continued to allow definition of the effective probe area (refs. 10 to 13). Yet with these contributions the guard must be small and the primary must not be enlarged greatly for the thermocouple. Otherwise, local data cannot be taken, and the plasma may be quenched.

In a prime sense, smallness is the contribution of this project. Separately and in large sizes thermocouples and guards are not new to the plasma probe. But together in minute probes thermocouples and guards are an innovation. Miniature plane, cylindric, and spheric plasma probes with guards and thermocouples were developed in this project.

Because their diameters were smaller than those of available refractory tubing, these plasma probes were made with ceramic cement between nickel electrodes. The present materials were utilized to reveal the problems and the potentials of minute plasma probes with guards and thermocouples. Ultimately, however, high-density alumina of high purity and a refractory metal, such as tantalum, niobium, or tungsten, will be used to assemble these probes. Then the guarded, thermocoupled plasma probes will be resistant to high temperatures and alkali metals.

These probes were designed and tested by the author and were made under contracts NAS-3 2179 and 4914 by the High Temperature Instruments Corporation, Philadelphia, Pennsylvania (ref. 14).

SYMBOLS

A_p area of primary probe

d_n diameter of gas atom

e electronic charge

i_e electronic saturation current

i_- net negative current in Maxwellian transition

j_e electronic saturation current density

j_- net negative current density in Maxwellian transition

m_e electronic mass

m_n mass of gas atom

n_e electronic number density

n_n number density of gas atoms

T_e electronic temperature

V_o plasma potential

V_p probe voltage

v_e electronic velocity

κ Boltzmann constant

λ_D Debye distance

λ_{ea} mean free path for electron-atom collisions

ν_{ea} frequency of electron-atom collisions

PROBE GEOMETRIES

The probe geometries are shown in figures 1 and 2. Except the probe size the diameters in the overall assembly (fig. 1) are between 0.25 inch for the actuator tube and 1.155 inches for the bellows. With this bellows, a 2.275-inch vacuum-tight stroke can be made. The movement is alined through the 0.5-inch-diameter guide section and the entry port in the vacuum nut on the end. When the nut is welded to a metal tube in which a plasma is to be contained, the adapter package can be screwed in to deform two copper gaskets. Thus, the translatable probe is sealed into the environment of the plasma.

During storing and shipping the internal gasket is replaced by a copper disk. With this disk contaminants are excluded from the inside of the package after it is heated in a vacuum. A stay rod that is not shown is used to prevent the fragile probe from being pushed against anything. When the adapter package is in place and the stay rod is removed, the probe can be inserted safely into the tube for the plasma. If these precautions are not taken, the probes can be destroyed easily; their insulating supports are only 45 mils for thermocoupled and 25 mils for nonthermocoupled versions.

Yet in figure 2 the insulating supports appear to be much larger than the other tip details of the guarded plasma probes. Here thermocoupled planar (fig. 2(a)), spheric (fig.

