NASA TECHNICAL NOTE

NASA TN D-5463

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NASA TN D-5463

EXPERIMENTAL INVESTIGATION OF A PLASMA-COVERED CAVITY-BACKED SLOT ANTENNA

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1969

1. Report No. NASA TN D-5463	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EXPERIMENTAL INVESTIGATION OF A PLASMA-COVERED CAVITY-BACKED SLOT ANTENNA		5. Report Date November 1969
		6. Performing Organization Code
7. Author(s) Thomas G. Campbell and William F. Croswell		8. Performing Organization Report No. L-6659
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 125-21-04-01-23
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

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17. Key Words Suggested by Author(s) Plasma diagnostics; Slot antenna; Antenna detuning; Communications blackout	18. Distribution Statement Unclassified – Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	22	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

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SUMMARY

The tuning (or detuning) effects of plasma upon an electrically small cavity-backed slot antenna have been studied by using a rectangular plasma slab. The results from the slot antenna are compared with experimental and theoretical results from a rectangular waveguide aperture at the same operating frequency. A Langmuir probe survey of the slab was made to determine the longitudinal, transverse, and normal variations of electron density. The rectangular waveguide measurements and calculations were also used to corroborate the electron density survey. Swept-frequency measurements indicated the increase in slot resonant frequency, and accompanying changes in signal strength were observed at the various resonant frequencies in air and in the plasma environment. The slot admittance measurements also indicated that plasma diagnostic information could be achieved during a reentry plasma experiment.

INTRODUCTION

In most very-high-frequency (VHF) spacecraft instrumentation systems, electrically small antennas are used to meet the size and weight requirements usually imposed by the spacecraft. Several techniques are used to reduce the physical dimensions of these antennas. These techniques include dielectric loading and attaching lumped constant tuning circuits (refs. 1 and 2). The penalties for using these techniques are that the antenna is nonamenable to a theoretical analysis, suffers a reduction in bandwidth and efficiency, and becomes very sensitive to the reentry environment. A cavity-backed slot antenna is one example of an electrically small antenna that has been used for many spacecraft and reentry applications.

The purpose of this paper is to present the changes in input admittance of a typical spacecraft telemetry antenna (i.e., a cavity-backed slot antenna) and those of a rectangular waveguide when both antennas radiate into the same plasma slab under identical experimental conditions. Calculated admittance values for the rectangular aperture are used to determine the limitations of the plasma slab in simulating a plasma sheet of infinite extent. From a comparison of the experimental results, certain empirically determined conclusions about the performance of electrically small antennas in a reentry environment are suggested.

The experimental plasma sheet was provided by a brush-cathode glow discharge slab (ref. 3) described herein. The results of a Langmuir probe survey of the plasma slab are also presented.

SYMBOLS

D	width of coaxial waveguide adapter
e	electron charge
I	probe current
j_e	random plasma electron current density
k	Boltzmann's constant
$(L/\lambda_v)_r$	slot resonant length-to-wavelength ratio
m	mass of electron
N_e	electron density
$N_{e,o}$	peak electron density
$R/Z_o, X/Z_o$	normalized slot resistance and reactance, respectively
T_e	electron temperature
V	probe voltage
z_o	plasma thickness, inches (centimeters)
Γ	reflection coefficient
ϵ	relative dielectric constant

λ_v wavelength in a vacuum

ν electron-neutral collision frequency

ω angular frequency of propagation

ω_p plasma frequency, $2\pi(8.97 \times 10^3)\sqrt{N_e}$

PLASMA EXPERIMENT APPARATUS

The plasma facility used in this experiment was similar to the one used in reference 4 with respect to fabrication, operation, and calibration. Photographs and a sketch of the discharge plasma slab are shown in figure 1. The apparatus is composed of a brush cathode and an anode contained in a rectangular quartz box 24 by 24 by 1.62 inches (61 by 61 by 4.12 cm). The quartz-box wall thickness is 0.125 inch (0.318 cm). The brush cathode was fabricated by stacking and soldering onto a base plate 8000 pointed tungsten needles 20 mil (0.0508 cm) in diameter 2 inches (5.08 cm) in length.

The rectangular quartz box is open on the anode side and the remaining sides contain the discharge to form a homogeneous plasma slab with the box dimensions. The test antennas were attached to the center of the 24- by 24-inch (61 by 61 cm) ground plane and the discharge apparatus was placed over each antenna as shown in figure 1. The ground plane and antenna combination was coated with a 4-mil (0.01 cm) layer of poly(ethylene terephthalate) to insulate the ground plane from the cathode. A sheet of poly(ethylene terephthalate) was also placed in the section ABCD of figure 1(d) when the admittance measurements were made. For the electron density survey, the plastic sheet in section ABCD was replaced by a glass plate with Langmuir probes in test position.

These probes and plate could be arranged in section ABCD so that the longitudinal, transverse, and normal distributions of the electron density in the vicinity of the antenna could be determined. Helium was continuously supplied through the cathode and into the slab at a rate sufficient to maintain a pressure in the vacuum tank of 400 micrometers of Hg. The discharge performed best at this pressure. A voltage range from 0 to 5000 volts was furnished by a 10-kVA power supply. The ripple was less than 0.10 percent which was necessary to prevent the power supply from modulating the admittance measurements by producing instabilities in the plasma slab.

The rectangular slab and antenna ground plane as shown in figure 1(a) were placed on a metal stand in a 4-foot-diameter (1.22 m) cylindrical vacuum tank. Microwave absorber material was used to line the inside walls of the tank to minimize sidewall reflections. A receiving antenna (coaxial waveguide adapter) was placed at the top of the tank at a far-field distance greater than $2D^2/\lambda_v$ (where D is the width of the coaxial waveguide adapter). The necessary radio-frequency (rf) cables, power supply leads, and plastic tubing were routed through adapters in the rear of the tank. Digital meters were used to measure slab voltage, slab current, Langmuir probe current, Langmuir probe voltage, and tank pressure. Circuits were provided for obtaining probe characteristics, and the outputs of probe current, probe voltage, and discharge current were simultaneously recorded on a digital printer.

The admittance measurements were obtained by using a commercial impedance bridge with a visual Smith chart display and a signal generator whose frequency was continuously monitored by a direct readout frequency meter. The amplitude and phase of the impedance bridge could be balanced to achieve a calibrated admittance measurement at the desired reference plane. The changes in slot resonant frequency and the relative signal attenuation through the plasma slab were determined by using a swept-frequency measurement system. This system included a sweep oscillator, network analyzer, directional coupler, x-y plotter, and crystal detectors. Swept-frequency reflection-coefficient measurements could be obtained by connecting the sweep oscillator to a bidirectional coupler whose output was in turn connected to the antenna under test. The range of the sweep oscillator could be adjusted to observe the performance of the antenna over any frequency range between 1 and 2 GHz. The output power of the sweep oscillator was leveled externally to maintain a constant output over the swept-frequency range. The detected output of the reflected power port of the directional coupler was then connected to the network analyzer. After the proper adjustments were made to the network analyzer, an oscilloscope display of the reflection coefficient over the swept-frequency range was provided. Permanent curves of the reflection coefficient were obtained by connecting an x-y plotter to the recorder outputs of the oscilloscope.

The relative signal attenuation measurements were obtained by disconnecting the network analyzer from the reflected power port of the directional coupler and reconnecting the detector-analyzer combination to the receiving antenna at the inside top of the vacuum chamber. For these measurements the received signal from the test antenna was detected and then displayed on the oscilloscope of the network analyzer over the swept-frequency range. The x-y plotter again provided a permanent record, but for this case records of signal level variation for each plasma condition were provided.

This complete facility, including the plasma slab, power supply, instrumentation, and various rf measurement systems, provided the apparatus for conducting a well-controlled plasma experiment.

LANGMUIR PROBE SURVEY OF DISCHARGE SLAB

An electron density survey of the discharge slab was conducted by using Langmuir probes. This survey indicated the electron distributions and the peak density that could be generated in the slab. After determination of the peak density, the usable frequencies for the antenna tests were selected.

The Langmuir probes were made from 20-mil (0.0508 cm) platinum wires and placed into glass plates so that 0.394 inch (1 cm) of wire was exposed to the plasma. The probes were potted to the glass plates and several probe arrangements were used to determine the longitudinal, transverse, and normal distributions of electron density.

