1967-06

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https://hdl.handle.net/10945/11940

DESIGN, CONSTRUCTION AND OPERATION OF A LABORATORY SIMULATION OF THE RE-ENTRY PLASMA

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DESIGN, CONSTRUCTION, AND OPERATION OF A LABORATORY

SIMULATION OF THE REENTRY PLASMA

by

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[redacted]

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ELECTRONICS

from the

NAVAL POSTGRADUATE SCHOOL
June 1967

ABSTRACT

A Reentry Plasma Facility has been constructed which simulates the plane plasma slab that develops in front of a reentering blunt body. The Facility will be used to study planar plasma effects on incident electromagnetic radiation. Design, details of construction, and operating procedures are presented.

The pulsed discharge is developed above a ground plane in which is imbedded a slot antenna. Preliminary measurements, made with Langmuir probes, indicate that electron density is $4 \times 10^{12}/\text{cm}^3$ and electron temperature is 2 eV, placing the plasma cutoff frequency between X and K band frequencies.

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LIST OF SYMBOLS

$\vec{E}$	-	electric field intensity
μ	-	permeability
ϵ	-	permittivity
σ	-	conductivity
i	-	$\sqrt{-1}$
$\vec{K}$	-	propagation constant
$\vec{r}$	-	position space vector: $x\vec{i} + y\vec{j} + z\vec{k} = \vec{r}$
ω	-	angular frequency of electromagnetic wave
v_{phase}	-	phase velocity
v_{group}	-	group velocity
ϵ_o	-	permittivity of free space: 8.854×10^{-12} farad/m
μ_o	-	permeability of free space: 1.257×10^{-6} henry/m
n_e	-	electron density
e	-	electron charge: 1.602×10^{-19} coulomb
m_e	-	electron mass: 9.108×10^{-31} kg
ν_e	-	electron collision frequency
ω_p	-	plasma frequency in radians per second
f_p	-	plasma frequency in cycles per second
λ_D	-	Debye length
T_e	-	electron temperature
k	-	Boltzman constant: 1.38×10^{-23} joule/^{o}K
$I_{i(sat)}$	-	ion saturation current
V	-	probe voltage
n_i	-	ion density
A	-	probe area
m_i	-	ion mass

I_e	-	electron current
I_i	-	ion current
I_{e_1}	-	electron current collected by probe one
I_{e_2}	-	electron current collected by probe two
S	-	slope of I_e^2 vs. V curve

ACKNOWLEDGEMENTS

This project would not have been possible without the support of many people. I wish to express my thanks to Professor C.E. Menneken for his financial assistance; to my advisors, Professors A. W. Cooper and G. L Sackman, for their technical advice; and to Professors F. Bumiller and R. E. Reichenbach for equipment loans. I am grateful for the patience of Mr. H. Herreman and Mr. K. Smith, and for the knowledge gained from our many hours of discussion. My thanks to Mr. M. Odea, Mr. P. Wisler and Mr. R. Smith for their assistance in the construction of the Facility.

Finally, I wish to thank my wife for her understanding and cooperation throughout the last two years, and for typing the rough drafts of this thesis.

INTRODUCTION

The Problem

Three problems dominate the reentry phase of a space mission. They are prediction of the optimum reentry trajectory and control of the vehicle to follow that trajectory, the heating of the spacecraft as it slows from orbital speed to landing speed, and the communications and tracking problem associated with the plasma sheath which develops around the vehicle as it encounters the planetary atmosphere. The term "communications" includes all radio and radar links with the spacecraft -- voice communications circuits, telemetry channels, beacons, and tracking and acquisition radars.

The reentry phase of a space mission is considered to be bounded by an upper altitude of 400,000 feet and a lower altitude of 50,000 feet. As a spacecraft penetrates the regime of increasing air density, a sheath of ionized air and ablation products forms about the vehicle. Atmospheric drag converts most of the spacecraft's kinetic energy into heat, mostly by compression in the stagnation region and partially by skin friction in the boundary layer or shear layer. Temperatures between the shock wave and vehicle surface rise to sufficient magnitudes (5000°K) to dissociate and ionize the environmental air, making the flow field surrounding the body highly conductive, resulting in marked attenuation of rf signals [1].

A plasma attenuates incident electromagnetic waves by absorption and reflection. Thus, the interaction between the electromagnetic signal and the ionized flow field surrounding a reentering spacecraft degrades the overall performance of the communications systems. The proximity of the plasma to the antenna introduces severe impedance mismatches reducing signal power, minimizing channel capacity of the telemetry system, and making voice communications impossible. Tracking errors result due to a degradation of Doppler range rate measurements. Skin tracking becomes unsatisfactory due to confusion introduced by the ionized vehicle wake and the precursor ionization in front of the shock which greatly change the vehicle's radar cross section.

Although the so called blackout problem due to the plasma sheath exists for all reentering bodies, it is not considered as critical in ballistic missile reentry because of its relatively short duration, well defined trajectories, and the feasibility of information storage during blackout for transmission after the recovery of radio contact. For the same reasons, the blackout problem was not considered critical in the Mercury and Gemini Programs [2].

A more serious condition of communications and tracking blackout is expected during reentry of the Apollo vehicle due to higher reentry velocity (35,000 fps). Furthermore, with the proposed use of lifting reentry vehicles for both manned and unmanned missions, the requirements for real-time communications becomes critical, in that blackout may eliminate ground support during the maneuver phase of the reentry profile. This is highly significant since lifting reentry trajectories cannot be predetermined with as much precision as ballistic trajectories, and the periods of blackout are considerably longer (5 to 10 min.) [1, 2].

Previous Work

As evidenced by the large number of reports and papers on the plasma sheath and the communications blackout problem, the technical community has and still is expending considerable effort in an attempt to find a satisfactory alleviation technique. Publication of the Proceedings of the First (1961), Second (1964), and Third (1965) Symposiums on the Plasma

Sheath are indicative of this effort. Though much progress has been made, the pace at which the space exploration program is moving makes the blackout problem more critical than ever.

There have been many attempts to analyze the electrical properties of the medium surrounding a reentering vehicle [3, 4]. Vehicles such as Trailblazer II [5] and Asset [6] have been instrumented to gather data on the plasma sheath. New techniques have had to be developed and evaluated. Langmuir probes have proven successful in collecting data [7, 8].

A review of representative current literature pertaining to high power rf field-plasma interactions was presented by Robert J. Papa at the AIAA Plasmadynamics Conference held at the Naval Postgraduate School in March 1966 [9]. This is a theoretical approach to the problem, and includes a discussion of the works of Ginzburg, Gurevich, Margenau, Epstein, King, Papa, Sodha, Yen, and Reilly.

A major drawback in the development of a satisfactory alleviation technique is the difficulty in constructing and analyzing an accurate laboratory model of the plasma sheath from the limited information available on its composition.

Some recent experimental attempts to study the problem of plasma effects on microwave radiation are those by Cloutier and Bachynski [10], Coe and Linder [11], Meltz [12], Galejs, Montzoni, and Seshadri [13, 14], and the Plasma Research Laboratory group at Aerospace Corporation. In brief, these studies have shown that the effect of the plasma sheath on the far field radiation pattern of a slot antenna is to attenuate and redistribute the radiated energy. The plasma produces an impedance mismatch to the antenna, therefore some of the radiated signal is reflected. Cloutier and Bachynski have found that the signal level at normal incidence may be decreased by as much as 25 db at plasma cutoff and that antenna side-lobe levels exceed those when there is no plasma present.

The results of the above experiments are degraded by the fact that the plasma model utilized is not representative of the plasma actually encountered upon reentry.

Cloutier and Bachynski develop their discharge between two flat electrodes in a cylindrical container whose length is about one half the diameter of the tube. The discharge is uniform throughout the container, but the density variation is perpendicular to the direction of propagation. The plasma is in contact with the walls and sheath effects will influence transmitted radiation. The microwave radiator is not in contact with the plasma.

Galejs, et.al. develop a nearly uniform plasma in a teflon container. Measurements are made during the diffusion controlled afterglow of the pulsed discharge. Density variation is not consistent with the actual case and sheath effects are present.

Coe and Linder form an rf discharge over a ground plane using a pair of electrodes mounted above the plane. The desired density profiles are approximated, but it would be expected that the presence of the electrodes would markedly affect radiation patterns. Also, the discharge was developed in air and consequently electron density and ion density are not equal, making interpretation of Langmuir probe measurements (the analysis technique used) invalid.

Dr. G. E. Stewart, at Aerospace Corporation [26] has developed a pulsed plasma which seems to simulate more closely the reentry plasma. The discharge is developed above a ground plane and maintained by particles emitted from that surface. Density variations in the positive portion of the discharge simulate those encountered upon reentry, being approximately uniform over the surface of the plate and varying in the direction of propagation with the higher densities nearer the surface. The plasma slab is in contact with the container walls at the periphery of the discharge and there are no physical objects above the plate to influence the plasma or radiated energy. The antenna is imbedded in the ground plane. It is the information from Aerospace upon which the Plasma Facility at the Postgraduate School has been developed.

The principal aim of this study was to design, build, and establish operating procedures for the Reentry Plasma Facility at the Postgraduate School. An attempt was made to make the Facility readily adaptable to various techniques for analyzing the plasma parameters and instrumenting for radiation studies. Preliminary analysis of the plasma parameters in the form of electron temperature and density was conducted to ensure design objectives. Recommendations for future analysis and study are included in the report.

LABORATORY SIMULATION OF THE REENTRY PLASMA

Requirements

Ideally it is desired to produce a thin, uncontained, uniform, infinite, plasma above a ground plane and measure its effect on a microwave radiator imbedded in the ground plane as a function of the plasma parameters. This would lend itself well to a comparison of experimental and theoretical results. Practical considerations, however, lead to a finite, non-uniform model. The plasma itself is not in contact with the container, but a dielectric material, the belljar, is still required in the transmission path.

In order to determine the plasma parameters of interest and the range of these parameters, a discussion of plasma effects on an incident electromagnetic wave must be considered.

Electromagnetic Waves in a Plasma [15, 16, 17, 18]

Maxwell's equations may be used to obtain a wave equation

$$\nabla^2\vec{E} - \mu\epsilon \frac{\partial^2\vec{E}}{\partial t^2} - \mu\sigma \frac{\partial\vec{E}}{\partial t} = 0$$

defining wave propagation in a charge-free, linear isotropic region.

If a variation of the fields in the wave of the form

$$\exp i(\vec{K} \cdot \vec{r} - \omega t)$$

is assumed and a solution of the wave equation obtained, a dispersion relation relating the magnitude of the propagation constant to the frequency of the wave may be defined

$$K^2 = \epsilon\mu\,(\omega^2 - i\frac{\omega\sigma}{\epsilon}).$$

The direction of the propagation constant indicates the direction of propagation of the wave, and the magnitude equals 2π divided by the wavelength of the wave. The imaginary term in the dispersion relation may lead to attenuation of the wave.

If the frequency is known, using the real part of the propagation constant, phase and group velocities may be computed

$$v_{phase} = \frac{\omega}{Re\,K} \qquad v_{group} = \frac{\partial\omega}{\partial(Re\,K)} .$$

For a vacuum where $\sigma \rightarrow 0$, $\epsilon = \epsilon_o$, $\mu = \mu_o$

$$v_{phase} = v_{group} = \frac{1}{\sqrt{\epsilon_o \mu_o}} \cong 3 \times 10^8 \text{ m/sec}$$

and velocity of propagation is independent of frequency.

In a plasma the conductivity of the medium is frequency dependent. We assume that the plasma is composed of electrons and positive ions and that charge neutrality exists. Furthermore, the mass of an electron is at least three orders of magnitude less than that of the positive ions.