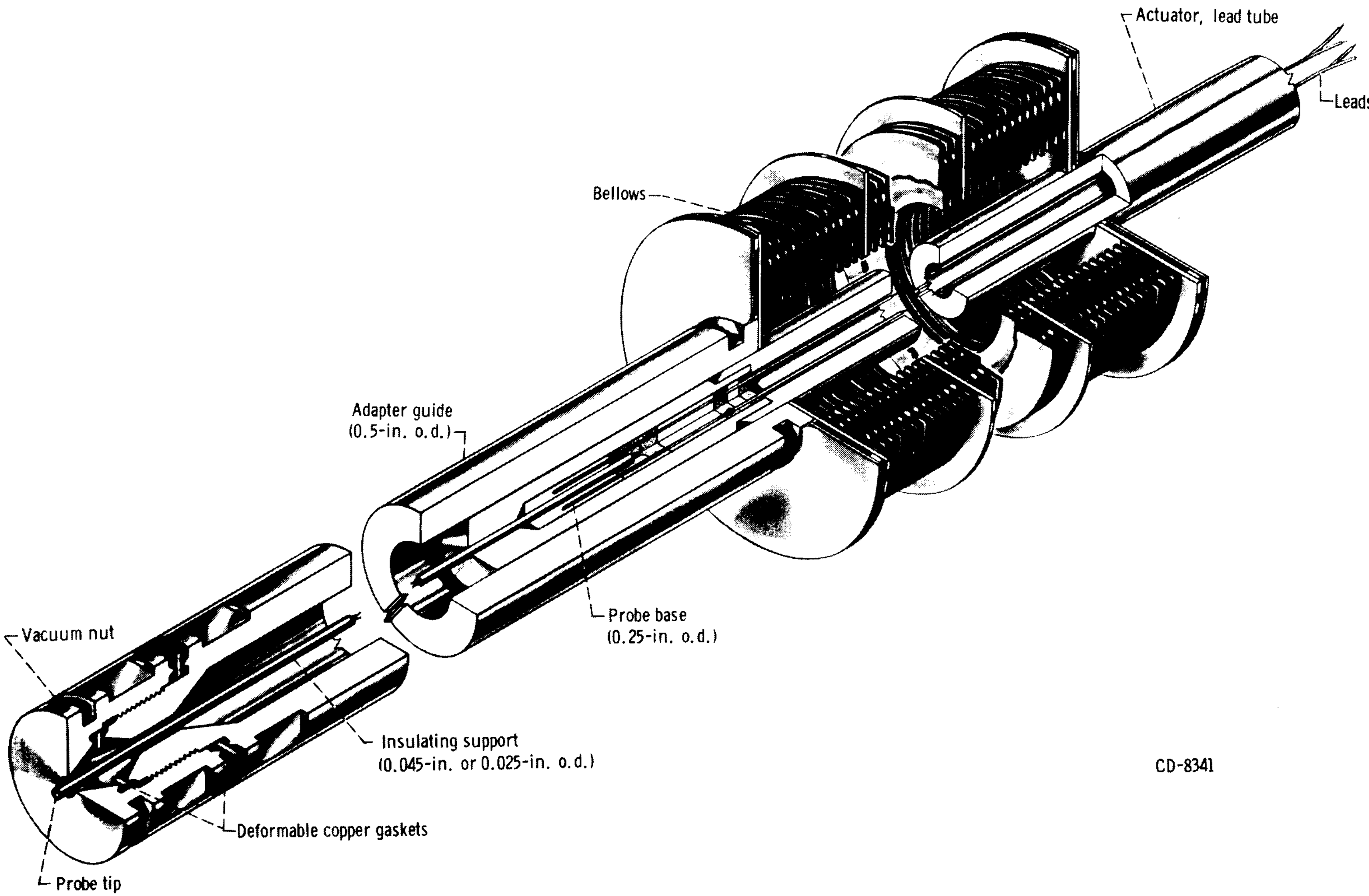
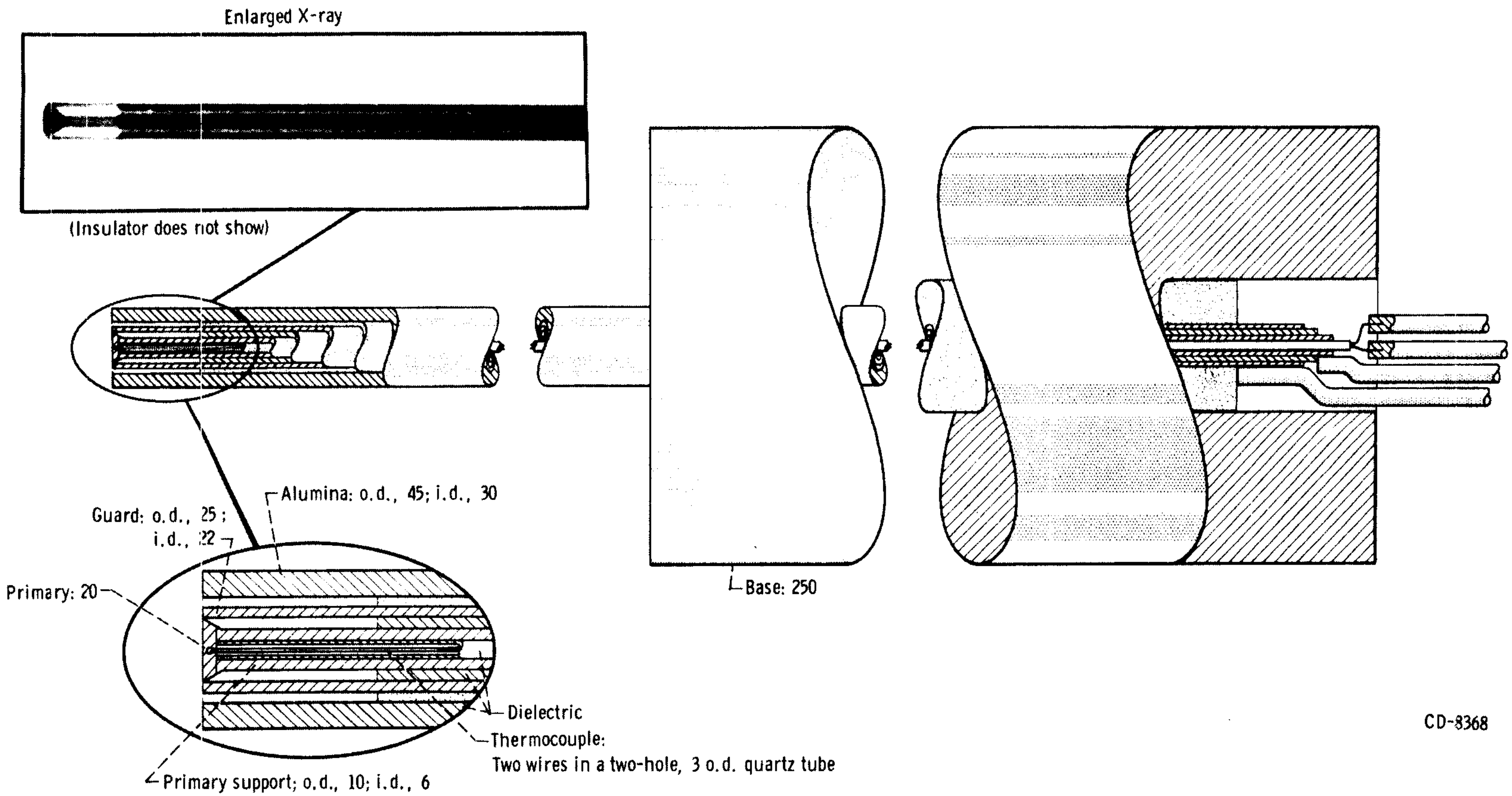
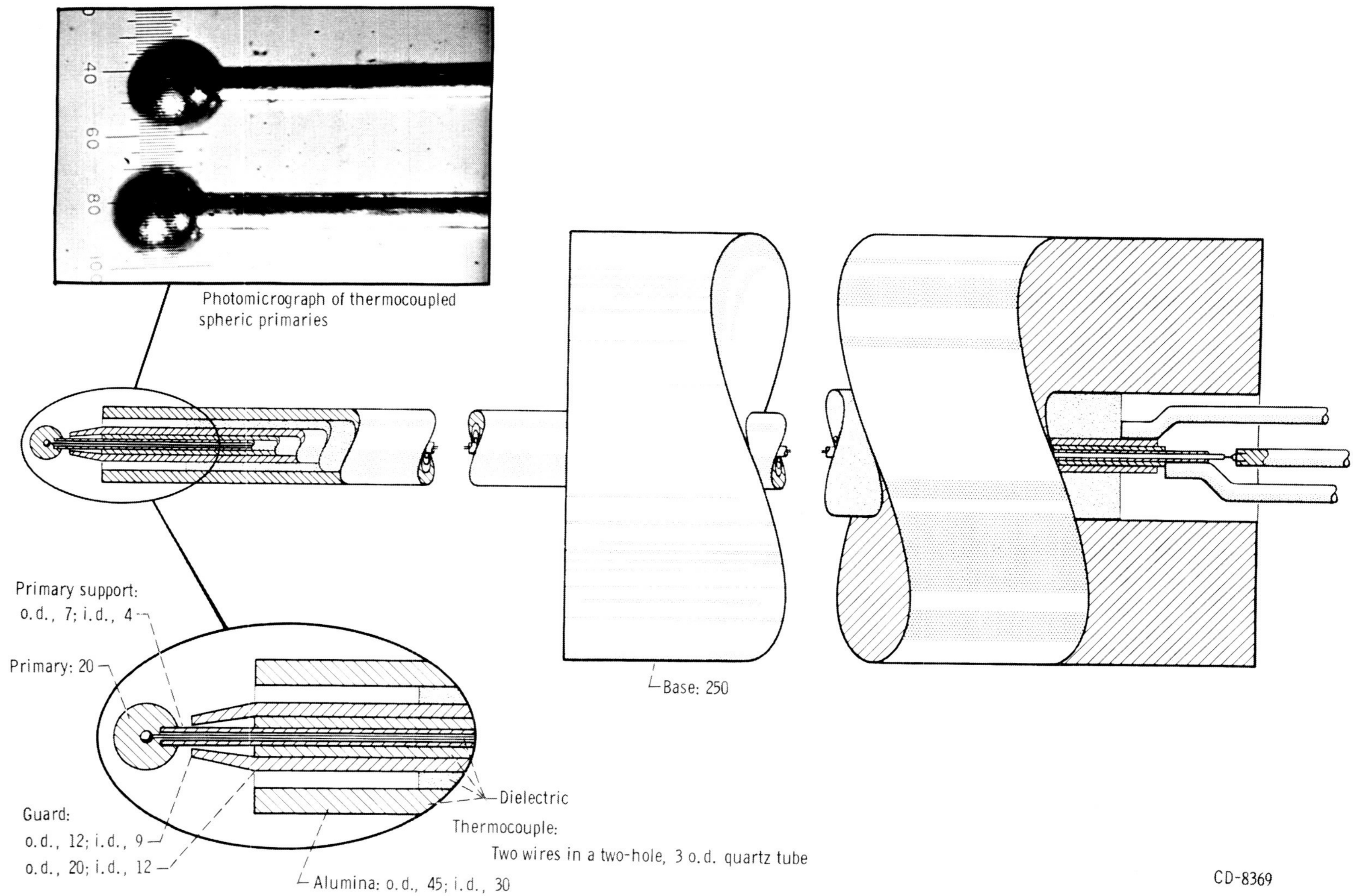


Figure 1. - Plasma probe in adapter package.