As described in reference 5 (pp. 19-20, 138-140), the absolute electron temperature T_e can be determined from the slope of the curve of the logarithm of current as a function of voltage in the retarding field region of the probe. This method indicated that the electron temperature in the experimental plasma slab was 7600° K. The theoretical electron density can be determined from the following equation:

$$N_e = \frac{j_e}{e}\sqrt{\frac{2\pi m}{kT_e}}$$

The actual electron density in the slab cannot be determined quantitatively because of the measurement uncertainty of the Langmuir probe. The I-V characteristics of the Langmuir probes were obtained, and the slope intercept method indicated that the peak electron density $N_{e,o}$ was approximately 7.3×10^{10} cm^{-3}. Again, due to the measurement uncertainty of the probes used, this density is believed to be lower than the actual density by a factor of 3. The measured density was sufficient, however, for rf measurements through critical density at a frequency of 1.27 GHz with a resultant peak value of $\left(\omega_p/\omega\right)^2$ of 3.6. Since the brush cathode is similar to the one used in reference 4, the collision frequency was expected to be the same, that is, 4.45×10^8 collisions/second. Therefore, the theoretical collision frequency would make $\nu/\omega = 0.05$ at this operating frequency.

The relative longitudinal distribution of electron density, as shown in figure 2, is approximately exponential across the length of the slab. Consequently, about a 25-percent drop in electron density occurred across the surface of the small slot antenna and approximately a 38-percent drop occurred across the rectangular waveguide aperture. The transverse electron density was found to be fairly uniform across the slab, and there was essentially no variation in electron density normal to the antenna surface within 0.125 inch (0.318 cm) of the container surface.

ADMITTANCE OF A RECTANGULAR WAVEGUIDE APERTURE

To adjudge the limitations of the plasma slab in simulating a plasma sheet of infinite extent, the admittance of a plasma-covered 3.25- by 6.25-inch (8.25 by 15.88 cm) waveguide aperture was measured and the values were then compared with the calculated values. The rectangular waveguide was attached to the ground plane of figure 1 and placed in the plasma facility. By use of the commercial impedance bridge described previously, the admittance of the waveguide aperture was obtained as a function of the plasma slab current at an operating frequency of 1.27 GHz. From these measurements, the reflection coefficient could also be determined as a function of the plasma slab current. Theoretical values of the aperture admittance were obtained at the operating frequency over a range of $(\omega_p/\omega)^2$ from 0.05 to 100 for several values of collision frequency. These admittances were calculated for a plasma thickness z_o of 1.62 inches (4.12 cm) which is the thickness of the experimental plasma slab (fig. 1).

In figure 3, the measured and calculated waveguide reflection coefficients are plotted as a function of plasma tube current and $(\omega_p/\omega)^2$. The Langmuir probes were used to infer the electron density or $(\omega_p/\omega)^2$. This comparison is presented primarily to indicate that, even though the electron density may not be quantitatively determined, at least the experimental plasma will exceed critical density since the measured reflection coefficient Γ for the maximum tube current generally corresponds to a calculated Γ for $(\omega_p/\omega)^2 > 1.0$. The saturation of the measured Γ also indicates that $(\omega_p/\omega)^2 > 1.0$. Disagreement evident in the slope of the measured curve is probably due to the experimental plasma nonuniformities over the waveguide surface and collision-frequency effects. As mentioned previously, a 38-percent drop in electron density occurs across the aperture.

The admittance results are presented in figure 4. Additional waveguide admittance values were computed for several collision frequencies and for $z_o = 1.62$ inches (4.12 cm). Measured admittance values at the lower densities were in better agreement with the computed values for $\nu/\omega = 0.04$ and $z_o = 1.62$ inches. Therefore, this agreement between theory and experiment for $\nu/\omega = 0.04$ indicates that the plasma collision frequency ν is slightly lower than that predicted in reference 4. A lower collision frequency at the lower densities could possibly be due to the existence of fewer organic impurities in the slab. At the higher densities, the collision frequency increased as indicated by the higher measured conductance values. This condition can be seen in figure 4 as the measured admittance curve crosses the computed curve at $(\omega_p/\omega)^2 = 0.90$. The increase in collision frequency could possibly be due to temperature effects altering the collision frequency as attempts were made to generate higher electron densities with the experimental slab.

RESULTS FROM PLASMA-COVERED CAVITY-BACKED SLOT ANTENNA

The dimensions of a VHF cavity-backed slot antenna (2- by 10-inch (5.08 by 25.4 cm) slot with a cavity depth of 3 inches (7.62 cm)) used on a recent reentry spacecraft were reduced to 0.20 scale and fabricated accordingly. A suitable scale factor was chosen based on the peak electron density expected in the discharge slab. The dielectric window material was quartz ($\epsilon = 3.3$); the feed and tuning arrangements were similar to the full-scale antenna and are shown in figure 5. The cavity on the full-scale slot antenna was encapsulated with a low-density foam to prevent corona.

The 0.20-scale slot antenna was designed so that it would exhibit impedance characteristics similar to those of the full-scale VHF slot antenna. The impedance characteristics of the 0.20-scale slot antenna attached to a 24- by 24-inch (61 by 61 cm) ground plane are compared with those of the full-scale slot antenna in figure 6. The antennas did provide somewhat similar impedance and bandwidth characteristics so that the response of the 0.20-scale slot antenna should be indicative of the response of the full-scale slot antenna.

Results of measurements of the swept-frequency reflection coefficient, admittance, and transmission loss made on the 0.20-scale cavity-backed slot antenna are presented in figures 7 to 9.

The detuning of the cavity-backed slot due to the plasma slab was determined by using the swept-frequency measurement system. The resonant frequency of the slot was 1.275 GHz in free space (fig. 7). As the electron density of the plasma was increased, the slot resonant frequency increased. This condition was indicated by the swept-frequency reflection-coefficient measurements. The relative signal attenuation curve pertaining to the peak signal level was found to agree with the resonant-frequency shift determined by the swept-frequency reflection-coefficient measurements. From an inspection of the transmission loss curves in figure 7, it can be seen that the attenuation at the free-space resonant frequency (1.275 GHz) is quite significant (between 8 and 10 dB) at the peak electron density generated $\left(N_e = 7.3 \times 10^{10}\ \text{cm}^{-3}\right.$ at a tube current of $\left.600\ \text{mA}\right)$. This attenuation (8 to 10 dB) is not intended to be quantitative mainly because of the ground-plane edge effects and tank reflections that would affect the accuracy of such a measurement. The measurement does indicate, however, that a considerable loss in signal would be experienced with electrically small antennas as the plasma approaches critical density. The increase in resonant frequency would therefore cause an increase in the slot length-to-wavelength ratio $\left(L/\lambda_v\right)_r$ as the electron density is increased. This effect is shown in figure 8.

The admittance and reflection-coefficient measurements were made at the free-space resonant frequency (1.27 GHz). For comparative purposes, the slot admittance is shown in figure 4 along with the measured and computed admittances for the rectangular waveguide. As expected, the slot conductance is more sensitive and changes more rapidly than the waveguide conductance. However, the change in susceptance is not quite as sensitive. In figure 9, the impedance is presented as a function of tube current. Also shown in figure 9 is the impedance as a function of time (plasma density increases with time) of a plasma flight experiment discussed in reference 2. Therefore, it can be seen that the resonant characteristics of R/Z_o and X/Z_o of this slot antenna could be used in plasma diagnostics to denote critical density. In figure 3, the measured slot and measured rectangular waveguide reflection coefficients are shown as a function of tube current, and the maximum reflection coefficient for both antennas occurs within a factor of 2 of the same value of tube current.

CONCLUDING REMARKS

The results of the Langmuir probe and rectangular waveguide surveys of the rectangular plasma slab indicate that electron density nonuniformities did exist and that the collision frequency probably changed as the peak densities were generated. Even though this condition existed, as well as the fact that collision frequency and electron density could not be determined quantitatively, it is still believed that the rectangular plasma slab was adequately defined especially with respect to the occurrence of the electron critical density. It was also demonstrated that the slab was extremely stable and its repeatability of the same density for both the waveguide and the slot was excellent. The rectangular brush-cathode plasma slab produced an extremely quiet and stable discharge which allowed noise-free experimental admittance measurements. The cavity-backed slot admittance measurements indicated that narrow-bandwidth antennas could provide supplemental plasma diagnostic information during reentry experiments. However, the signal loss attributed to frequency detuning may preclude the use of electrically small antennas for optimum data acquisition from a given spacecraft.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 19, 1969.