The conductivity, then, is

$$\sigma = \frac{n_e e^2}{m_e(\nu_e + i\omega)} .$$

In view of the assumptions made and defining a plasma frequency

$$\omega_p^2 = \frac{n_e e^2}{m_e \epsilon_o} ,$$

the dispersion relation becomes

$$K^2 = \epsilon_o \mu_o \left\{ \omega^2 - \frac{\omega_p^2}{1 - (\frac{\nu_e}{\omega^2})} \left[1 - i\frac{\nu_e}{\omega} \right] \right\} .$$

Thus we see that the speed of propagation depends on the frequency of the incident wave.

We may assume a collisionless plasma, or that the applied wave frequency is much greater than the electron collision frequency, to interpret the dispersion relation.

Propagation is possible if electron density is low enough so that plasma frequency does not exceed the frequency of the applied wave.

The group velocity or speed of transmission approaches zero as the plasma frequency approaches that of the incident wave. Therefore the frequency beyond which no transmission of the incident wave exists is dependent upon electron density from

$$\omega_p^2 = \frac{n_e e^2}{m_e \epsilon_o} .$$

This is often called the cutoff frequency, and substitution yields $f_p = 8979\sqrt{n_e}$ where n_e is electrons/cm^3. The Debye length of the plasma can be related to the plasma frequency by

$$\lambda_D \omega_p = \sqrt{\frac{kT_e}{m_e}}$$

This indicates that the electrons may move a distance λ_D, in a time $\frac{1}{\omega_p}$. It can be shown that a wave of frequency less than ω_p is damped to 37% of its initial amplitude in a distance comparable to λ_D, so that the plasma, in effect, is shielded from frequencies lower than the plasma frequency.

From the above discussion it is evident that the plasma parameters of interest are electron density and electron temperature.

Determination of the effect of the plasma on a transmitted electromagnetic wave will require measurement of certain wave properties. Some of these properties are incident power, reflected power, transmitted power, attenuation, phase shift, polarization, and radiation patterns. A consideration of measurement techniques, requirement to be in the far field of the radiating antenna, and equipment available dictate the use of frequencies at X band and K band with frequencies approximately 9 GHz and 24 GHz respectively. Since it will be desirable to study the effects of the plasma on the wave in both the cutoff and transmitted modes, the plasma frequency must be between 9 GHz and 24 GHz. This determines that critical electron density must be between 10^{12} electrons/cm^3 and 7×10^{12} electrons/cm^3.

THE REENTRY PLASMA FACILITY

The facility consists of a vacuum system, belljar and feed-through collar assembly, pulse forming network to supply the discharge, Langmuir probes and circuits, microwave sources, anechoic chamber, and detection and recording equipment. A block diagram of the facility is shown in Fig. 1.

The vacuum system is capable of ultimate pressures in the 10^{-7} to 10^{-8} torr range. This was desirable to achieve a "clean" background for the discharge which is operated in argon gas at a pressure of approximately 200 microns.

The feed-through collar mates the vacuum system to the belljar. It provides for the mechanical and electrical support of the ground plane above which the plasma is generated. The vertically adjustable Langmuir probes are mounted to the collar, and the probe circuits are attached via the collar. rf energy is introduced through a microwave window. A butterfly valve provides a means of throttling the vacuum system to give the desired pressure in the belljar. A Bayard-Alpert ionization gage monitors vacuum system pressure, and a thermocouple gage monitors the higher pressure in the belljar. The background gas is bled in through the collar. Spare electrical feed-throughs and provisions for contaminant injection are provided for future projects.

The pulse-forming network which supplies the discharge consists of a delay line triggered by a thyratron. It is capable of supplying a 3-10KV, 10 amp pulse at varying pulse repetition frequencies from 20 - 1000 cps. The delay line may be matched to the load by varying the inductance of each stage and adjusting the values of series and shunt stabilizing resistors.

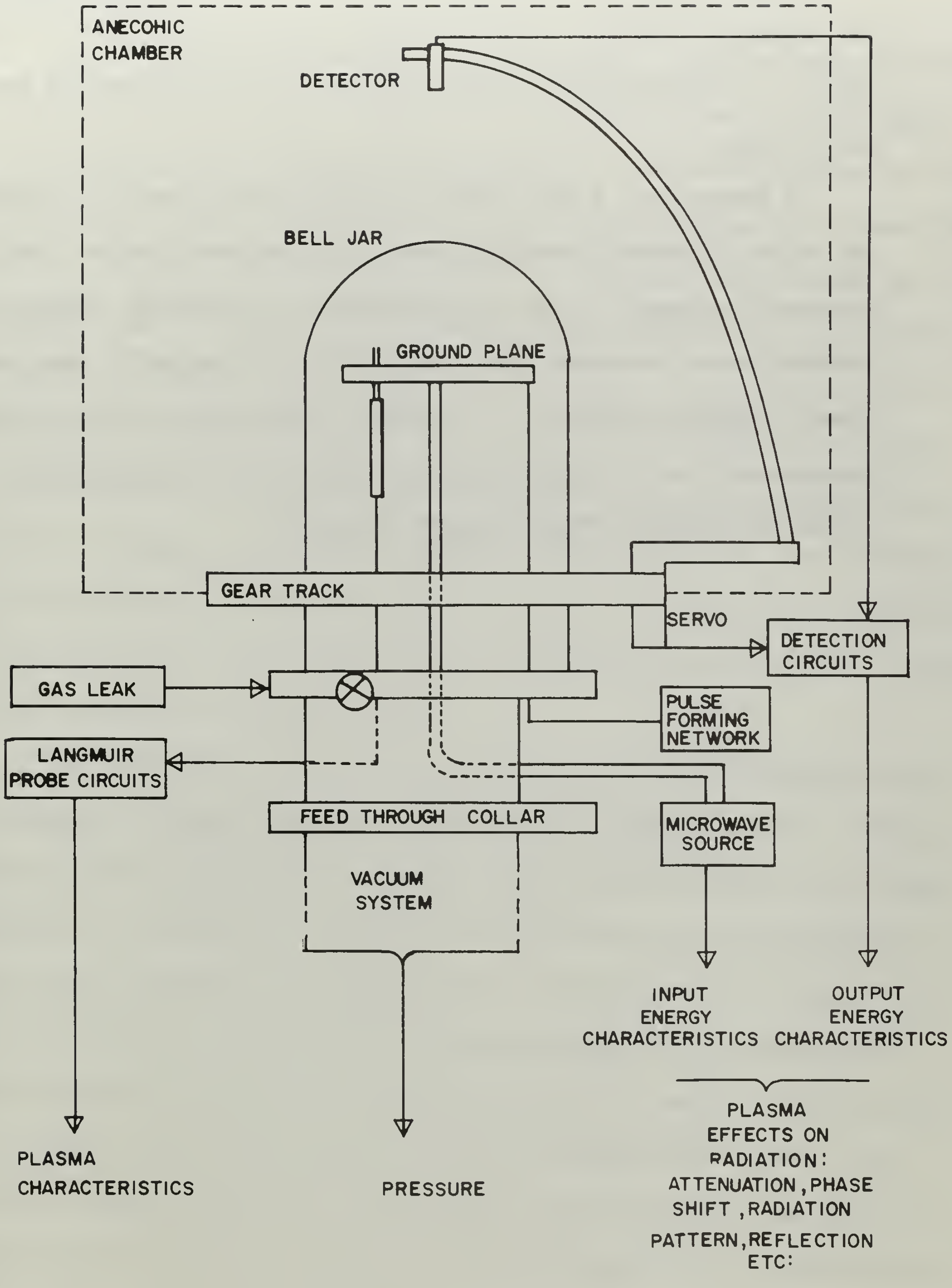


Fig. 1 BLOCK DIAGRAM OF THE REENTRY PLASMA FACILITY

Two double Langmuir probes are used to measure plasma parameters at two different distances from the center of the ground plane. These probes are adjustable vertically from zero to ten centimeters above the ground plane.

rf energy at 9.5 GHz (X band) and 24.5 GHz (K band) is provided by two reflex klystrons through appropriate microwave windows. The associated microwave equipment allows for measurement of frequency, reflected power, incident power, absorbed power (attenuation), phase shift, and three dimensional radiation patterns. An anechoic chamber minimizes distortion of measurements due to reflections and spurious external radiation. Pictures of the facility are shown on pages 67 and 68.

THE DISCHARGE

The discharge is developed above a ten inch aluminum plate (hereafter called the ground plane). Imbedded in the ground plane are four copper buttons insulated by boron nitride bushings. The discharge pulse is supplied to the copper cathodes via a circular bus bar below the ground plane. The lower surface of the aluminum plate is insulated from the bus bar by a teflon sheet. The bus bar and feed line are insulated by polyethylene wrapped with teflon tape. The microwave antenna, a wave guide stub, is inserted in the ground plane at the center and is insulated by a boron nitride bushing. Provisions have been made for both X band and K band guides. Langmuir probes for diagnosing plasma parameters are introduced into the plasma from below the ground plane. These probes are adjustable from the surface of the plate to ten centimeters above the plate. Details of construction are shown in Fig. 2.

The discharge appears to be a type of cold cathode, abnormal glow discharge. A negative pulse is applied to the copper buttons. Positive ions from the strong positive space charge which forms about the cathode impinge on the cathode. Electrons are emitted due to this impingement. The beam of electrons is accelerated in a strong field and executes ionizing collisions. These collisions produce more ions and electrons, supporting the discharge. The loss mechanism is twofold. Electrons are attracted to the ground plane or anode and recombine with ions. To a lesser degree recombination takes place in the fringes of the positive glow portion of the discharge far above the ground plane. Diffusion to the walls of the container must be considered as producing losses. A spectral analysis of the discharge might define the loss mechanism. The spectra should be discreet in the positive glow and a continuum where