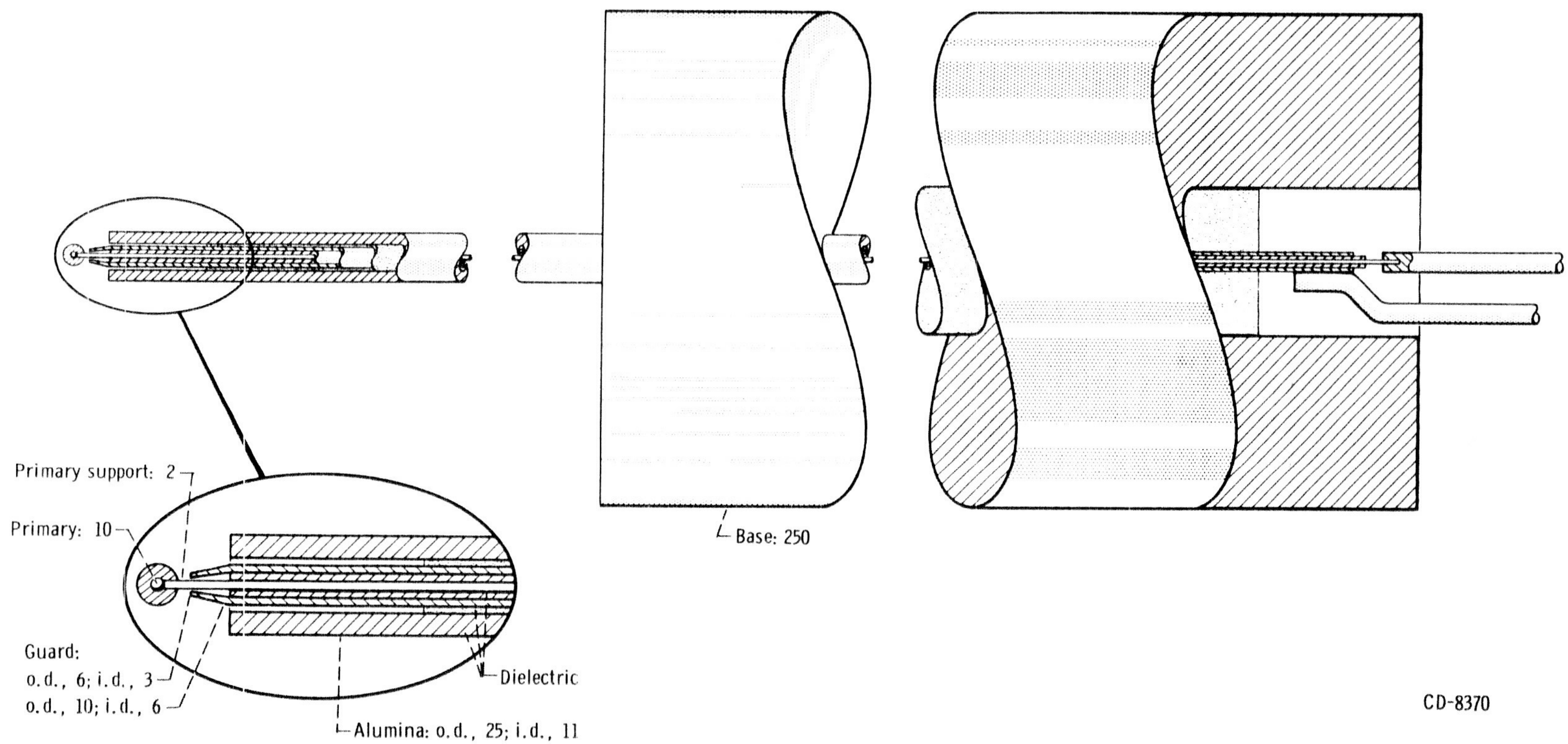
(a) Guarded, thermocoupled plane plasma probe.

Figure 2. - Plasma probes (diameters in mils).



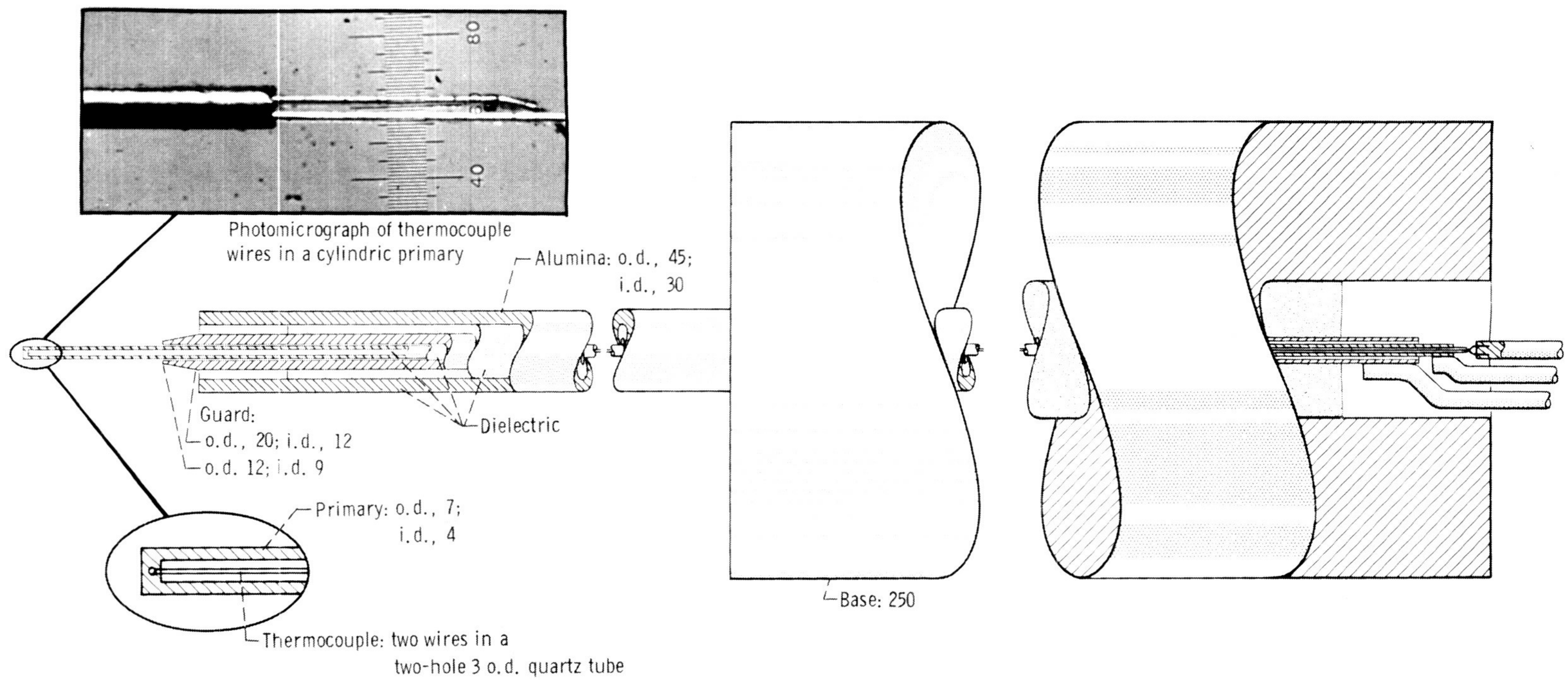
(b) Guarded, thermocoupled spheric plasma probe.