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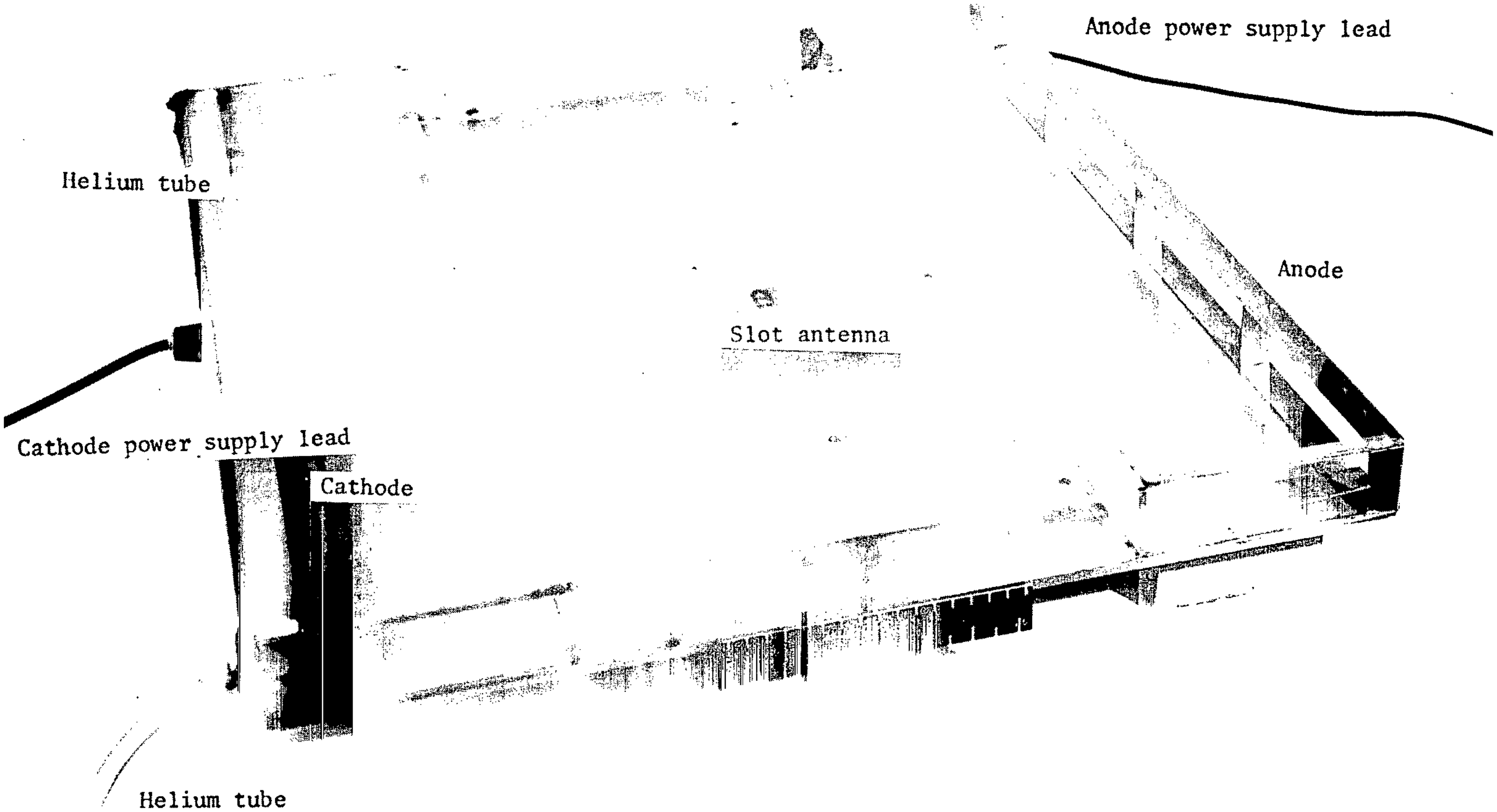
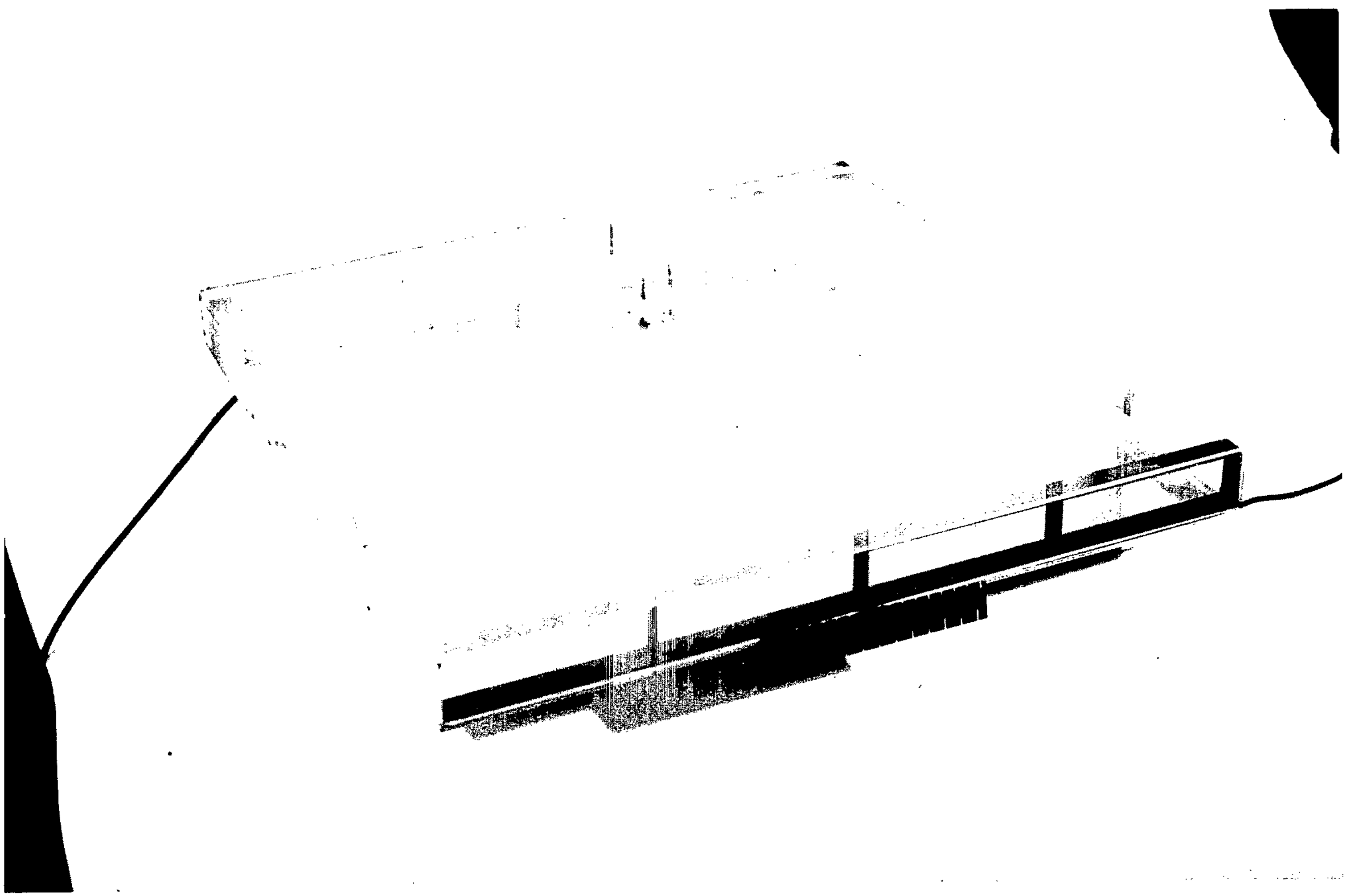


(a) Side view.