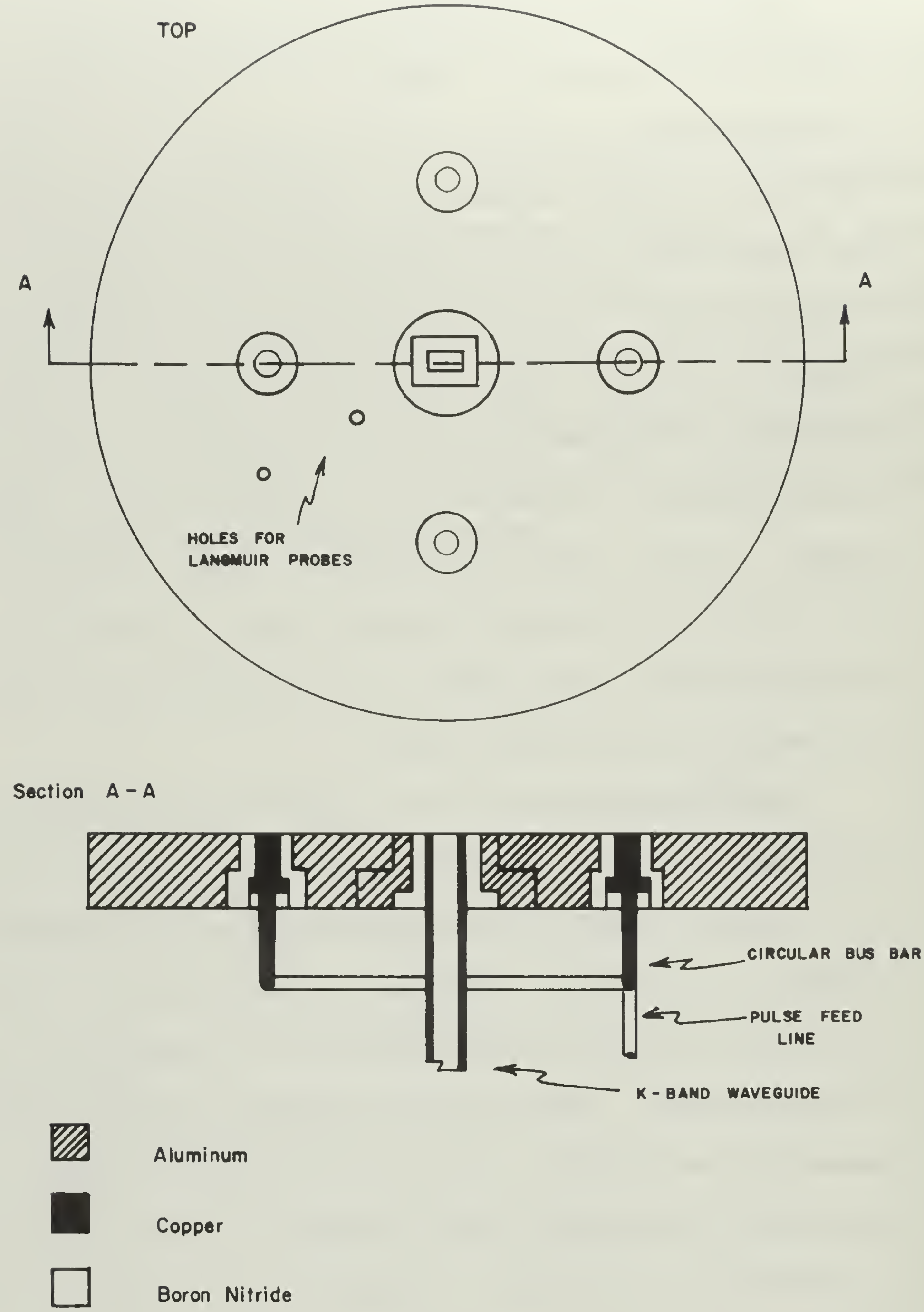


Fig. 2. THE GROUND PLANE

recombination occurs. The mean free path of the electrons in Argon at the operating pressure could be computed to obtain a recombination coefficient. Figure 3 depicts the discharge; see page 69 for photograph.

The ions which impinge upon the copper cathodes have sufficient energy to dislodge copper atoms as well as electrons. These sputtered copper atoms are deposited on the boron nitride insulators and the surrounding ground plane. This copper plating will eventually cause arcing at the electrodes and must be removed periodically.

Von Engel's treatment of glow discharges and cold cathodes would seem to support the above discussion [19]. For the pressures used in the experiment, the negative zones of a glow discharge should contract toward the cathode. The bright spot above each copper button is then the negative glow. Electron emission under the influence of a strong electric field is due to an intense space charge of positive ions situated about one mean path from the cathode. The dark space above each bright cathode spot is the Faraday dark space. The plasma, which diffuses over the ground plane and up into the belljar approximates the positive column, but without the usual axial electric field. The electrons from the positive portion of the discharge are attracted to the anode or ground plane. Positive ions are repelled. A negative space charge is set up above the ground plane and an anode fall potential is set up giving rise to the observed anode dark space. The conventional anode glow is not visible here since the anode is large, the electric field is not intense, and electrons reach the anode by diffusion rather than under acceleration.

The discharge is formed by a negative pulse from a thyratron-charged delay line. Ballast resistors are used to match the delay line to the plasma. Various combinations of pulse potential, pulse repetition

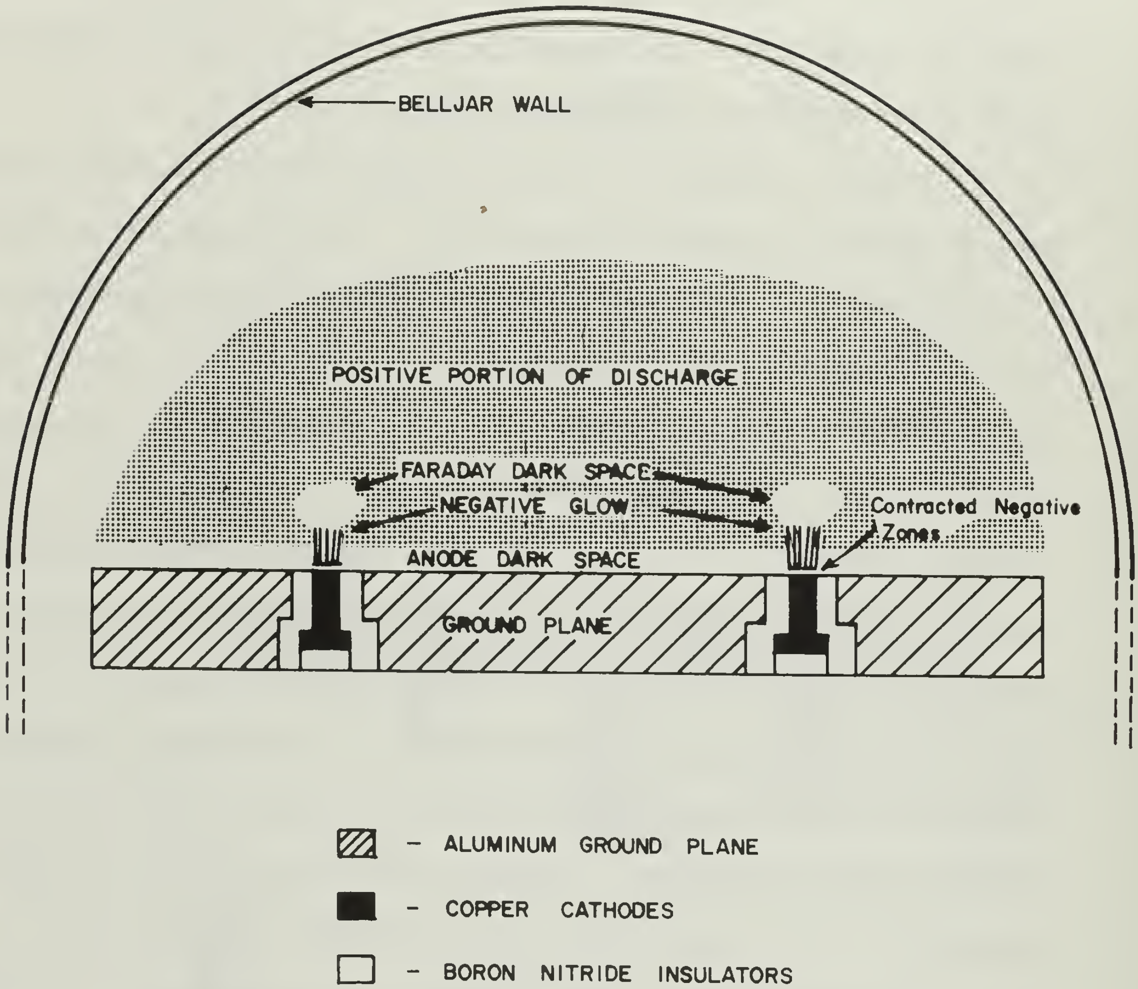


Fig. 3. THE DISCHARGE

frequency, matching resistance, and pressure have been studied. An optimum discharge is obtained for a pulse of 2500 volts at 100 pulses per second, 100 ohms, and 200 microns. Changing these parameters affects the afterglow portion of the pulse.

It is the afterglow of the plasma pulse which is of most interest in this type of discharge. A high energy electron beam is produced by the pulse to the cathodes. During the portion of the pulse when this beam is present it is likely that the electron distribution in the discharge is neither uniform nor Maxwellian. However, the distribution can be assumed to be Maxwellian in the afterglow region. This has been demonstrated in a previous pulsed plasma system [11]. Therefore it is necessary to determine plasma parameters and radiation effects in the afterglow of the discharge. This will necessitate a time-sampled measurement technique. These techniques will be discussed in the section under Plasma Diagnostics.

The following sections will describe the mechanical systems used to support the discharge.

FEEDTHROUGH COLLAR ASSEMBLY

The feedthrough collar (Fig. 4) provides for the physical support of the discharge. It mates the vacuum system, pulse forming network, microwave source and data gathering equipment.

The collar was machined from available aluminum stock. The upper and lower flanges were cut from one inch plate. The collar walls are one quarter inch thick. The quarter inch plate was cut to size, rolled, heliarc welded at the seam and rolled again. The upper and lower flanges were then heliarc welded to the walls. An expansion groove was cut in the surface adjacent to the weld to prevent warping of the flanges. Inner and outer welds were used at the collar wall seam. Outside spot welds were used to hold the flanges in place while they were being heliarc welded on the inside of the collar assembly. During initial pump down the inner, welded seam leaked at each of these spot welds and had to be treated with leak sealer.

Aluminum feedthroughs were made for the wave guide, ion gage and Langmuir probe circuits. The wave guide and ion gage feedthroughs were heliarc welded to the collar walls. Both of these welds leaked also. Connections for the probes are mounted to a feedthrough which is screwed into the upper collar flange.

The ion gage feedthrough is designed for a one inch tubulation. The double O-ring compression type seal must be carefully cleaned and assembled when the ion gage is installed or it will leak. It is designed for a hand-tight fit.

The wave guide feedthrough port is flanged. This allows for sealing the port with a blind flange if no microwave plumbing is desired. It also allows for the rapid conversion from K band to X band hardware. A

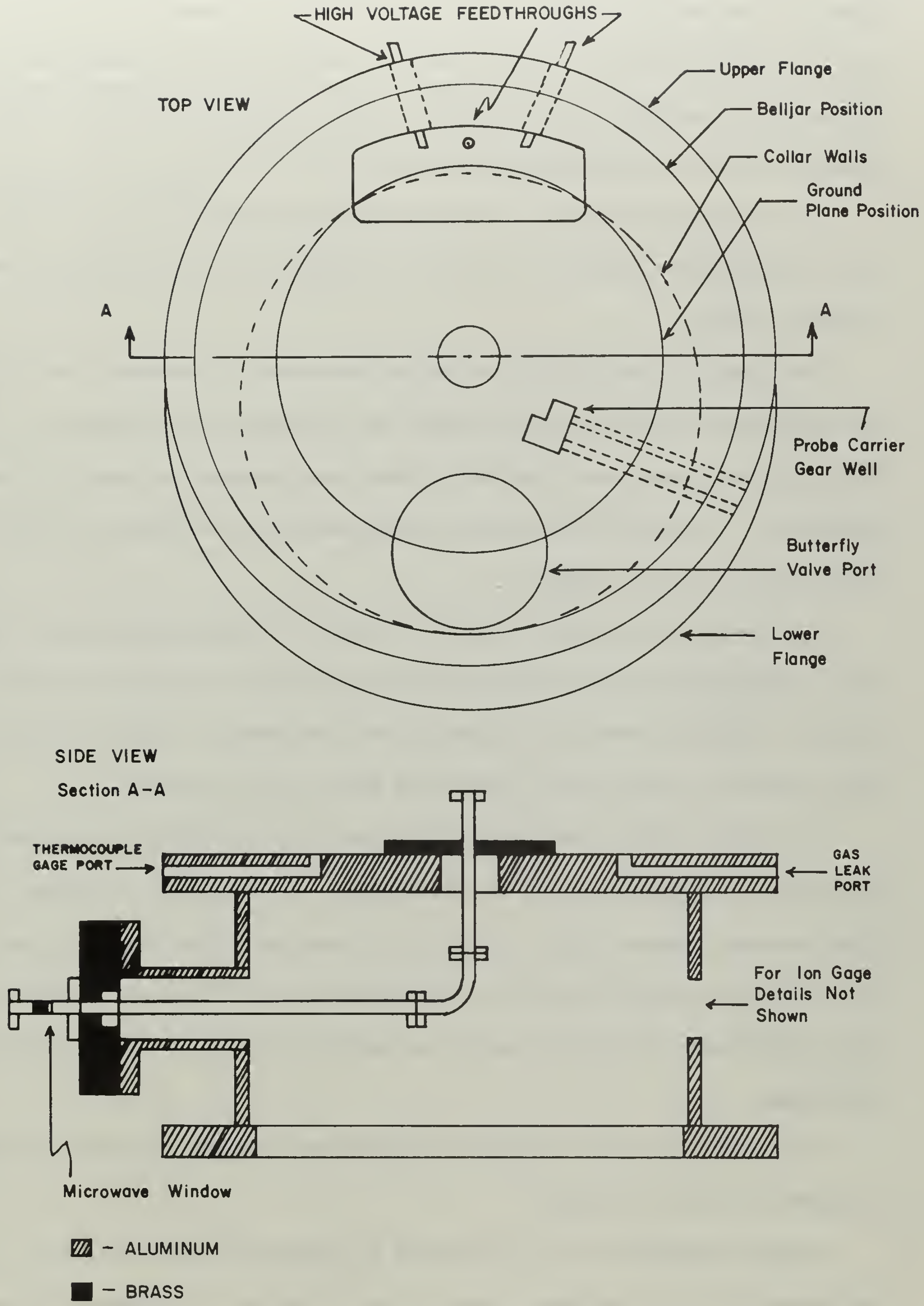


Fig. 4. FEED THROUGH COLLAR ASSEMBLY

ceramic microwave window provides the vacuum seal in the wave guide. This window is seated in a short length of wave guide flanged at each end. One end is provided with an O-ring groove and mates with the feedthrough port flange which supports the wave guide. Details of the microwave plumbing from the window to the ground plane are shown in Fig. 4.