Figure 2. - Continued.



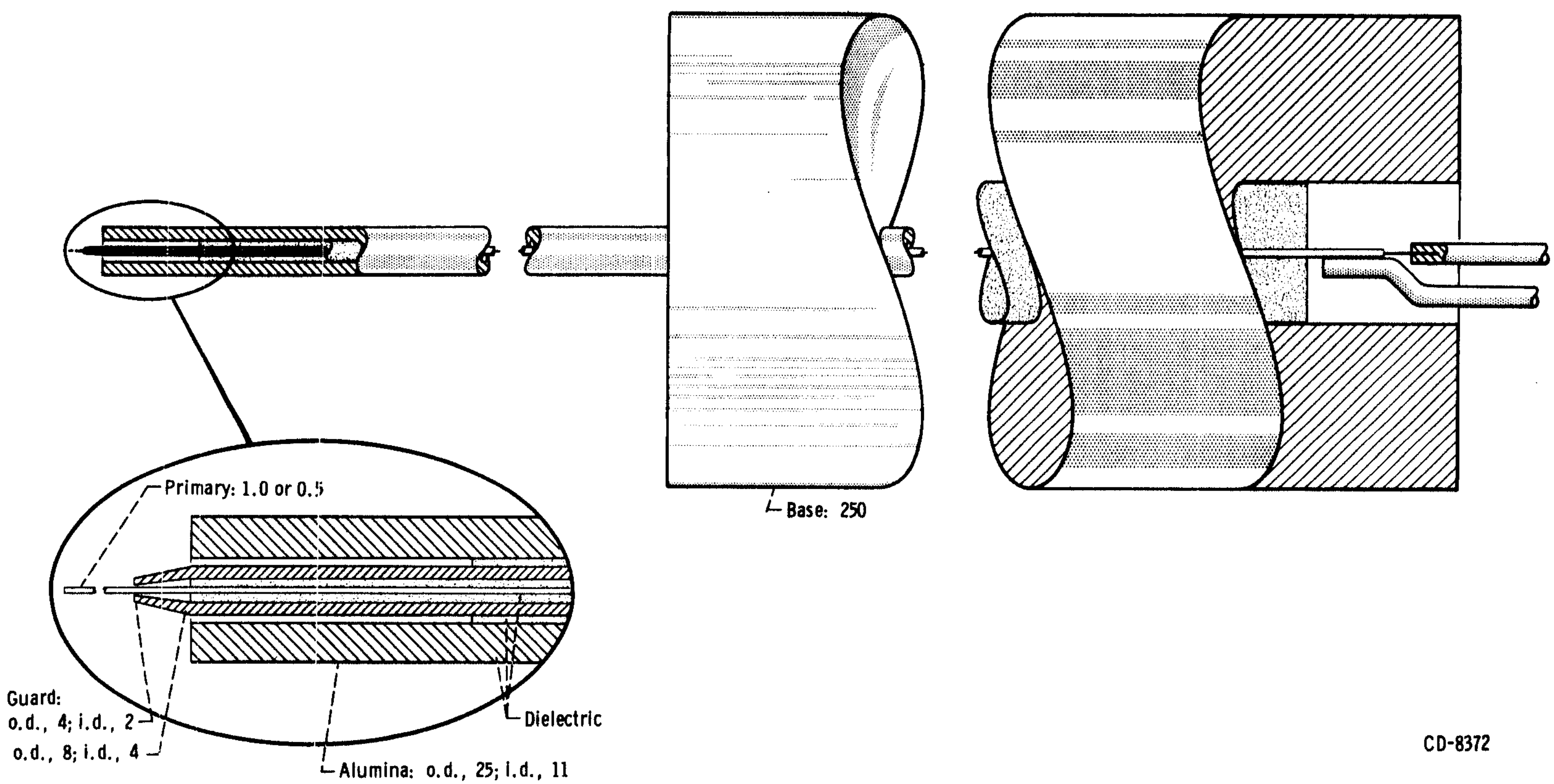
(c) Guarded spheric plasma probe.

Figure 2. - Continued.



(d) Guarded, thermocoupled cylindric plasma probe.

Figure 2. - Continued.



(e) Guarded cylindric plasma probe.

Figure 2. - Concluded.

2(b)), and cylindric (fig. 2(d)) and nonthermocoupled spheric (fig. 2(c)) and cylindric (fig. 2(e)) probes are shown. Diameters are specified in the drawings, but lengths are left to be determined for particular applications. For example, in a good design more or less of the guard is exposed as thicker or thinner sheaths on the insulating support are expected. Local measurements and small disturbances, however, are favored by short lengths as well as small diameters consistent with effective probe geometries.

The general structure of the probes is one of alternate concentric rings of conductor and insulator. Even the thermocouple was initially a single central wire of tungsten which was coupled with the nickel primary. Later this arrangement was changed to a Chromel-Constantan thermocouple in a 2-hole, 3-mil quartz tube (ref. 15). In each probe the guard is nearly touching the base of the primary. Between these electrodes, a gap is interposed to replace the usual insulator upon which charge is collected, a floating potential is developed, and a sheath is built up. The insulating support is also made to stand away from the guard. These narrow intervening spaces are intended to quench the plasma internally. In addition, the gaps prevent the collection of wall currents when films of conducting material are condensed from certain plasmas on the insulating supports. As a result, the guard, and not the primary, is affected by any edge effects.