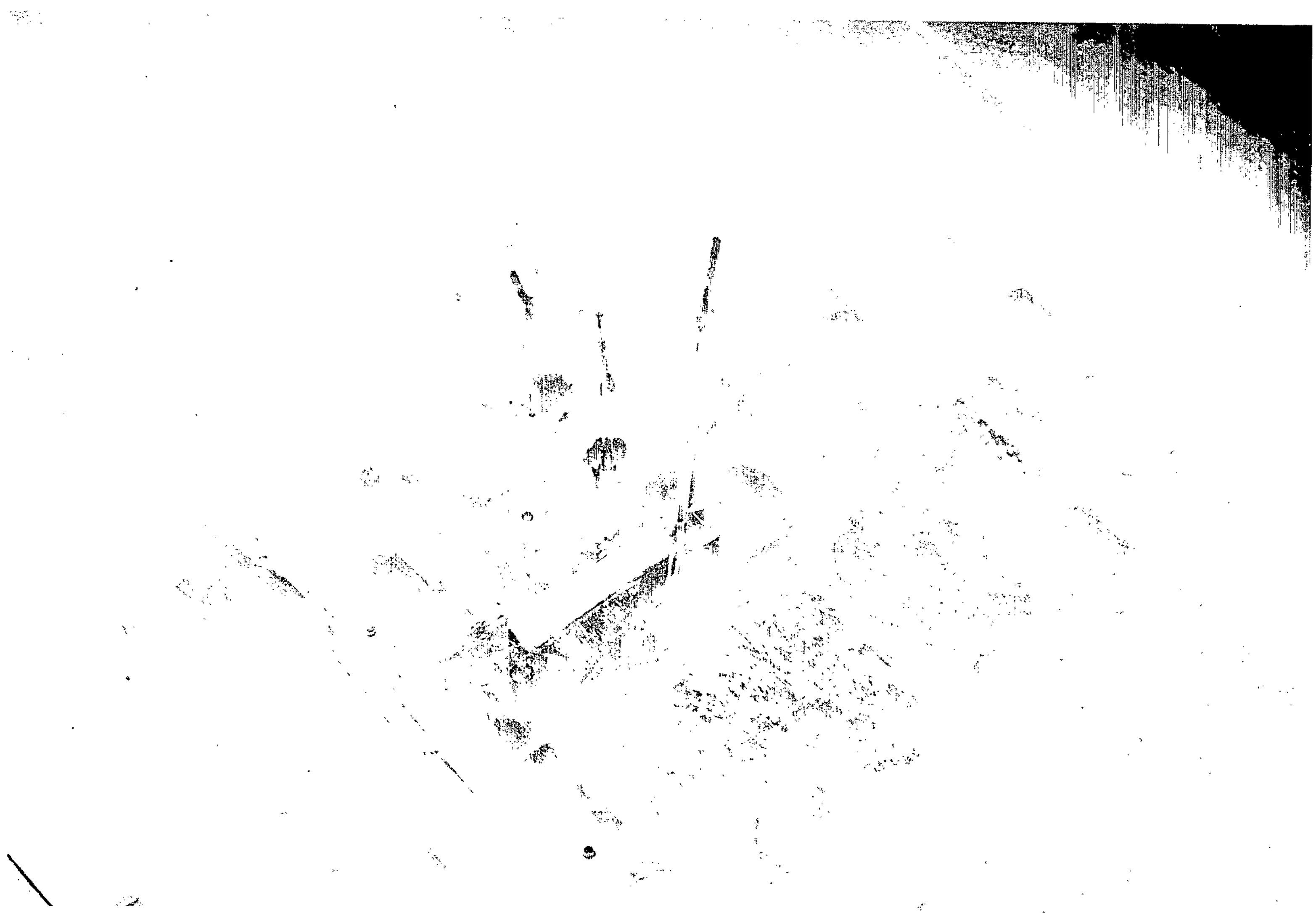
L-69-4150.1

Figure 1.- Discharge plasma slab used in the investigation.



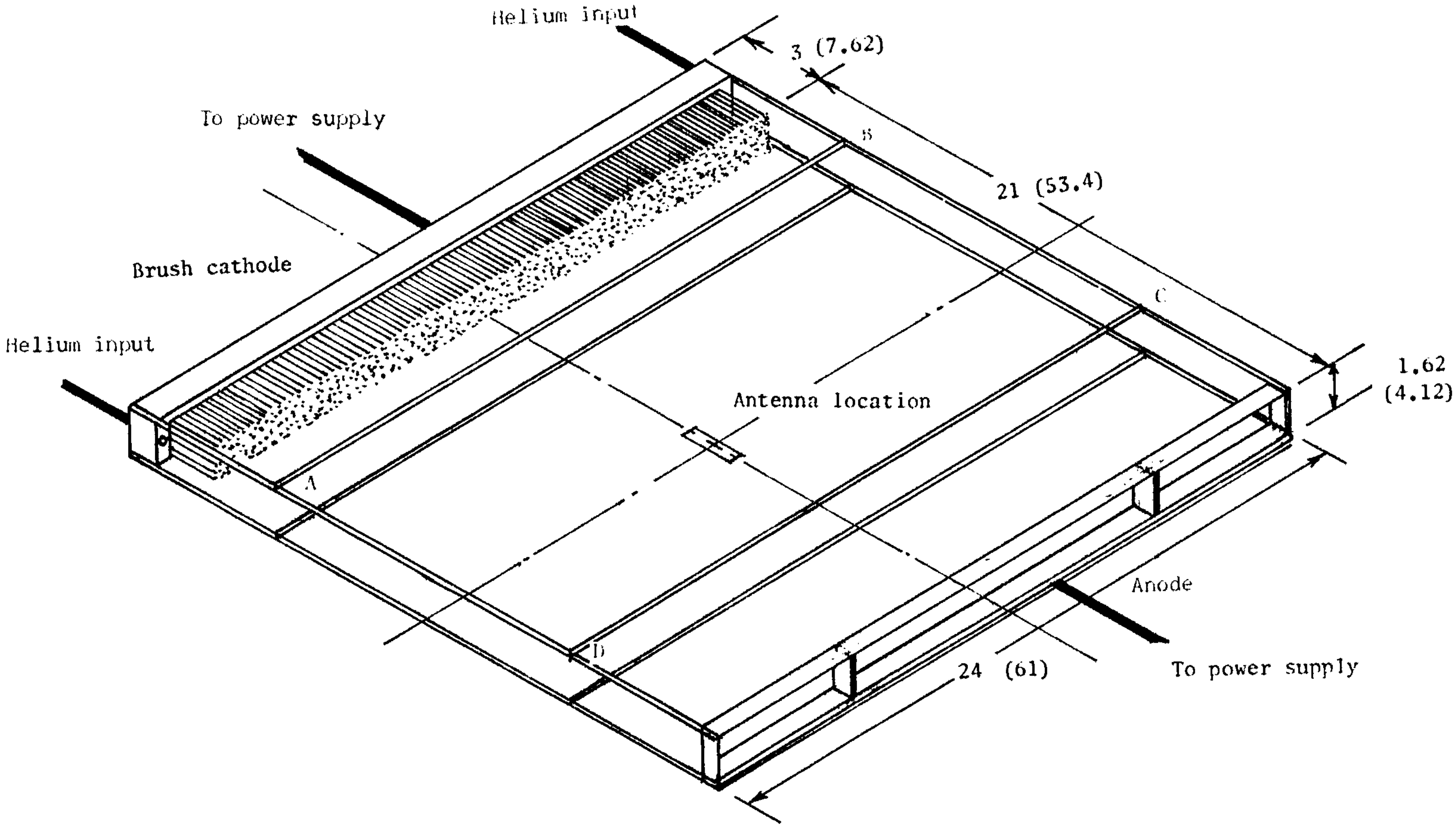
(b) End view showing position of Langmuir probes. L-69-4148

Figure 1.- Continued.



(c) Three Langmuir probes over slot antenna. L-69-4149

Figure 1.- Continued.



(d) Schematic representation. All linear dimensions are in inches (centimeters).

Figure 1.- Concluded.