The threaded electrical circuits feedthrough has provisions for eleven connections into the belljar. At present four are used for the Langmuir probes.

The pumping speed of the vacuum system makes it necessary to throttle the through-put from the belljar when the discharge is in operation. A four inch stainless steel butterfly valve was designed to meet this requirement. A beveled O-ring seat and pressure cap provides a vacuum seal around the valve shaft.

The two probe carriers consist of a pair of bevel gears and a screw. This arrangement changes horizontal rotary motion to vertical linear motion. The total vertical travel is ten centimeters. Double O-ring seals provide a vacuum seal around the probe carrier shafts.

The high voltage feedthrough for the discharge pulse is mounted vertically through the upper collar flange. It consists of a kovar to glass vacuum connector with a copper rod sweated to the end. A glass tube was fitted over the end of the connector and filled with epoxy. This feedthrough has been a source of arcing and results in an unstable discharge.

Two additional high voltage feedthroughs are also provided, neither of which is used at present.

Three threaded ports are provided in the upper collar flange. All are tapped for 1/8 inch NPT. One is used to mount a thermocouple gage which monitors belljar pressure. The second is a gas leak port. It has a bellows seal valve mounted in it and is used to leak argon in for discharge operation and dry nitrogen for purging. The third port is not used at present and was provided for future applications, such as contaminant injection.

PULSE FORMING NETWORK

Based on the discharge developed by G. E. Stewart at Aerospace Corporation, it was determined that a ten amp pulse with a pulse repetition frequency of 100 pps and variable to 3000 volts would provide the required plasma parameters. A positive pulse was desired. However, materials available and an existing operational design were instrumental in accepting a negative pulse.

The pulse forming network (Fig. 5) is one designed by Dr. Franz Bumiller for use at the Linear Accelerator at the Naval Postgraduate School. It consists of a trigger generator, thyratron, pulse shaping circuit (delay line) and associated power supplies. A timeing pulse is supplied by a General Radio 1217C Pulse Generator. This timing pulse controls an EFP-60 high voltage pulse tube in the trigger generator (Fig. 6). This tube provides a 1700 volt spike which is applied to the grid of a 5C22 thyratron (Fig. 7). The high voltage power supply (Fig. 8) provides plate voltage to the thyratron and is variable from zero to fifteen kilovolts. The thyratron charges a delay line consisting of fifteen sections. The shape of the pulse applied to the discharge may be varied by adjusting the inductance of the delay line sections, changing pulse repetition frequency and varying the network ballast resistors. These ballast resistors match the impedance of the pulse shaping circuits to the discharge. A pulse viewing circuit is provided as a means of monitoring the output pulse.