The guard is also essential for continuing the geometry of the primary to allow the probe area to be defined. The latter function is successful in the plane probe, where the face of the primary is extended by the guard. Such extensions can also be built into large spheric and cylindric probes. In these small spheric and cylindric geometries, though, the guard is effective in defining the area only when the probe voltage is near the plasma potential. But this capability is an improvement over nonguarded probes; their areas are always distorted by the wall sheaths of the insulating supports.

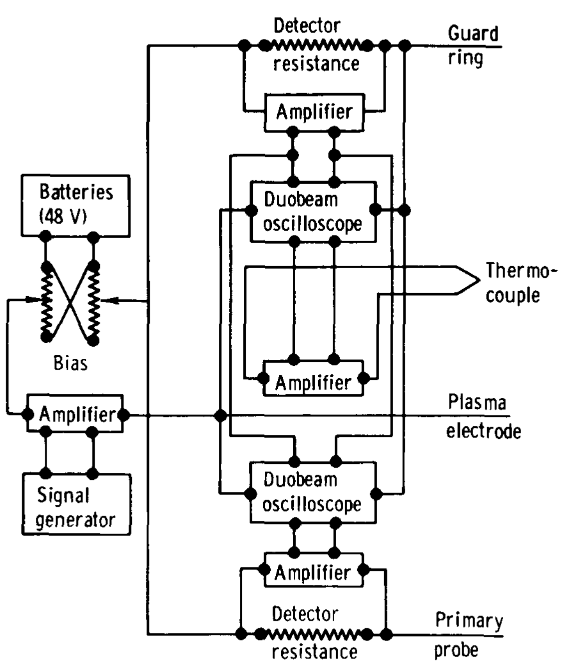


Figure 3. - Probe power and instruments.

With these comments and figures 1 and 2 the description of the probe geometries is completed. But because this new plasma probe is composed of a primary, a secondary, and a thermocouple, extra attention is required for the power supply and instruments.

PROBE INSTRUMENTS AND POWER

The probe system is an assembly of electronic shelf items (fig. 3). Some of these devices are used to generate a nearly 100-volt triangle wave with a bias and frequency that can be varied. Others are used to detect minute probe currents, to isolate and amplify thermocouple signals, and to synchronize and display guard and primary currents and temperature as functions of probe voltage.

On the left side of figure 3 are the components used to supply a biased triangle wave. This signal can be made to carry up to 40 milliamperes at 90 volts peak-to-peak with frequencies from 10^{-2} to 10^{-4} cycle per second. In the middle of the figure are the amplifiers that are used to enlarge the signals listed on the right by factors up to 10^3. These amplified data are displayed on oscilloscopes each having two traces.

The currents and temperature are shown for probe potentials that are varied about the potentials of either the emitter in the direct-current arc or the collectors in the plasma ionized by electron bombardment (fig. 4).

Although the probe and plasma systems seem simple enough, there were complications; for example, the measurements were lost initially in noise. But extensive shielding and grounding were found to remove this problem. Then only the difficulties of the probes were left.

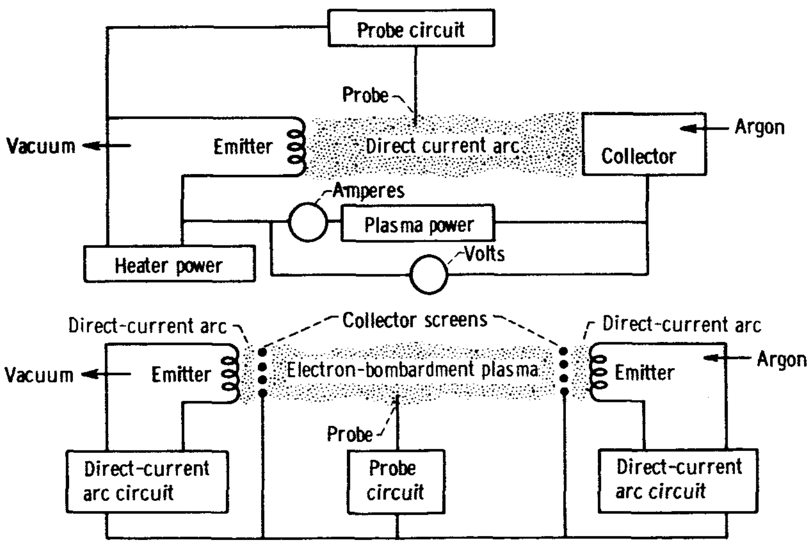


Figure 4. - Test plasmas for probes.

PROBE RESULTS

The important contributions of this work are shown in figures 1 and 2. These small yet complex plasma probes with guards and thermocouples have been made. If larger versions are required for particular conditions, the problems of assembly are less difficult. But as it was stated previously, available refractory tubes were not small enough. The probes were constructed, therefore, of an alumina external tube, nickel tubing, a ceramic cement, and the thermocouple elements. And again, though these materials were suitable to demonstrate the fabrication and operation of the probes, they are not resistant to high temperatures and alkali metals. Furthermore, the great thermal expansion of nickel is in opposition to putting the probe elements together and keeping them together during temperature changes. As a result, the probes were ruined by thermal effects before the conditions and instruments could be adjusted in many tests.

Some data were collected, however, which can be used to show how guards and thermocouples are essential to plasma probes. These added elements are intended to remove or solve the problems of edge and thermal effects. Therefore, simple interpretations of some data are given here to demonstrate the functions of the guards and thermocouples, not to exhibit detailed probe results for various plasmas.

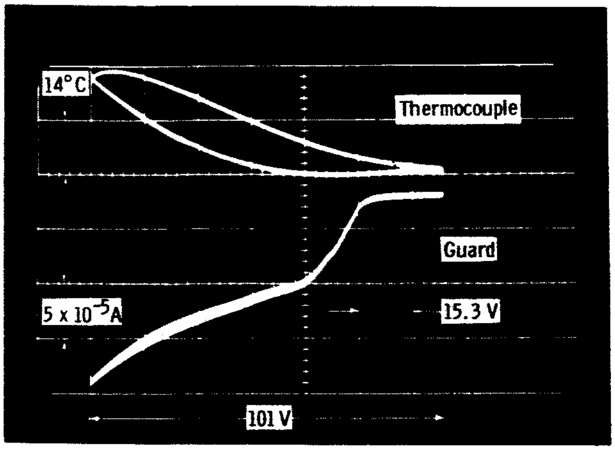
In figure 5 measurements are shown that were made with a plane probe (fig. 2(a)) in an electron bombardment plasma of argon (fig. 4, bottom). Temperatures (figs. 5(a) to (d)), primary (fig. 5(e)) and guard currents (figs. 5(a) to (e)), and calibrations are given for probe potentials that were varied at 0.1, 1, 10, and 100 cps from -75.5 to 25.5 volts relative to the collector screens. While the data were taken, the probe tip was centered radially and axially between the screens. These anodes were $3\frac{1}{2}$ centimeters in diameter, 10 centimeters apart, and 2 centimeters from their cathodes. The emitters were taken from 872A rectifier tubes made without mercury and were each heated with 8 amperes. In the direct-current arcs, 3.3 amperes each were maintained when the voltage drops were 32 volts for the discharge near the argon inlet and 9 volts for the other discharge. During this test the pressure was held at 40 microns of mercury.