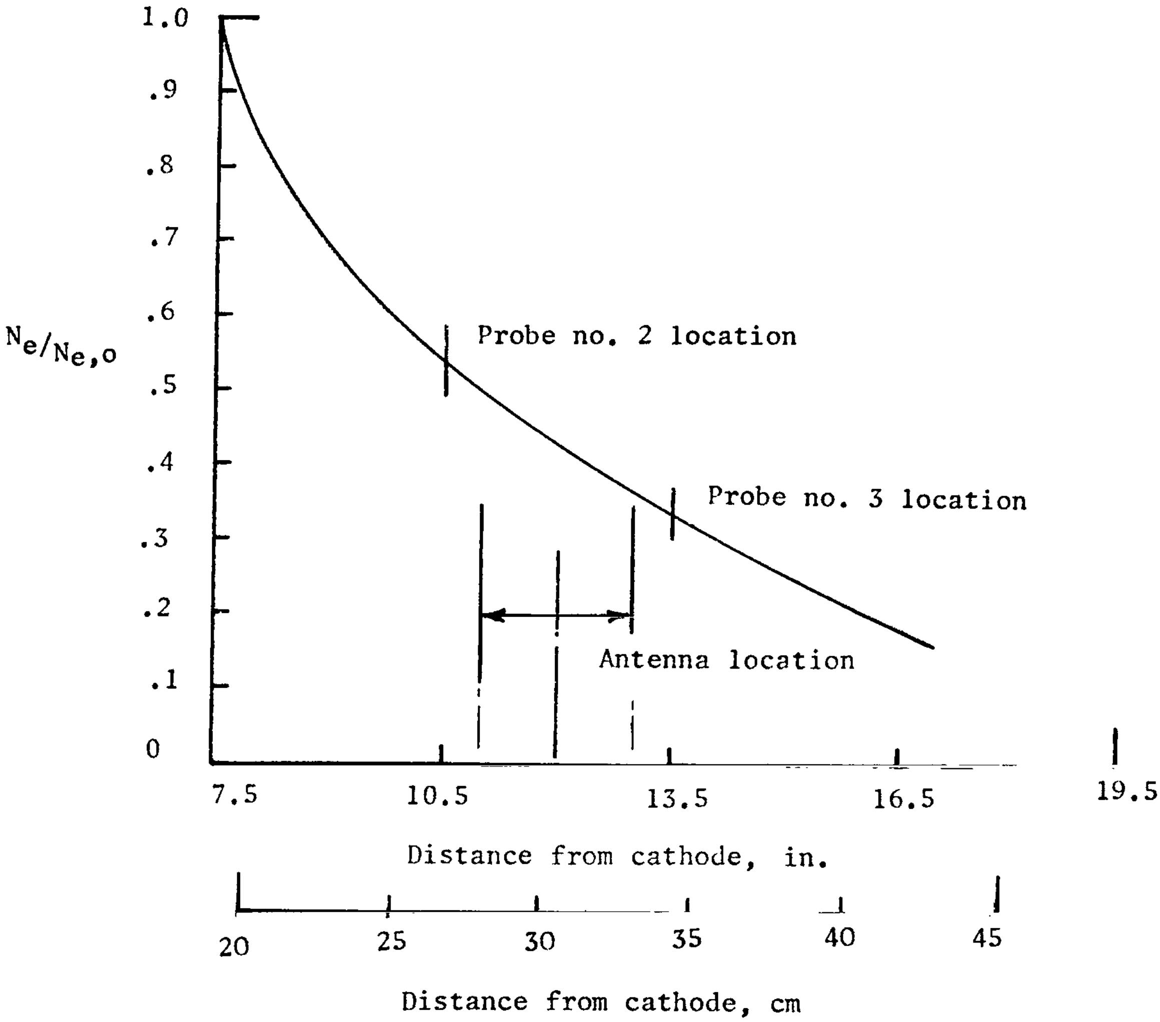


Figure 2.- Relative longitudinal distribution of electron density.

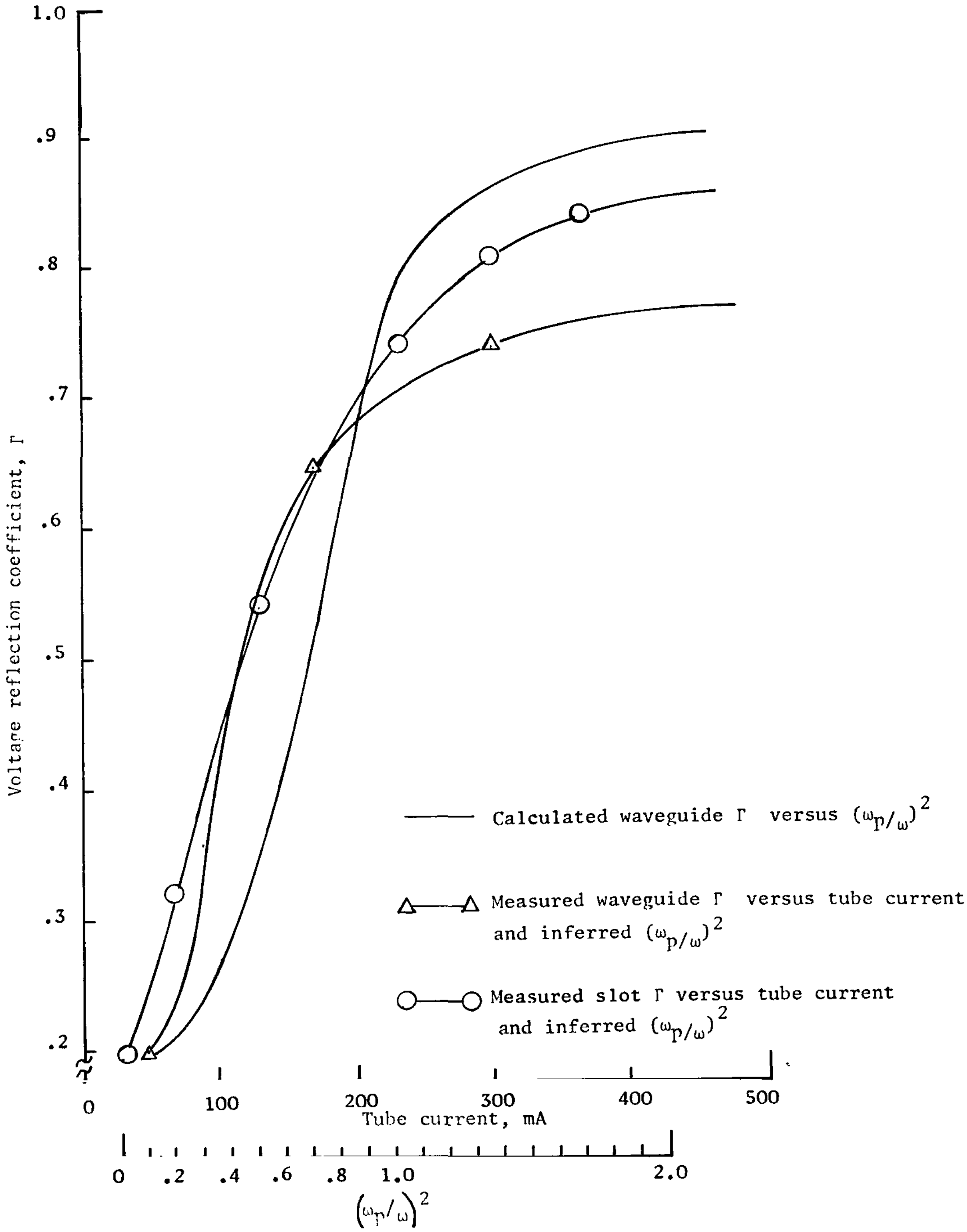
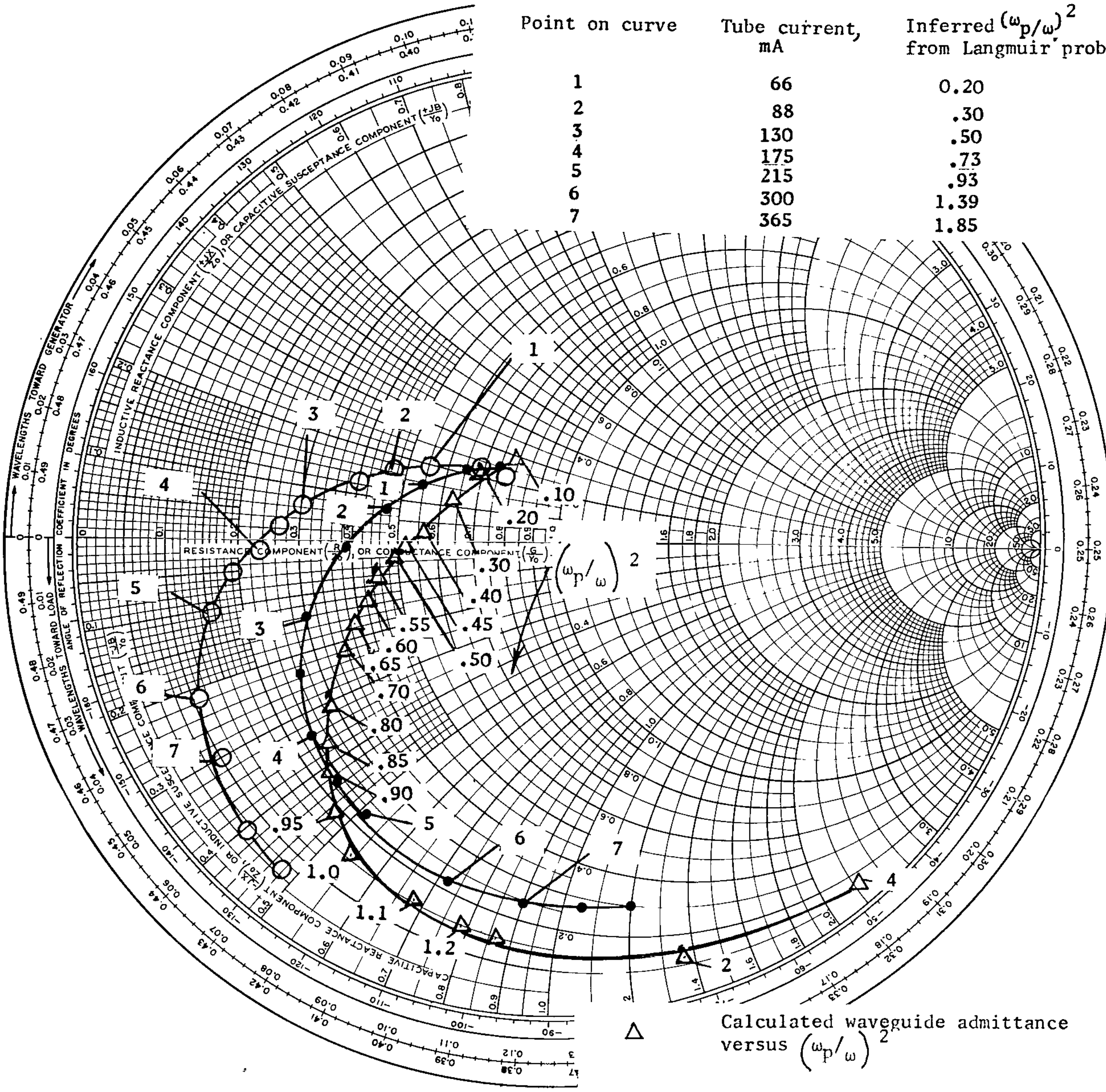