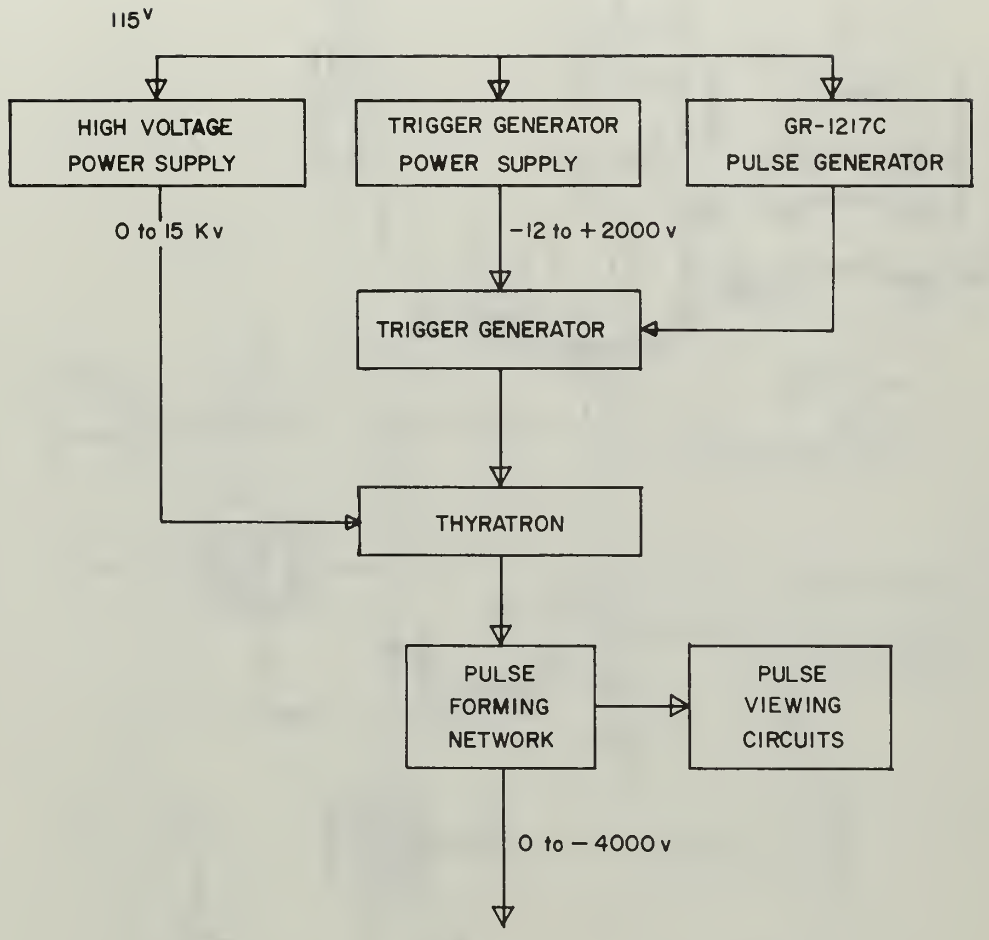


Fig. 5 BLOCK DIAGRAM OF PULSE FORMING NETWORK

INPUT: MIN. +10V, 20 NS

RESOLVING TIME: 1.5 X OUTPUT PULSE WIDTH

OUTPUT RISETIME < 8 ns

WIDTH: 2×10^{-7} FOR C = 100 pf

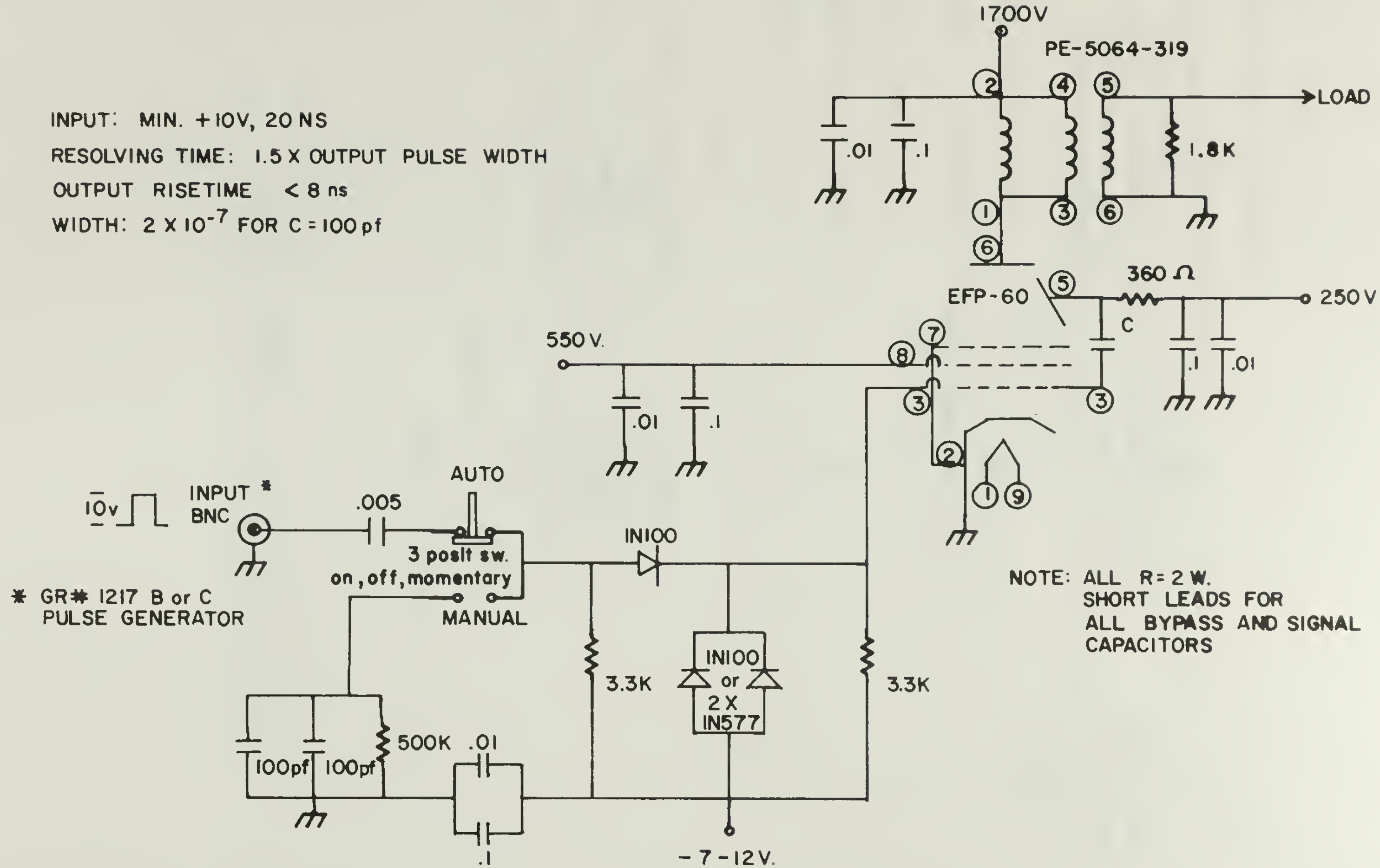


Fig. 6. TRIGGER GENERATOR

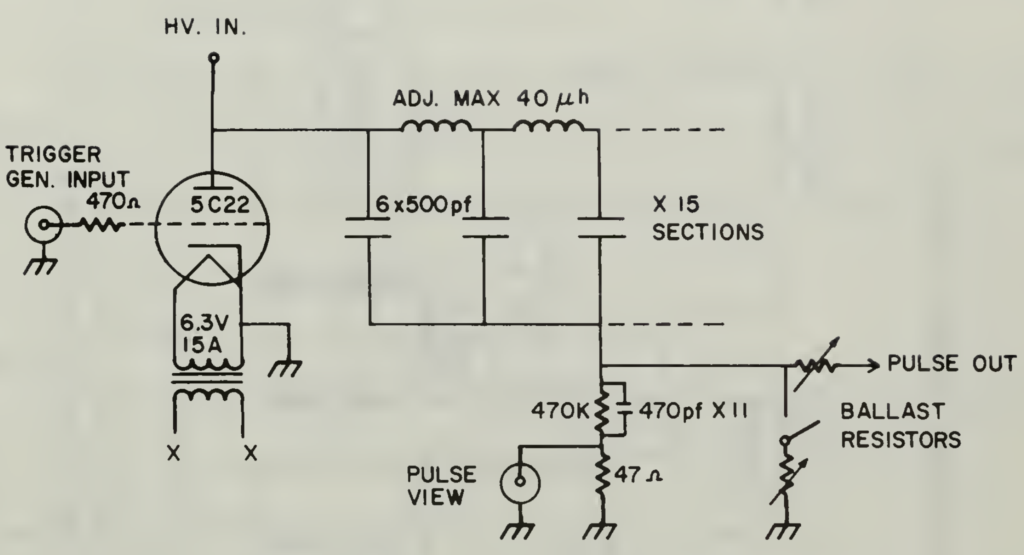


Fig. 7. THYRATRON AND PULSE SHAPING CIRCUIT

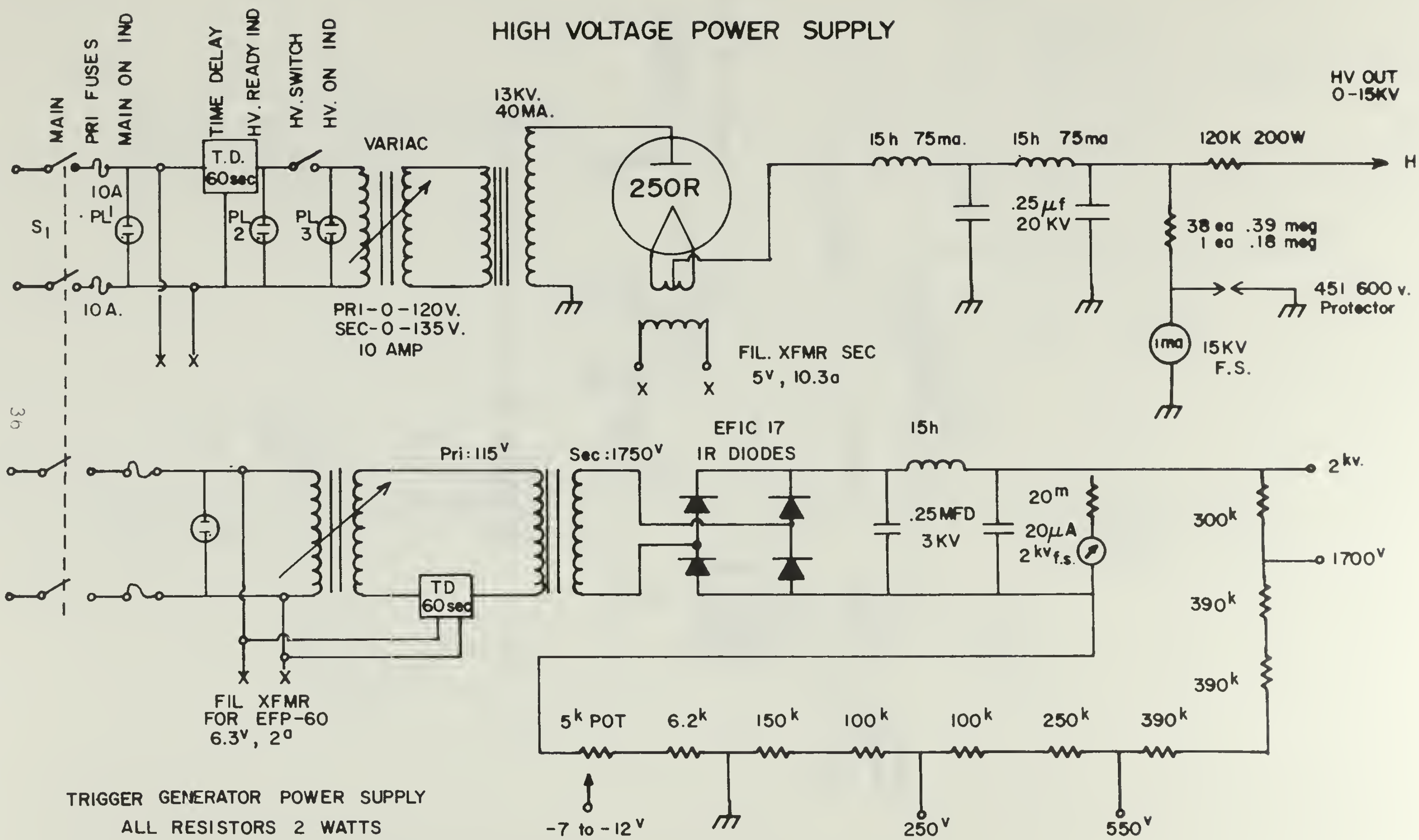


Fig. 8. POWER SUPPLIES

THE VACUUM SYSTEM

The following requirements were considered in the design of the vacuum system:

1. Ultimate pressure of approximately 10^{-8} torr to be maintained in a three to four cubic foot volume for vacuum chamber (belljar) clean-up purposes.

2. A throttling mechanism which would allow a ten to five hundred micron working pressure in the belljar.

3. A continuous gas feed system (argon was used) to support the discharge with sufficient through-put to prevent accumulation of impurities in the belljar, insuring reproducible plasma conditions.

4. An "unbakable" system.

5. Pump down time of less than one hour.

6. Ease of dis-assembly, modification and reassembly of the chamber to insure adaptability for future study.

7. Utilization of available "on hand" equipment.

8. A system of protection devices which would allow unattended operation of the system.

A block diagram of the final design is shown in Fig. 9. Operating instructions for the vacuum system are included in Appendix A.

All design considerations were realized. Ultimate pressure is 1.5 x 10^{-8} torr, attainable after two hours. After pumping for one hour, pressure is usually about 1 x 10^{-7} torr. The system is unbakable and ultimate pressure seems to be determined by the outgassing rates and vapor pressures of system components rather than equipment limitations.

The stainless steel butterfly valve incorporated in the aluminum feed through collar supports a three to four order of magnitude pressure

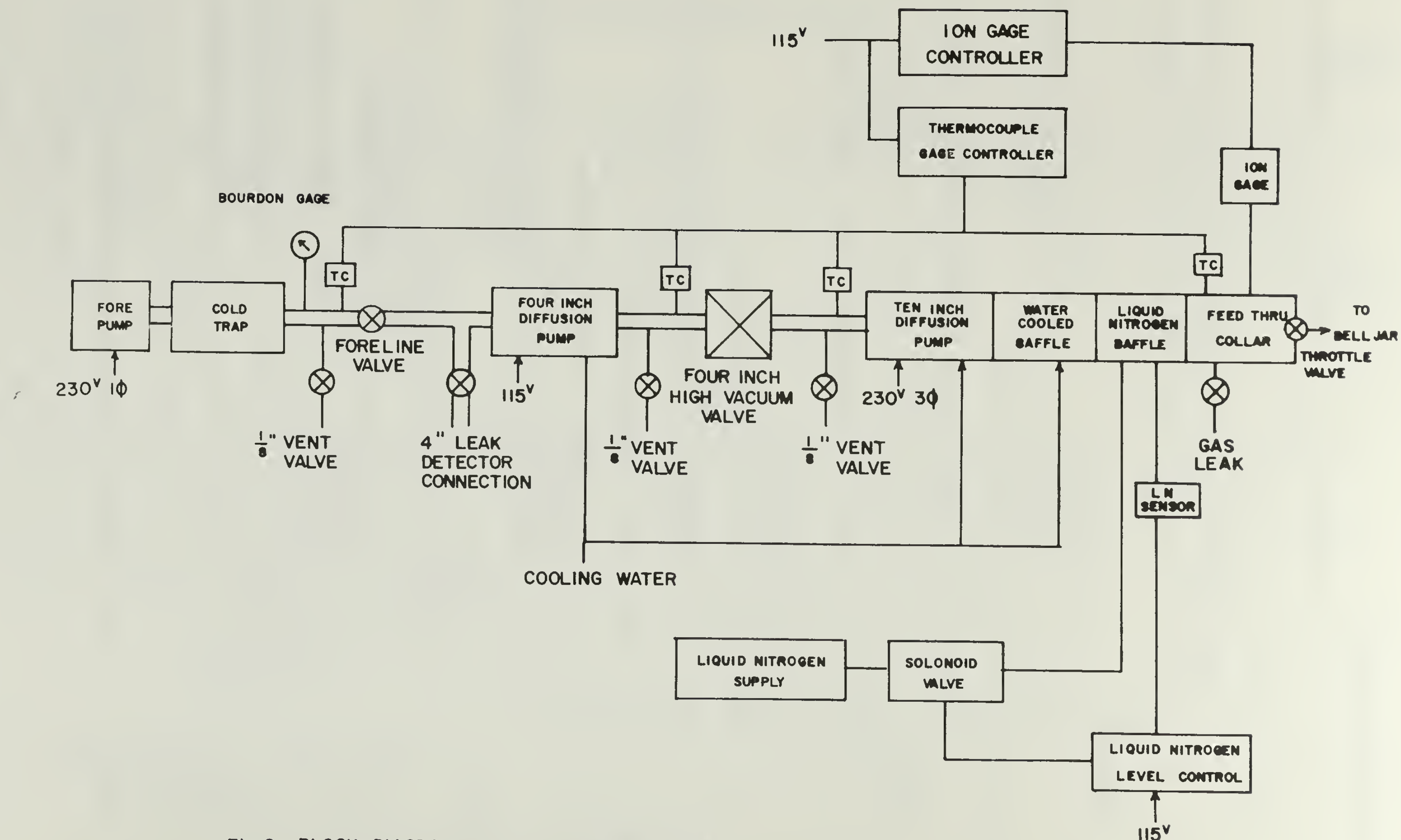


Fig. 9. BLOCK DIAGRAM OF THE VACUUM SYSTEM

differential between the discharge (belljar) and the vacuum systems. This allows the argon discharge to operate at fifty to two hundred microns and allows sufficient flow to maintain a relatively clean system.

Overload relays protect the forepump motor and both diffusion pumps. A water pressure switch will turn off the diffusion pumps if cooling water flow is interrupted. An overheated condition of either diffusion pump is sensed by a thermal switch, which turns off the respective pump (Fig. 10).

The cooling water flow diagram is shown in Fig. 11.