From experience, it seemed probable that the nickel probe would have a short lifetime. Therefore, two different amplifications were used for the guard and primary currents to ensure at least partial success of the experiment. The circuits for the thermocouple at 1 millivolt for each large division and the guard at 5×10^{-5} ampere per division were adequately set (figs. 5(a) to (d)). With 5×10^{-4} ampere per division, however, the primary probe curve (fig. 5(e)) was not extended enough to analyze properly. Before the second series of tests with higher amplification the probe was destroyed by thermal effects.

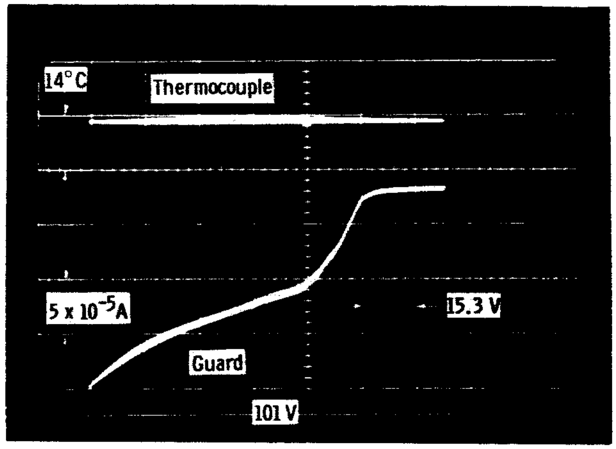
Prior to a discussion of the temperature data the plasma conditions might be estimated. Because the primary curve appears worthy of nothing elaborate, the simple Langmuir probe theory will be used. The validity of this approach will be indicated by the results.

In figure 5(e) the curve for the guard is shown above that for the primary. The line for the electron current at the top of the primary curve and its break into the transition region are quite clear. That knee can be used to compute the plasma potential (the no-sheath, total-random-current point):

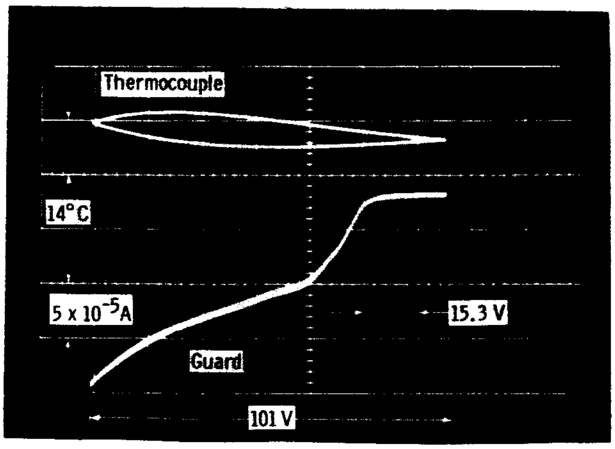
$$V_o = 25.5 - \frac{2.1}{8.7}(25.5 + 75.5) = 1.1 \text{ V} \tag{1}$$



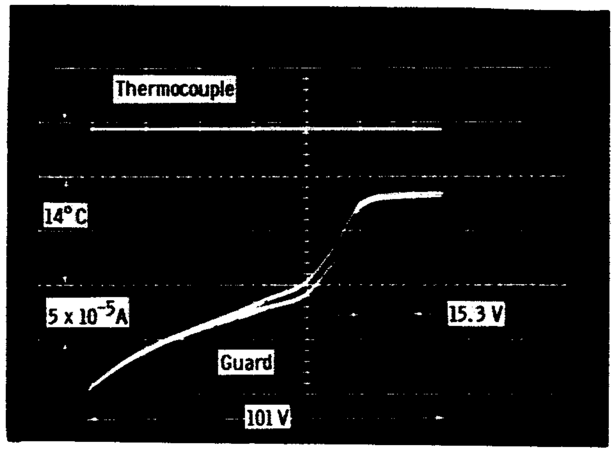
(a) Thermocouple and guard traces. Voltage cycle frequency, 0.01 cps; temperature variation, $\Delta T = 28°$ C.



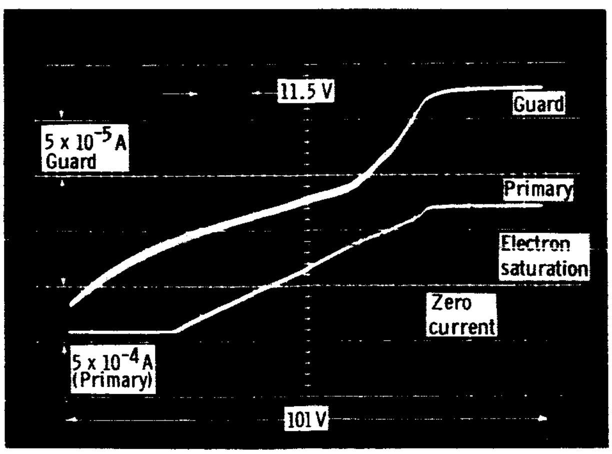
(b) Thermocouple and guard traces. Voltage cycle frequency, 10 cps; temperature variation, $\Delta T = 2°$ C.



(c) Thermocouple and guard traces. Voltage cycle frequency, 1 cps; temperature variation, $\Delta T = 10°$ C.

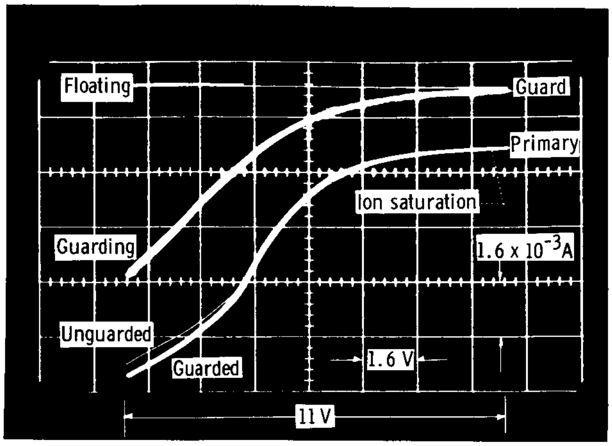


(d) Thermocouple and guard traces. Voltage cycle frequency, 100 cps; temperature variation, $\Delta T = 0°$ C.