Figure 3.- Measured waveguide and slot Γ as a function of tube current and inferred $(\omega_p/\omega)^2$ from Langmuir probes; calculated waveguide Γ as a function of $(\omega_p/\omega)^2$ for z_0 = 1.62 inches (4.12 cm) and $\nu/\omega = 0.04$.

Point on curve	Tube current, mA	Inferred $(\omega_p/\omega)^2$ from Langmuir probes
1	66	0.20
2	88	.30
3	130	.50
4	175	.73
5	215	.93
6	300	1.39
7	365	1.85

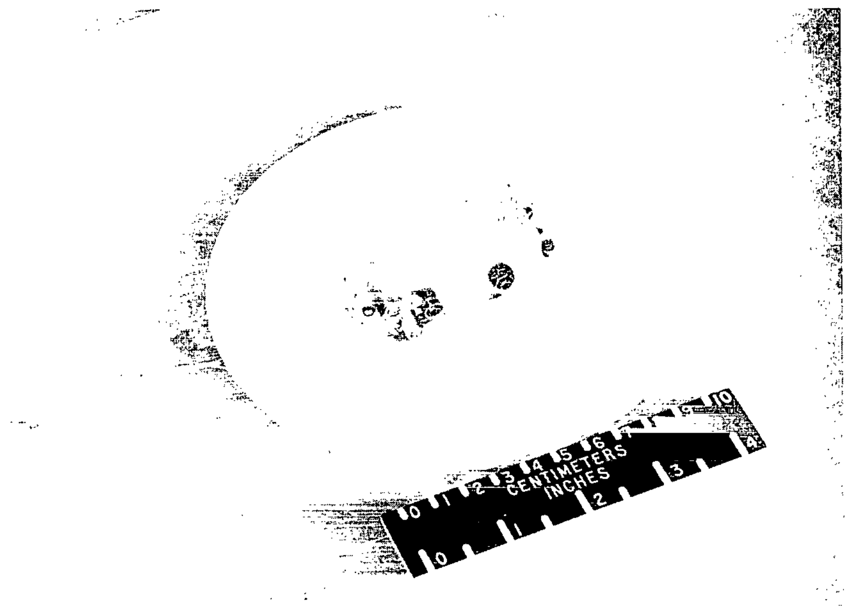


△ Calculated waveguide admittance versus $(\omega_p/\omega)^2$

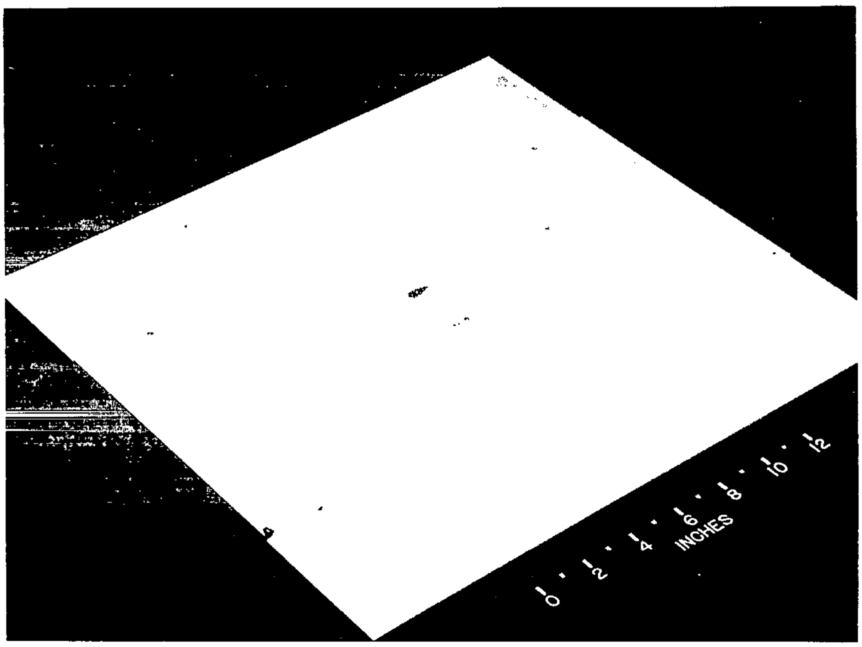
○ Measured slot admittance versus tube current and inferred $(\omega_p/\omega)^2$

• Measured waveguide admittance versus tube current and inferred $(\omega_p/\omega)^2$

Figure 4.- Measured waveguide and slot admittance as a function of tube current; calculated waveguide admittance as a function of $(\omega_p/\omega)^2$ for z_0 = 1.62 inches (4.12 cm) and ν/ω = 0.04.



(a) Rear view. L-69-1925



(b) Top view. L-69-1924

Figure 5.- The 0.20-scale cavity-backed slot antenna attached to ground plane.