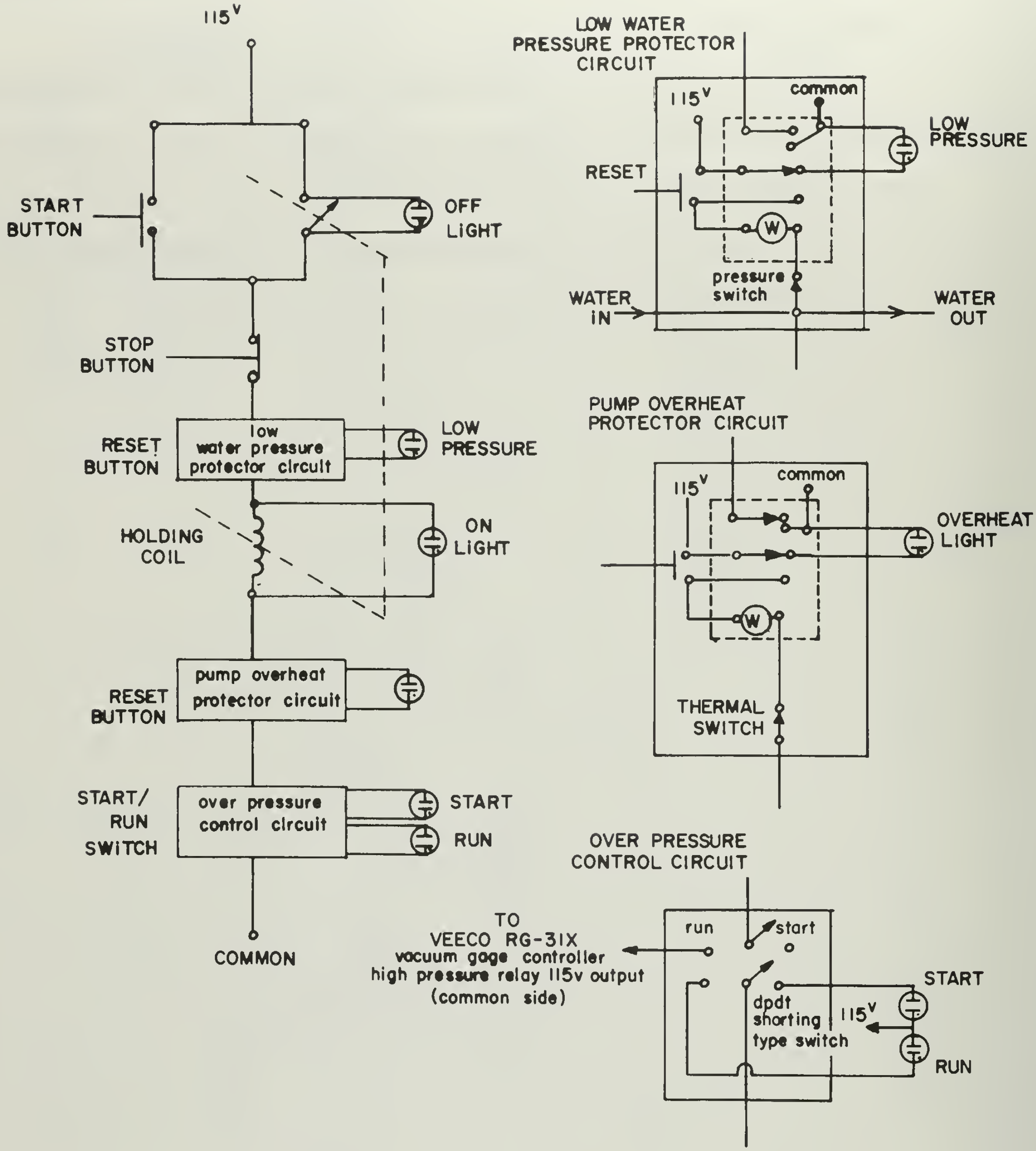


Fig. 10 . DIFFUSION PUMP CONTROL CIRCUIT

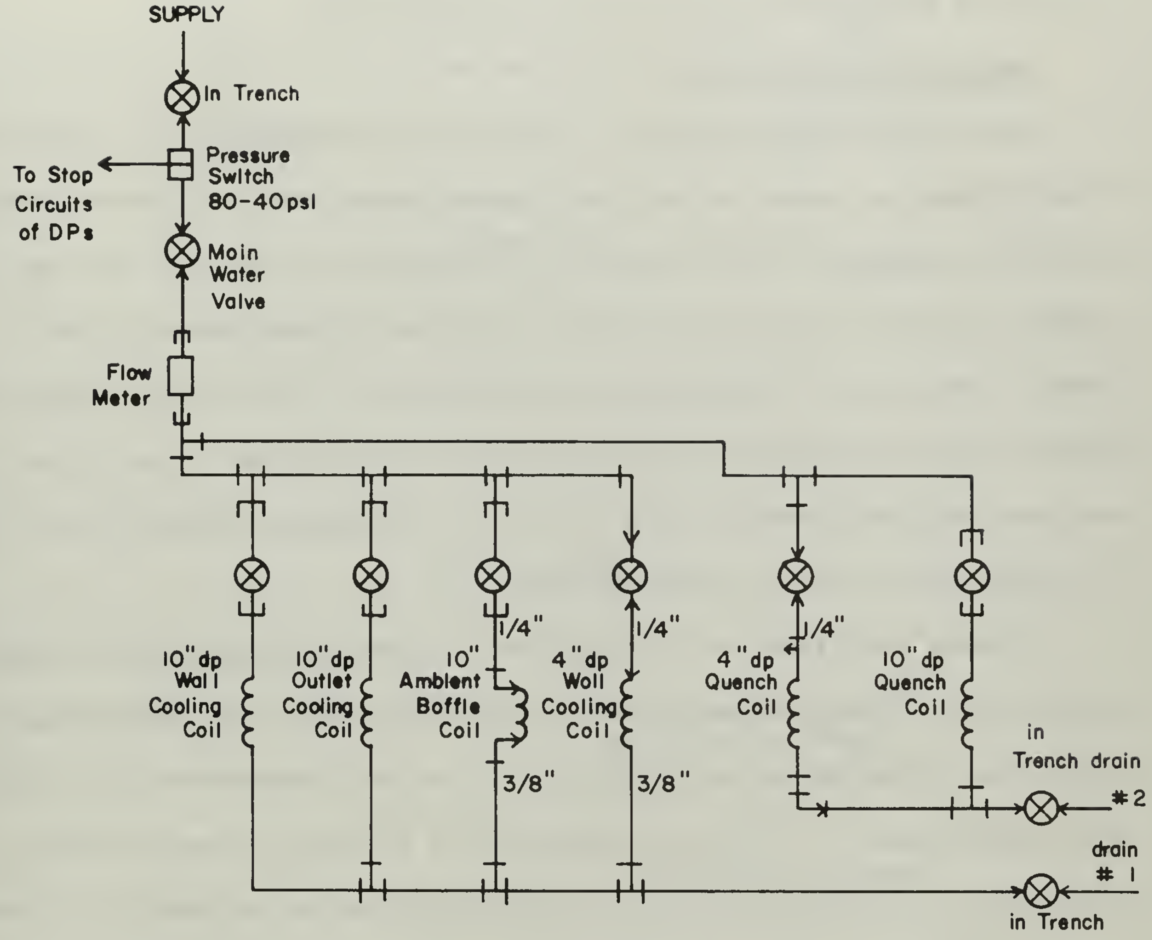


Fig. 11. COOLING WATER FLOW DIAGRAM

PLASMA DIAGNOSTICS

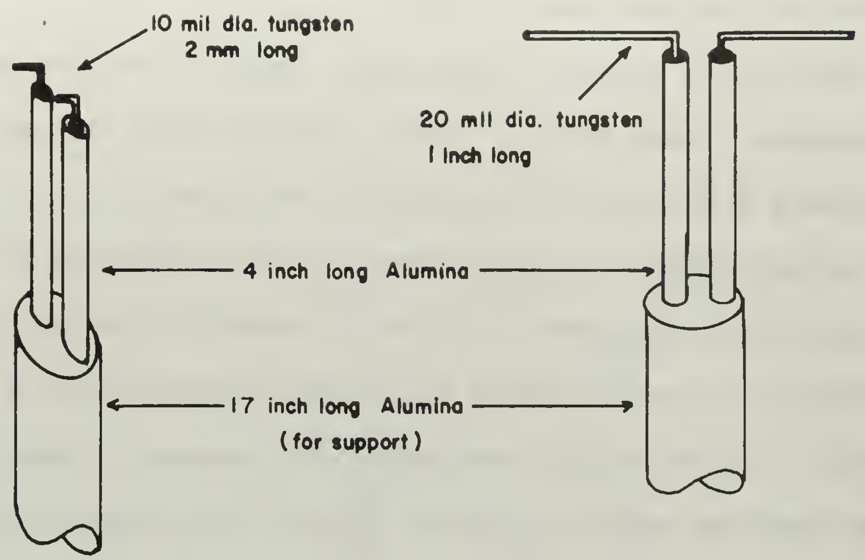
The physical makeup of the apparatus required to generate the discharge, equipment available for analysis of discharge parameters, and the expected spatial variation of plasma parameters of interest led to the selection of the Langmuir probe as the primary diagnostic tool. Probes are easily constructed and are simple to instrument.

Description of Equipment

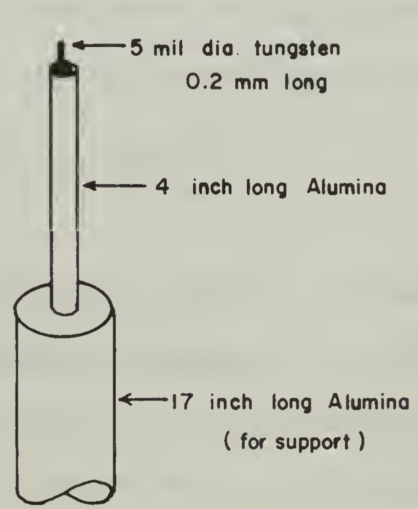
Two sets of double Langmuir probes were designed for the experiment. These probes are shown in Fig. 12. It was hoped that the better design would be determined. The first set, and smaller of the two, are 2mm in length and made from 10 mil tungsten wire fed through double alumina tubing. The tips of each probe are parallel and 2.5mm apart. These two double probes were mounted perpendicular to one another in an attempt to evaluate shielding effects (see Fig. 12). The larger probes are one inch in length and of 20 mil tungsten wire.

Probing the plasma was accomplished by attaching each double probe assembly to a carriage mounted on the upper flange of the feedthrough collar and below the ground plane. This avoids interference with microwave measurements. The tip of the probe is allowed to pass through a small hole in the ground plane. Probe height may be adjusted by a mechanical linkage, from the ground plane surface to ten centimeters above the plate. The plasma was probed at two positions relative to the center of the ground plane.

The double probe method was selected since it appears more suitable in an active discharge. Perturbations due to noise from the discharge should be more easily eliminated in a balanced circuit. In the final analysis, however, due to the circuit single probe techniques had to be used and proved satisfactory. The single probe is shown in Fig. 12.



DOUBLE PROBES



SINGLE PROBE

Fig. 12 LANGMUIR PROBES

Probe Theory

Since both single and double probe techniques were utilized, both theories will be discussed briefly.

The original work of Langmuir [20] begun in 1924 has been refined and extended by many people. Chen's treatment [21] and that in Glasstone and Lovberg [17] were used as the basic reference.