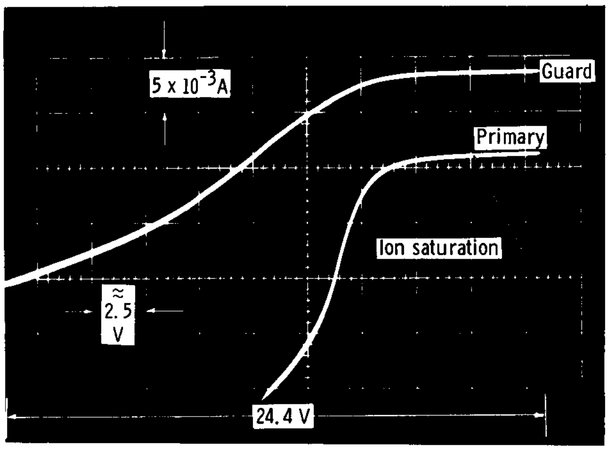


(e) Primary and guard traces. Voltage cycle frequency, 10 cps.

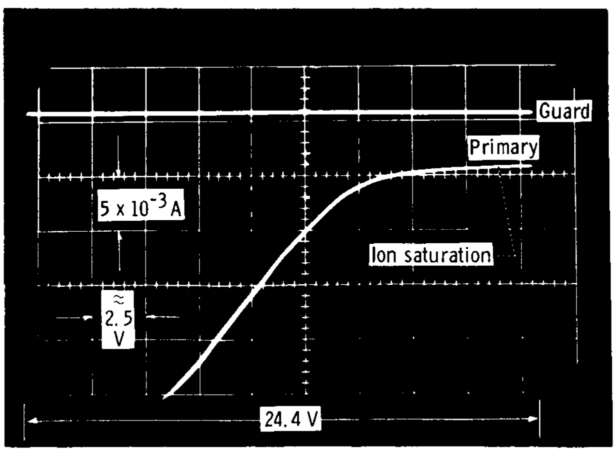
Figure 5. - Thermocouple, primary, and guard traces for runs in an electron bombardment plasma to show temperature variations with voltage cycle frequency for plane probe.



(a) Plasma held at 35.3 volts, 3 amperes, and 23 microns of mercury.



(b-1) Guarded.



(b-2) Unguarded.

(b) Plasma held at 41 volts, 0.9 ampere, and 2 microns of mercury. Voltage cycle frequency, 100 cps.

Figure 6. - Cylindric probe with and without guarding in a hot-cathode direct-current argon arc 12 centimeters long in an 8-centimeters-diameter tube.

Another characteristic of the primary curve should be pointed out. The unblurred, exactly horizontal line at the bottom left is due to amplifier saturation, not ion saturation. There is a slight bend in the probe curve 15 volts below the plasma potential, however, where the current is nearly zero. But this leveling tendency of ion saturation was apparently overwhelmed by some prebreakdown mechanism (refs. 16 and 17). As the voltage was made more negative, greater ion currents were observed. If the potential became too negative, a bright discharge was noted at the probe tip.

A second anomaly was responsible for separating the probe trace into two nearly parallel curves in the ion-saturation and transition regions. This splitting was recorded for the guard as the voltage-cycling frequencies were increased to 100 cps (fig. 5(d)). The hysteresis was probably the result of the resistance and capacitance of the positive-ion sheath (refs. 18 and 19). As the voltages were changed rapidly, the currents and the structure of the sheath were unable to shift quickly enough to follow the same curve for both rising and falling potentials.

Although the separation effect might be the product of instrumentation problems, several pieces of evidence are alined against this conclusion. First, the same instruments, power supplies, and leads to the probe tip that were used for figure 5(d) at 100 cps were utilized in obtaining the data at 100 cps for figure 6. The latter curves are not split. Next, the hysteresis (fig. 5(d), 100 cps) became less as the prebreakdown mechanism became more effective. Then ionization and recombination were occurring within and around the probe sheath. Therefore, ions were made or lost as they were required, charging and discharging the sheath internally and avoiding the lag to bring in or return plasma ions. Finally, if the sheath of positive ions was the cause of the curve separation, the hysteresis should have terminated at the plasma potential where no sheath exists. This closing of the curve is near the plasma potential. But these are data for the guard, which was always in contact with the sheath of positive ions of the insulating support. The probe curve for the primary, which was shielded from the sheath of the insulating support, began to split near 1000 cps.

This phenomenon is interesting as a diagnostic tool for cylindric probes. These probes are unable to give curves with sharp breaks at plasma potentials. By increasing the frequency of probe-voltage cycling to the point of curve splitting, however, the operator might estimate the plasma potential as the end of the hysteresis loop near electron saturation. Such a technique seems as good as many that are now used. Of course, the cylindric probe should be equipped with a guard to avoid effects of the ion sheath of the insulating support.

But these observations are delaying the proposed calculations of plasma conditions for the plasma of figure 5. Calibrations for the full 101-volt cycle were compared at all potential-cycling frequencies to assure their applicability. From these calibrations the electron saturation current was found to be

$$i_e = 2.55\times10^{-4}\ \mathrm{A} \tag{2}$$

The primary area was

$$A_p = \pi(0.01)^2(2.54)^2 = 2.03\times10^{-3}\ \mathrm{cm}^2 \tag{3}$$

Therefore,

$$j_e = \frac{2.55\times10^{-4}}{2.03\times10^{-3}} = 0.126\ \mathrm{A/cm}^2 \tag{4}$$

Because a semilogarithmic plot of the Maxwellian transition is impractical, another approach to the electron temperature seems necessary. The following relation can be used if the distribution is Maxwellian:

$$\frac{d \ln j_-}{dV_p} = \frac{dj_-}{j_-\,dV_p} = \frac{di_-}{i_-\,dV_p} = \frac{-e}{\kappa T_e} = \frac{11\ 600}{T_e} \tag{5}$$

The slope of the Maxwellian transition for the primary curve (fig. 5(e)) in the region of electron saturation is approximately

$$\frac{di_-}{dV_p} \approx 5.65\times10^{-5}\ \mathrm{A/V} \tag{6}$$

This rate (6) and the electron saturation current (2) can be used in equation (5) to estimate the electron temperature:

$$T_e = 11\ 600\ \frac{i_-\ dV_p}{di_-} \approx 52\ 400^{\circ}\ \mathrm{K} \approx 4.5\ \mathrm{eV/electron} \tag{7}$$

Then, the electron number density is given by

$$n_e = \frac{j_e V_o}{e}\left(\frac{2\pi m_e}{\kappa T_e}\right)^{1/2} \approx 2.2\times10^{10}\ \mathrm{cm}^{-3} \tag{8}$$

If the gas temperature were 386° K at a pressure of 40 microns of mercury, 10^{15} neutrals would occupy a cubic centimeter of such a plasma. This type of ionized gas would be similar to the Lorentz electron and atom model ($n_e << n_n$, $m_e << m_n$), where the temperature of the neutrals should be low, of the order of 386° K. In such a gas collisions of electrons would be primarily with neutral atoms. The mean free path for these encounters between electrons and atoms should be near

$$\lambda_{ea} = \frac{v_e}{\nu_{ea}} \approx \frac{1}{\pi n_n d_n^2} \approx 0.22\ \mathrm{cm} \tag{9}$$

where d_n is the cesium atom diameter ($\approx 3.8\times10^{-8}$ cm). This length is in contrast with average distances between coulombic collisions of the order of 10^3 centimeters (refs. 20 and 21). But of course, mean free paths near to or greater than the plasma dimensions lack significance. For this test, therefore, the length separating collisions of electrons with atoms (eq. (9)) must be considered in the selection of probe dimensions. Because the probe diameter is about half of the smallest mean free path, replenishment of the distribution is partially blocked, and the measured electron number density is probably slightly low.