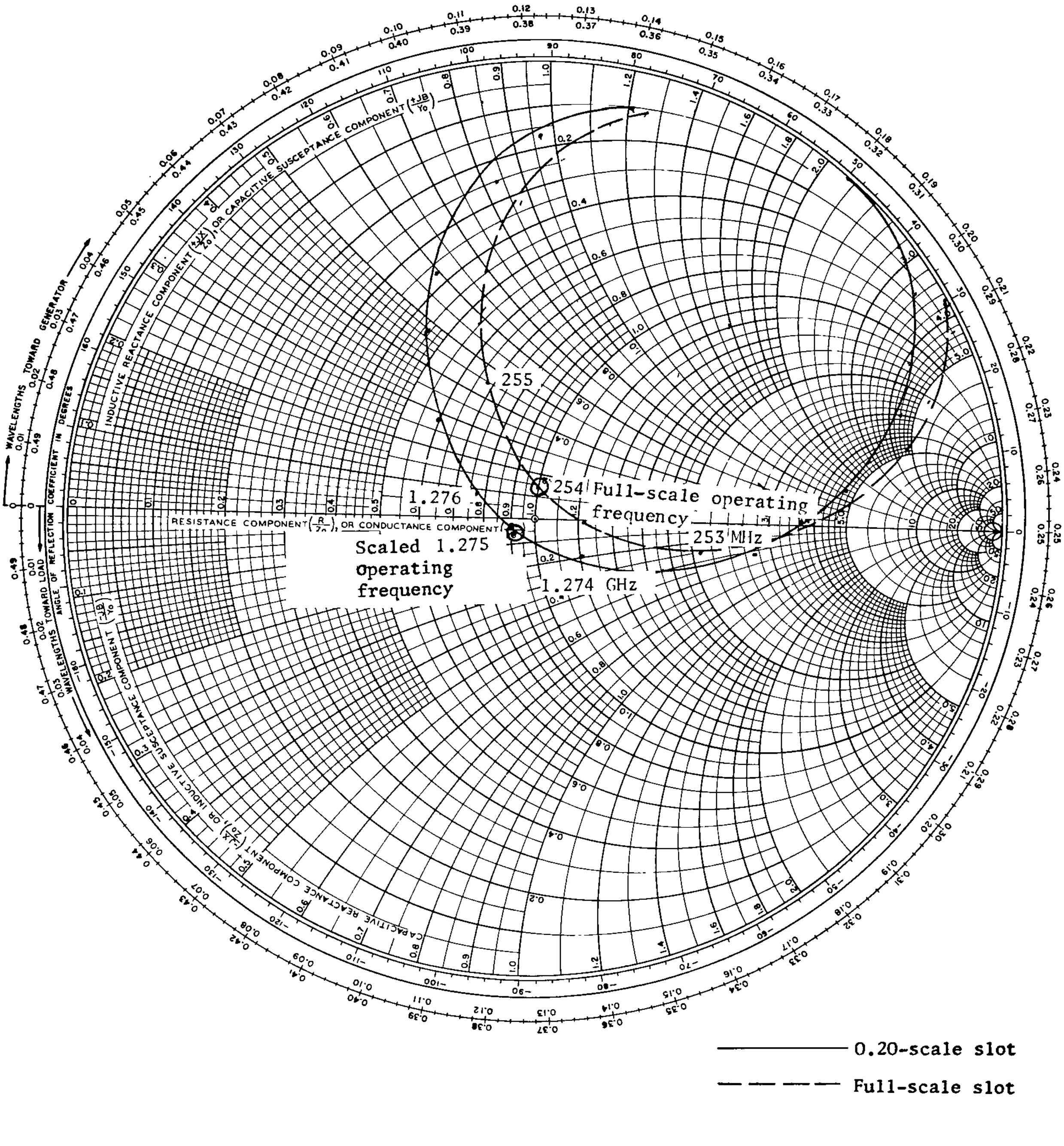
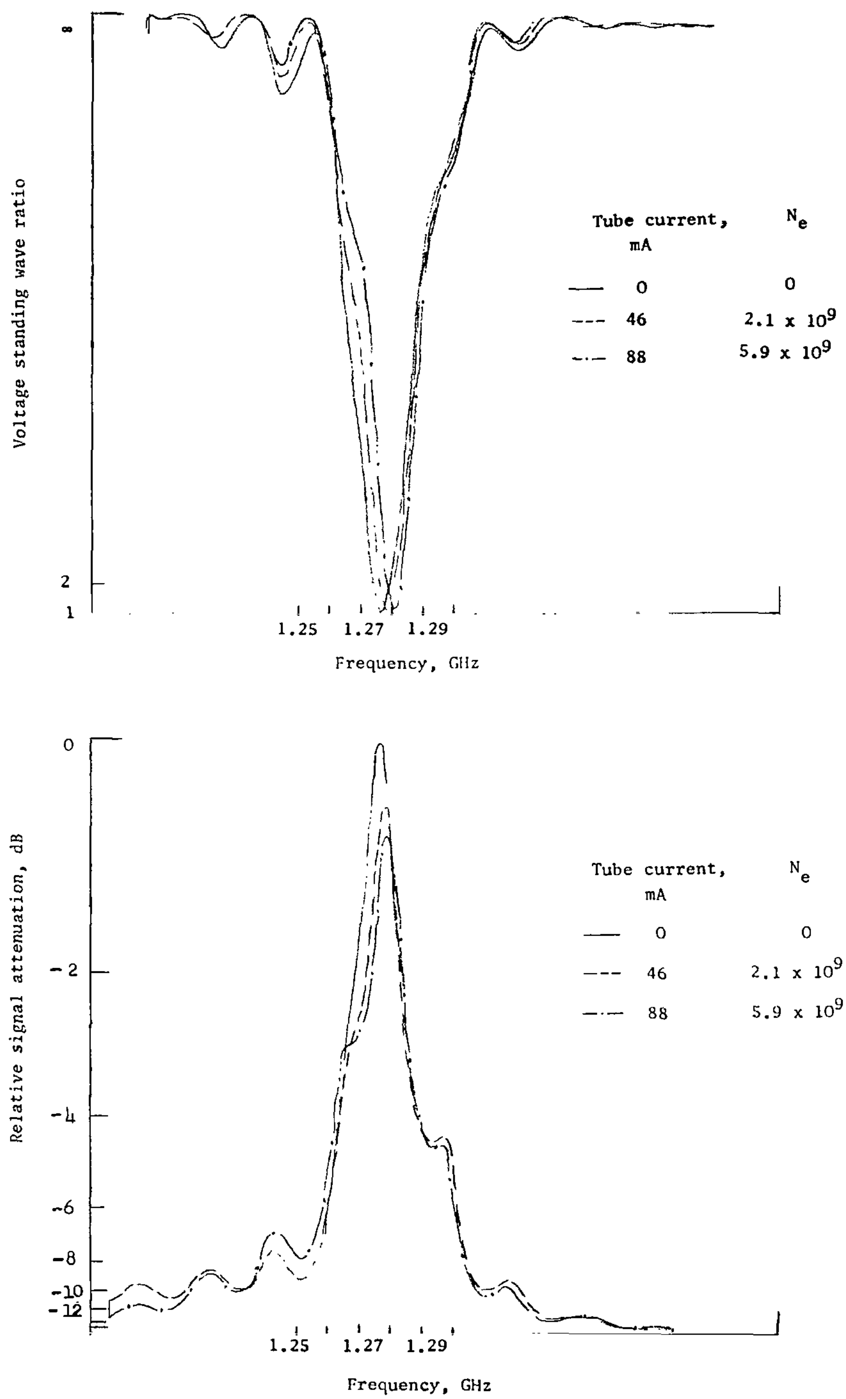
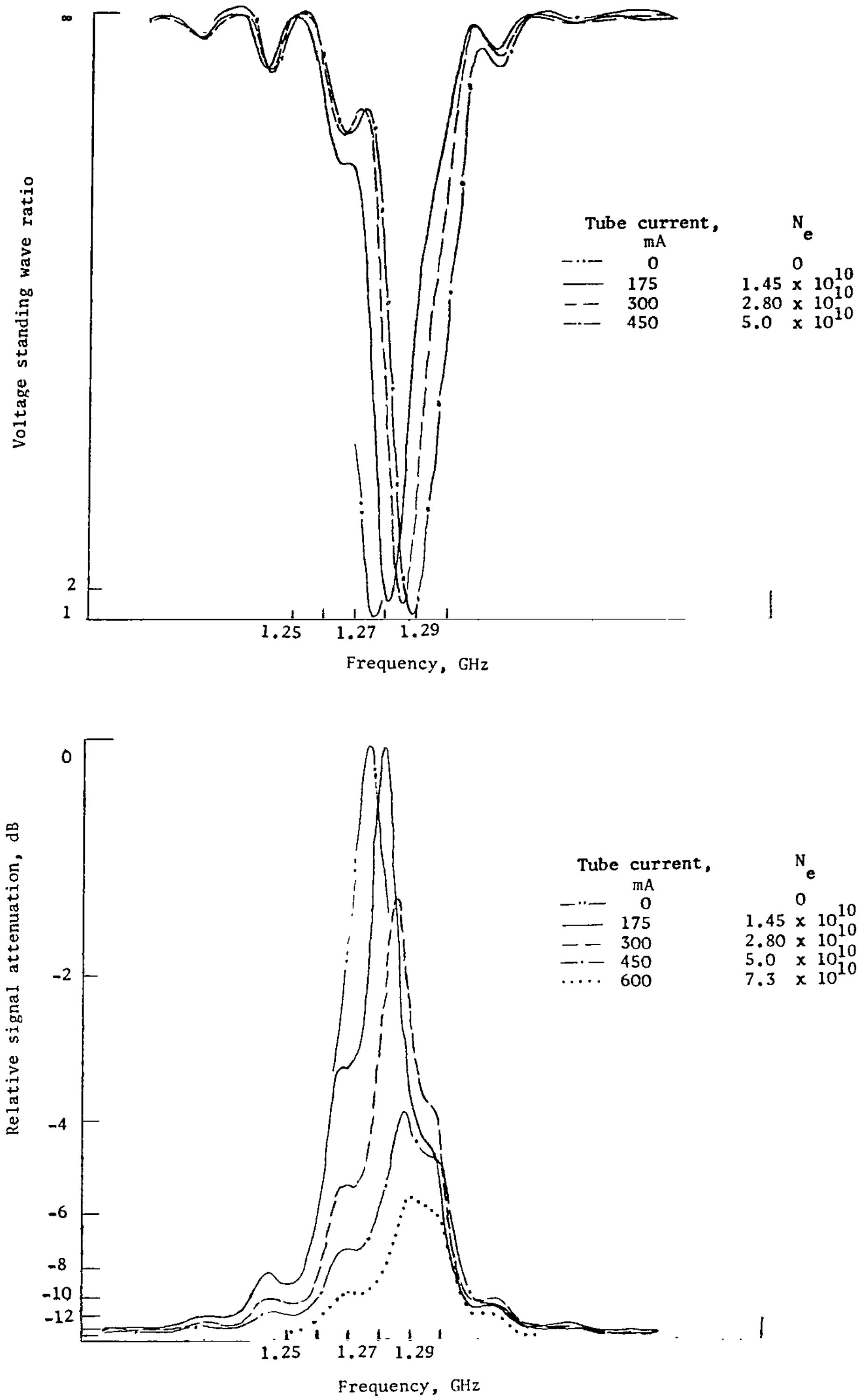


Figure 6.- Impedances of 0.20-scale and full-scale slot antennas.