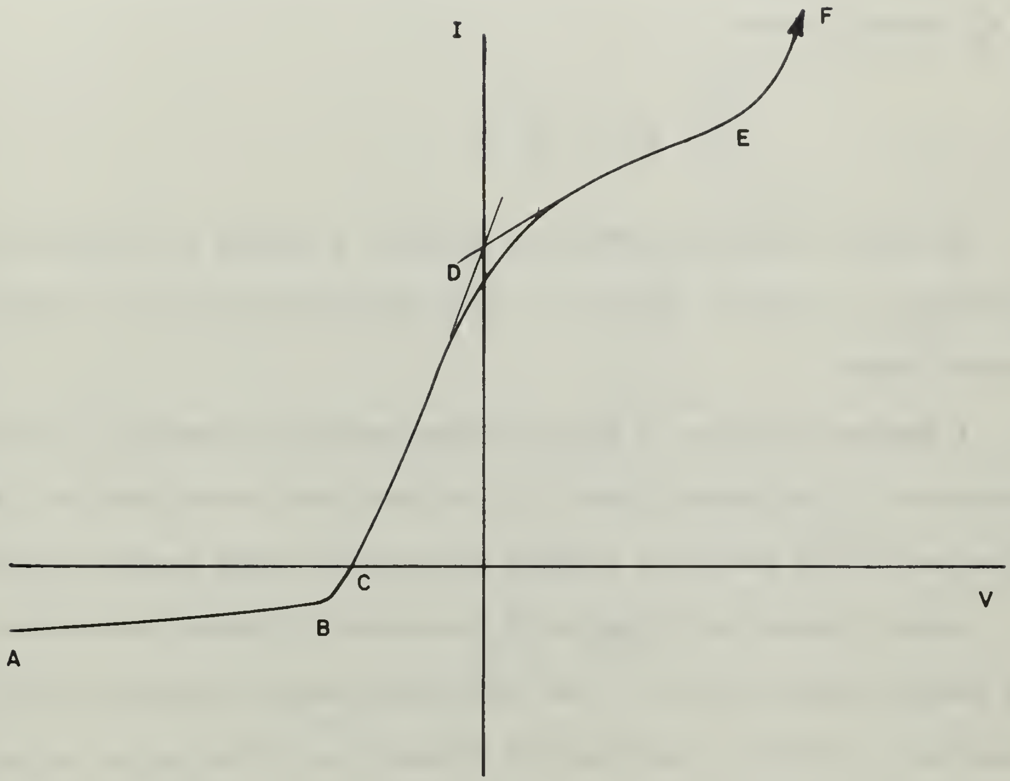
In its simplest form the electric probe consists of a small electrode in contact with the plasma. Current collected by the probe is plotted as a function of probe voltage as the latter is varied about plasma space potential. Probe voltage is measured with respect to some reference such as the discharge anode or cathode. Most of the change in voltage between the plasma and the probe occurs in the sheath which develops around the probe. An idealized probe characteristic is shown in Fig. 13.

When the probe is highly negative with respect to the plasma, all electrons are repelled and the current collected is due to ions entering the sheath. This is the ion saturation region. Langmuir has shown that the ion density can be determined from the slope of the square of this saturation current versus voltage:

$$\frac{dI^2_{i(sat)}}{dV} = - \frac{2e^3 n_i A^2}{\pi^2 m_i}$$

As the probe is made less negative, less ion current reaches the probe and the more energetic electrons can penetrate the sheath. If a Maxwellian distribution is assumed to exist in the plasma, the electron temperature can be determined from the slope of a plot of the logarithm of electron current versus probe voltage, i.e.

$$T_e = 0.434 \Big/ \frac{d(\log I_e)}{dV} .$$



REGIONS ON I-V CURVE

A B — Ion Saturation Current
B C — Increasing Electron Current, Ion Current Predominates
C — Floating Potential
C D — Increasing Electron Current, Electron Current Predominates
D — Plasma Space Potential
D E — Electron Saturation Current
E F — Neutral Particle Ionization

Fig. 13. IDEALIZED PROBE CHARACTERISTIC

When probe potential reaches plasma potential the sheath vanishes and random electron current is collected. Electron temperature is known and electron density can be found from

$$I_e = Aen_e \sqrt{\frac{kT_e}{2\pi m_e}} .$$

Also, from Chen, the electron density can be determined from a plot of I_e^2 versus V, since

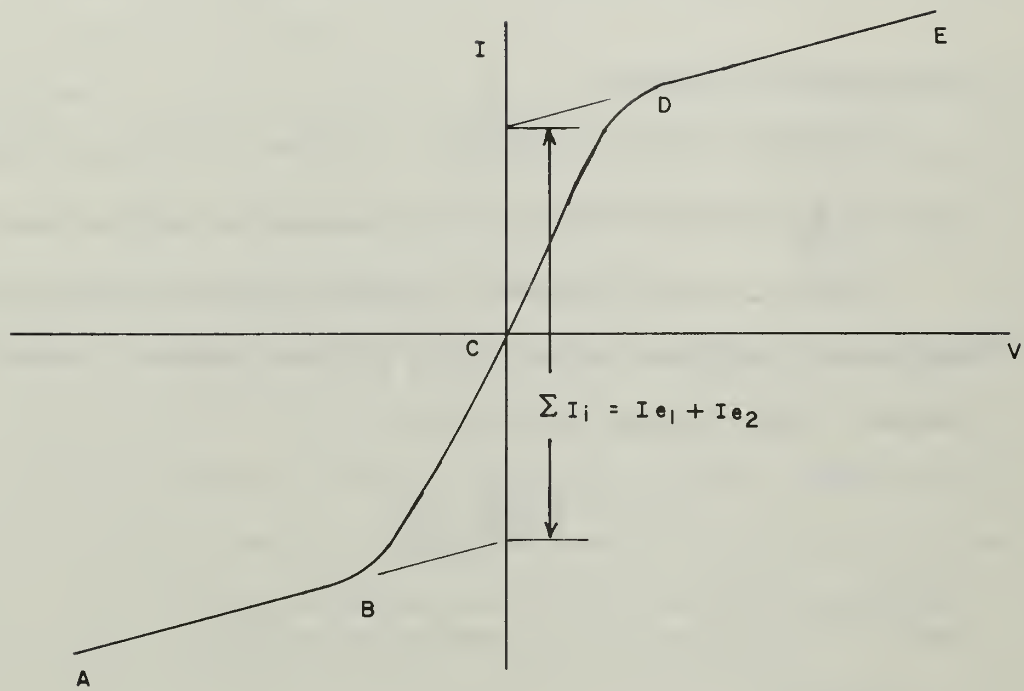
$$\frac{dI_e^2}{dV} = \frac{2}{\pi^2} A^2 \frac{e^3}{m_e} n_e .$$

As probe voltage is made more positive a region of electron current saturation is reached, similar to that discussed for the ion current saturation region.

A further increase in probe voltage results in neutral particle ionization in the probe sheath. These additional electrons are also collected by the probe and a sharp increase in probe current results.

Double probes were originally discussed by Johnson and Malter [22]. The double probe consists of two small electrodes in contact with the plasma with a bias voltage applied between them. The entire probe circuit must be isolated from ground in order that it follow plasma potential, and draw no net current from the plasma. This fact makes the double probe technique applicable to decaying discharges. The theory is based on the plasma sheath properties of a gas discharge and Kirchhoff's current law.

An idealized double probe characteristic is shown in Fig. 14. Again the flat portions of the curve represent saturation currents. Note that for zero voltage between the probes no net current is collected (i.e. the probes float).



REGIONS ON I-V CURVE

A B – Ion Saturation Current
B C – Increasing Electron Current, Ion Current Predominates
C – Floating Potential
C D – Increasing Electron Current, Electron Current Predominates
D E – Electron Saturation Current

Fig. 14. DOUBLE PROBE CHARACTERISTIC

The summation of the ion current collected is equal to total electron current collected by both probes.

$$\sum I_i = I_{e_1} + I_{e_2}$$

If I_i is not a function of V then I_i can be determined as shown in Fig. 14. It can be shown that

$$\frac{\sum I_i}{I_{e_1}} = 1 + e^{-\frac{eV}{kT_e}} \quad \text{or} \quad \ln\left(\frac{\sum I_i}{I_{e_1}} - 1\right) = -\frac{eV}{kT_e}$$

for symmetrical probes.

Therefore a plot of $\ln\left(\frac{\sum I_i}{I_{e_1}} - 1\right)$ versus V yields a straight line with slope $-\frac{e}{kT_e}$ from which the electron temperature can be found.

Johnson and Malter and more recently Clements [23] describe an equivalent resistance method, using the same approach, which is less tedious. This approach shows that

$$T_e = \frac{1}{4}\frac{e}{k}\left[\frac{dV}{dI}\right]_{V=0} \sum I_i$$

Density is found as in the single probe technique.

Results

A double probe analysis was unsuccessfully attempted utilizing the method described by Hosea [24], a time sampled technique. An x - y recorder was used and again no meaningful results could be obtained. Finally point by point measurements were taken using an electrometer and ammeter to record probe voltage and current but monitoring these quantities on an oscilloscope. These results, too, seem meaningless when double probe theory was applied.

A suggestion was made by Major Dan Brockwell that the data seemed to resemble the tail end of a single probe characteristic.

An analysis based on single probe theory was attempted and electron density and temperature were determined to be in the range desired. Five more data taking runs were made and the data proved to be reproducible.

Figure 15 is a plot of probe current versus probe voltage and the load line. From this, the plot of $\log I_e$ versus V is obtained (Fig. 16). The slope of this plot gives the electron temperature. Electron density is found by plotting I_e^2 versus V (Fig. 17).

Measurement of electron density and temperature were taken one centimeter above the ground plane 1½ and 3 inches from the center of the plane. Values of 4×10^{12} electrons per cubic centimeter (Fig. 17) and 2 eV (Fig. 16) were obtained at both radial positions.

Although the plasma appears uniform radially above the Faraday dark space, it can be assumed, from the nature of the discharge, that there is a variation in plasma parameters above the cathodes. Computation of the mean free path of the electrons and relaxation time should give an indication of the non-uniformities which extend around and above the cathodes during the afterglow portion of the plasma pulse.

No measurements were made of the plasma parameters as a function of distance above the ground plane, however based on previous studies [11, 26] it is expected that electron density will vary at least two orders of magnitude from the surface upward to 10 centimeters above the ground plane. An increase in density near the center of the ground plane is expected due to diffusion into the slot antenna. Plasma parameters are also functions of time, pressure and excitation power.