When the distance between collisions is large compared with the sheath thickness, the Langmuir theory is applicable. Because there is no sheath at the plasma potential, the point for which these calculations were made, the assumption of no collisions was fulfilled. It might be wise, though, to check how the sheath thickness could vary through the Maxwellian transition to the floating potential, where the wall sheath is present. The distance through the wall sheath, which maintains the plasma, is assumed to be of the order of a Debye length:

$$\lambda_D \approx 6.9\left(\frac{T_e}{n_e}\right)^{1/2} \approx 6.9\left(\frac{52\,400}{2.2\times10^{10}}\right)^{1/2} \approx 0.01 \text{ cm} \tag{10}$$

The value obtained is much smaller than the smallest computed mean free path for electrons. The Debye length is also less than one-sixth of the overall active probe diameter. Thus, within the limits of the assumptions, the Langmuir theory should be a good approximation.

For the plasma with properties given by equations (7) and (8), temperature data taken with the Chromel-Constantan thermocouple in the planar primary are shown in figures 5(a) to (d). The probe was operated at 0.1, 1, 10, and 100 cps from 24.4 to -76.6 volts relative to the plasma. The thermocouple circuit was set to amplify by 10^3; thus, 14° C was spread vertically over one big division.

The probe temperature for 0.1 cps (fig. 5(a)) was terminated on the right at 29° C for 24.4 volts. There the probe was receiving the random electron current. At the left end of the loop the temperature was near 53° C for -76.6 volts, where accelerated ions heated the probe. Apparently ion currents that were created by the previously mentioned prebreakdown mechanism were responsible for much of the temperature rise. Usual thermal inertial effects were the cause of the maximum of 55° C and the minimum of 27° C, an overall change of 28° C. This difference was lowered through 28°, 10°, 2°, and 0° C as the probe-voltage frequency was raised through 0.1, 1, 10, and 100 cps. But the average temperature was changed only a few degrees upward as the frequency was increased from 0.1 to 100 cps.

In the series shown in figure 5, thermal effects are emphasized even though the data were collected from a plasma with little heating tendency. Probe surfaces are altered with temperature changes, and the resulting differences in contact potential between the probe and the plasma are sources of error. Many plasma devices are run with high temperatures, great thermal gradients, and condensing gases. When probes are needed in these conditions, thermocouples can be used to correct for or to avoid large thermal effects. Furthermore, with the right geometry or proper calibration, a thermocoupled probe can be used to estimate overall energy transport in a plasma.

In any event, the thermocouple is necessary to follow or to fix probe temperatures. But the guard is even more essential. If the probe is operated in an ionized gas containing a conducting material that is condensing, the guard is a shield against wall currents. However, many important plasmas are made up of gases that are neither condensable nor conductive at wall temperatures. Then the guard can only be used to separate the primary from the floating potential and the wall sheath of the insulating support. These base effects are important in plane probes; cylindric versions, though, are made long compared with their diameters to reduce end errors. Operating a cylindric probe at constant plasma conditions first with the guard disconnected and then with the guard at the primary potential should test shielding against the voltage and sheath of the support.

Figure 6 gives the results obtained with the guard either isolated or connected to the voltage of a cylindric primary. The thermocoupled probe was centered axially and radially in a direct-current hot-cathode arc of argon (fig. 4, top) 12 centimeters long in an ungrounded metal tube 8 centimeters in diameter. When the probe voltage was cycled in a hundredth of a second, the problem of temperature variation was removed. While the plasma for figure 6(a) was held at 35.3 volts, 3 amperes, and 23 microns of mercury, the probe was driven from 5.9 (left) to -5.1 (right) volts relative to the emitter. The heavy curves are data for the guard at primary potential, which can be compared directly with results for the disconnected guard shown by the light lines.

Without shielding, the electron current of the primary is lowered because of the negative wall potential at the base of the probe. This shift is approximately 0.4 milliampere, but the relative change is great enough to reveal the problem. Although the end effect seems to be confined to the electron collection region in figure 6(a), situations can be found to show guard contributions near ion saturation.

For example, figures 6(b) and (c) were obtained for the probe and plasma tube of figure 6(a) in a direct-current hot-cathode arc of argon. Here, though, the data were taken at primary voltages near the floating potential with operating conditions changed to 0.9 ampere, 41 volts, and 2 microns of mercury. The right ends of the traces are 10.9 volts below the emitter with the left ends of the curves 13.4 volts above the emitter but slightly out of the photographs.

In figure 6(b) the curve for the guarded primary is seen to break abruptly away and to slope sharply downward from the nearly horizontal line for the ion current. In figure 6(c) the trace for the unguarded primary is shown to curve slowly away and to slant gently downward from ion saturation. Actually, the primary data of figure 6(c) are much like the guard data of figure 6(b). This similarity might be expected because both results were influenced by floating potential and wall sheath. Even in this probe curve the ion current is changed little from the guarded to the unguarded primary, but ion currents are generally near zero. Shielding, however, is responsible for major differences in the Maxwellian transition near ion saturation.

When these errors in the transition and electron saturation regions are not removed by a proper guard, the two best measurements of the Langmuir probe are jeopardized.

From these data the electron temperature and number density are computed. Thus, guards are needed by plasma probes even when wall currents are not problems, and thermocouples in primaries are necessary to correct probe data or to avoid such adjustments by isothermal operation and to obtain additional information.

For these reasons, guards and thermocouples are essential if plasma probes are required to determine local properties in ionized gases. The minute plasma probes developed in this work, however, are not resistant to alkali metals and high temperatures. But a prototype of tantalum and alumina has been made and cycled without failure for hours in a plasma that the nickel probes would not have survived long. Unfortunately, this new cylindric probe was equipped with a faulty thermocouple. Development of refractory probes is continuing.

CONCLUDING REMARKS

Ionized gases are changed by Langmuir probes. Part of this transformation is caused by the insulating support with its floating potential and wall sheath. The floating potential and the wall sheath are also immediately adjacent to the base of the probe itself. Thus, the usual Langmuir probe is a wire extending from a negatively charged insulator through a positive ion sheath into a plasma altered by the presence of a foreign body.

Of course, any attempt to make a truly local measurement is expected to affect the ionized gas. But if this kind of testing is necessary, it should be done accurately. Minute plasma probes with guards and thermocouples can be used to obtain data corrected for thermal and base effects. These probes are also small enough to cause little more disturbance than conventional versions and to take spatially discrete data in many plasmas.

Lewis Research Center,
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