(a) Low tube currents.

Figure 7.- Voltage standing wave ratio and relative signal attenuation of plasma-covered cavity-backed slot antenna.



(b) High tube currents.

Figure 7.- Concluded.

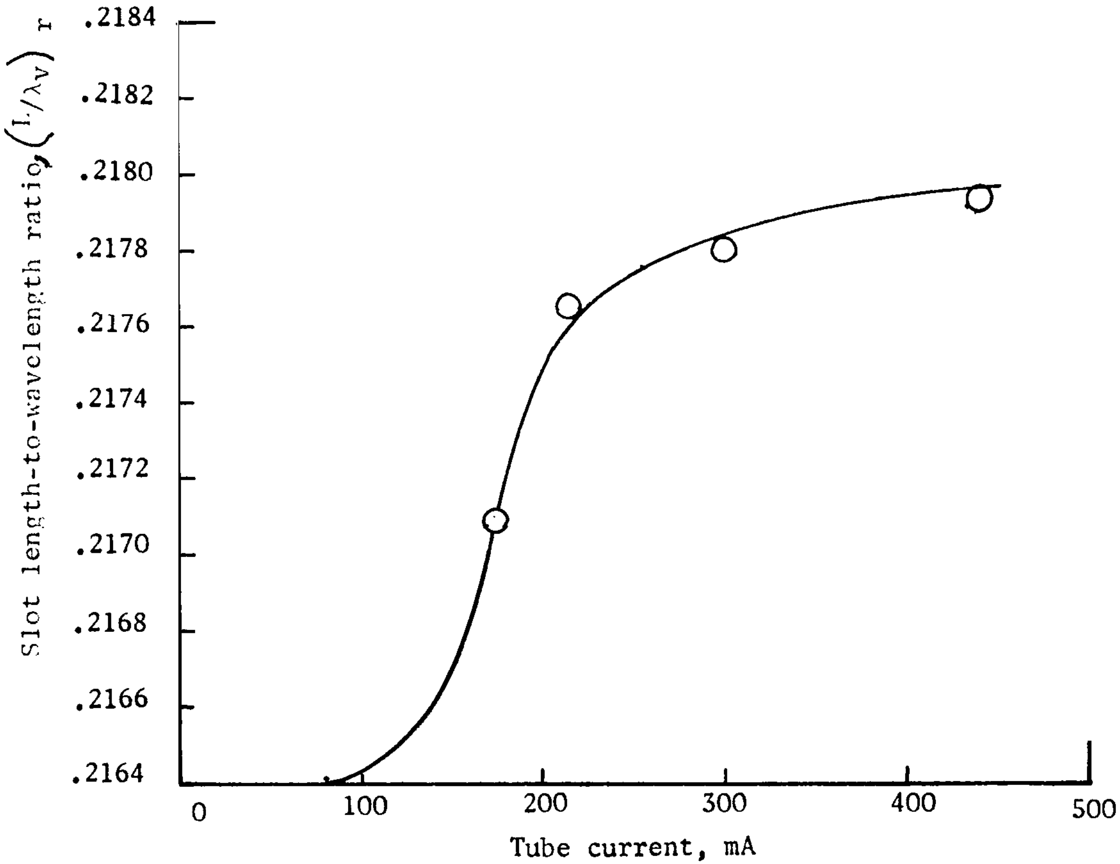
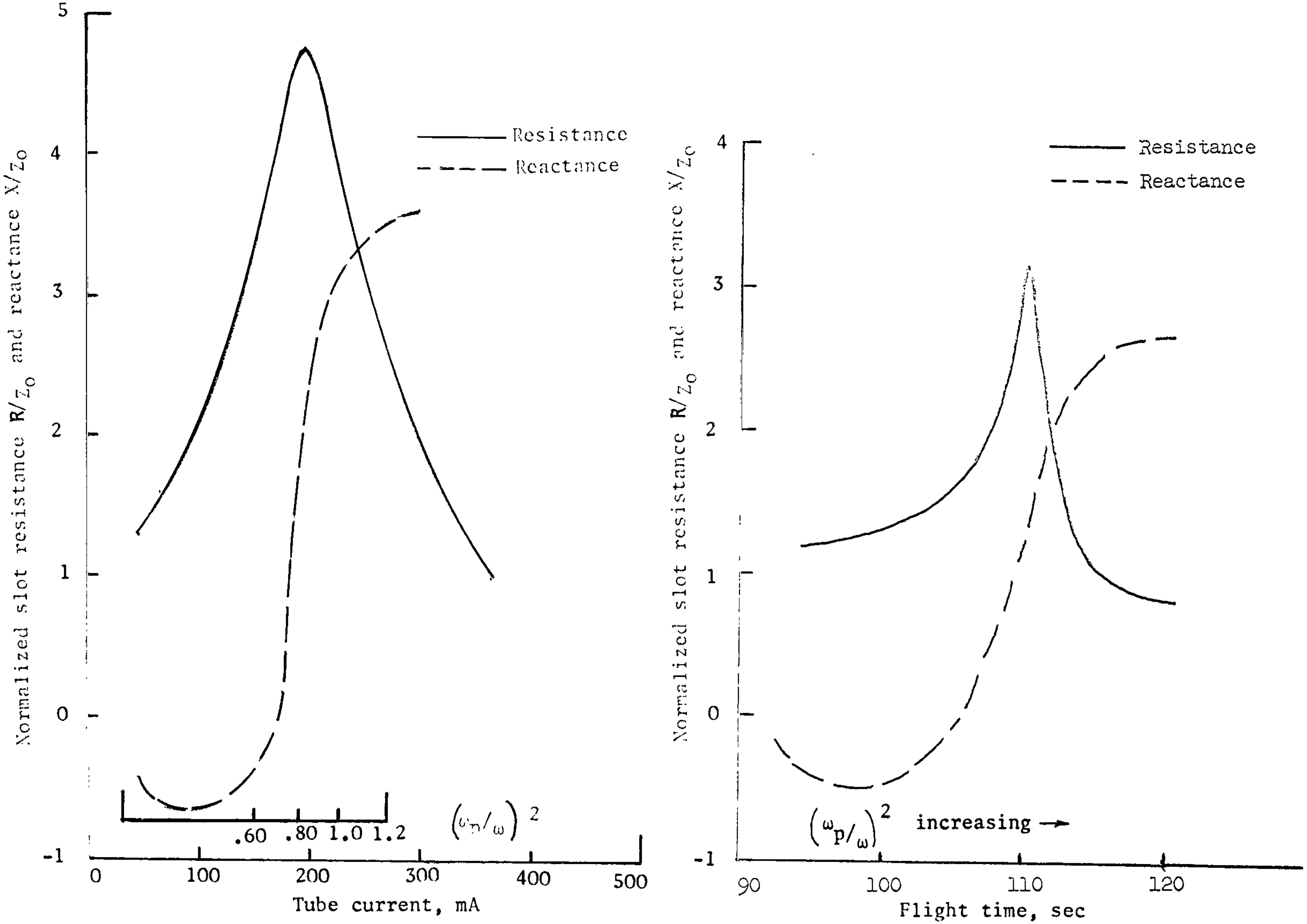


Figure 8.- Resonant slot length-to-wavelength ratio as a function of plasma-slab tube current.



(a) Impedance of slot antenna in plasma facility.

(b) Impedance of narrow-bandwidth slot antenna during reentry.

Figure 9.- Impedance of cavity-backed slot antenna in plasma facility and impedance of a similar slot antenna during a recent reentry flight experiment.

NASA-Langley, 1969 — L-6659

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