Sources of Error

The analysis of plasma parameters utilizing the double probe,

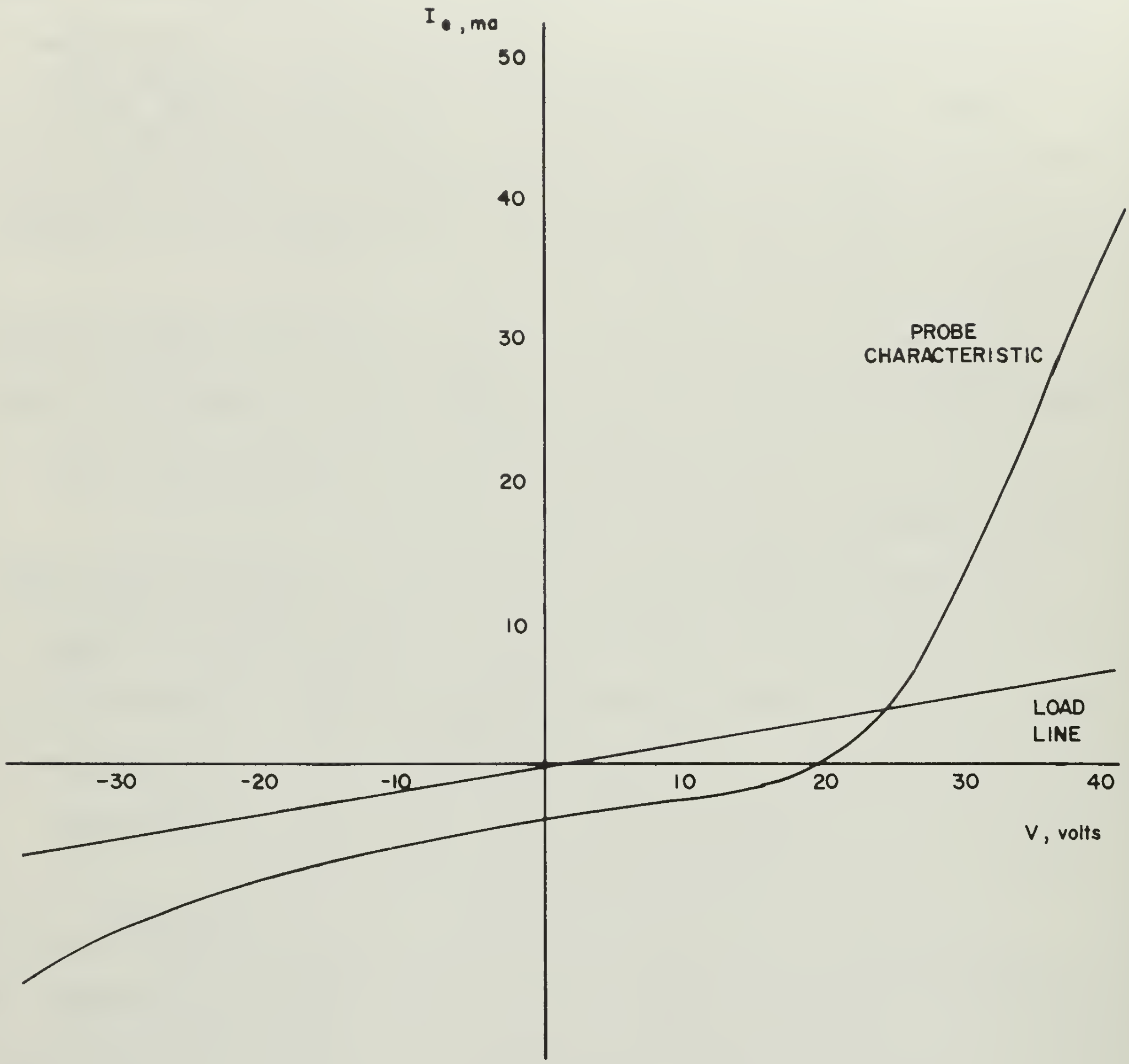


Fig. 15. PROBE CHARACTERISTIC AND LOAD LINE

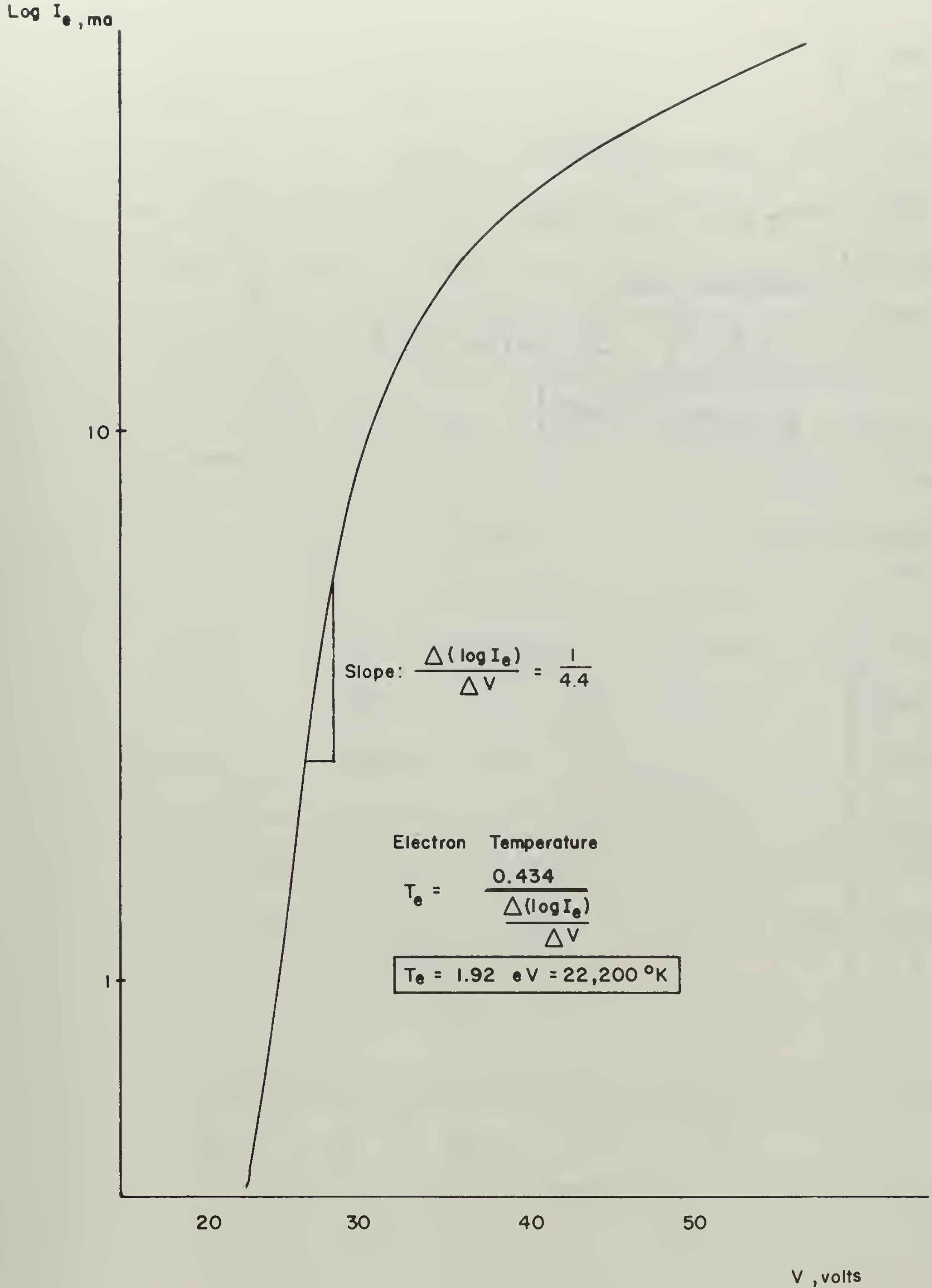


Fig. 16. log I_e vs. V - ELECTRON TEMPERATURE

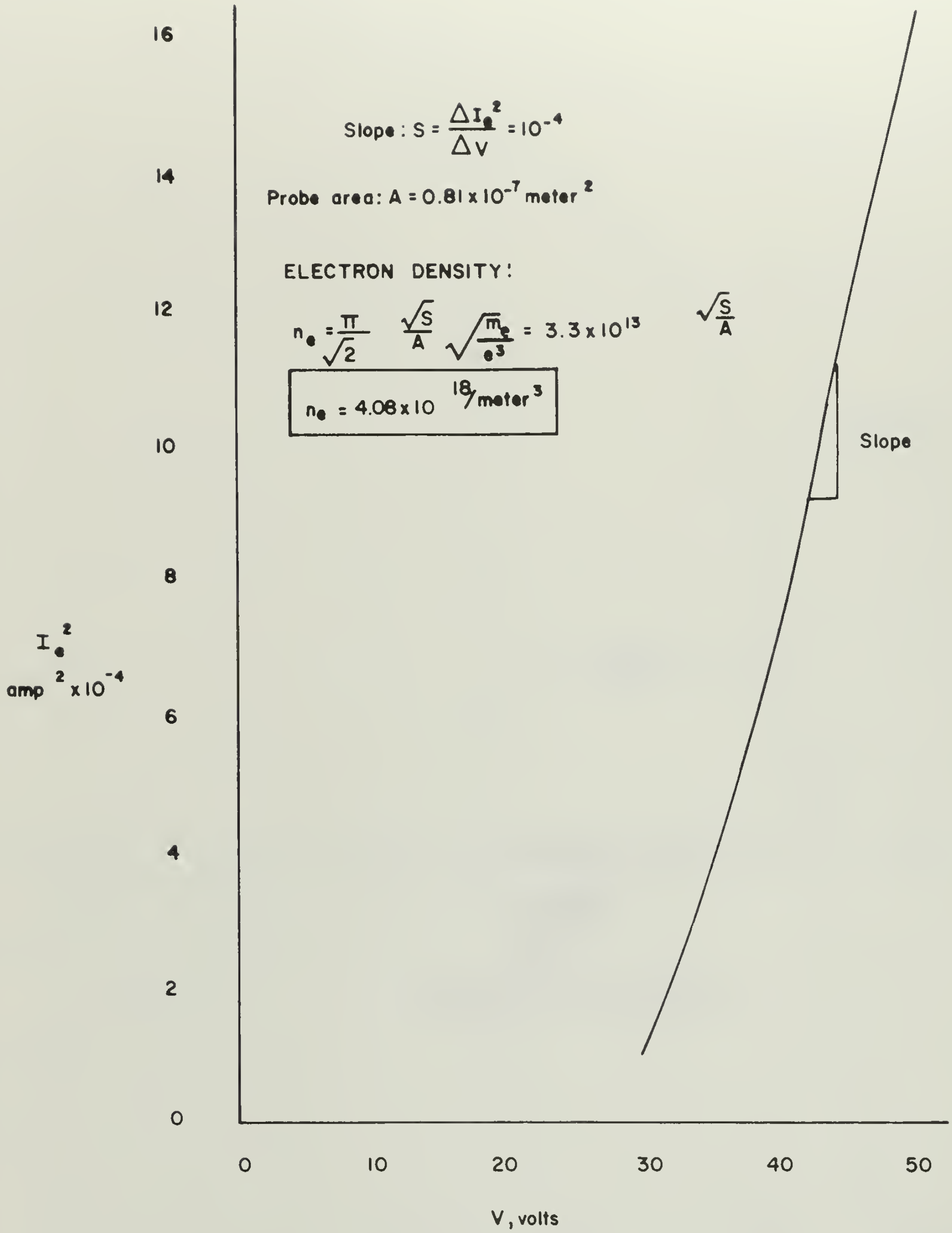
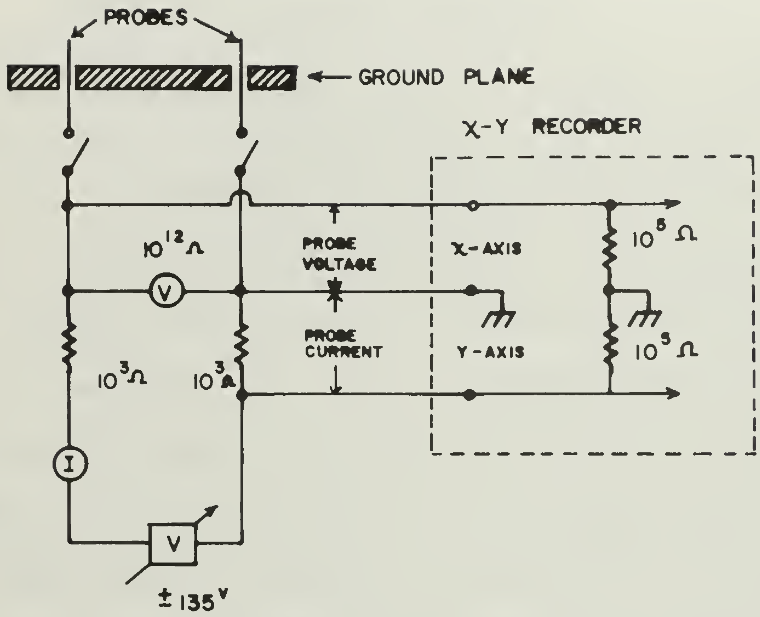


Fig. 17 I_e^2 vs V – ELECTRON DENSITY

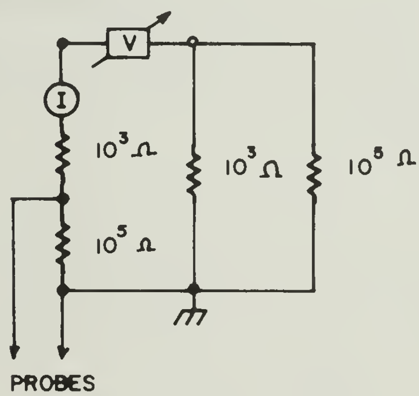
time-sampled technique described by Hosea [24] failed for two reasons. First, spurious arcing below the ground plane resulted in an unstable discharge, making it impossible to achieve an exactly reproducible plasma from pulse to pulse. Second, this same arcing produced a sufficient noise level so as to make the scope characteristic meaningless.

Steps were taken to reduce the arcing below the ground plane, and an attempt was made to get double probe measurements using an x-y recorder. Figure 18 shows the circuit used for these measurements. As can be seen, one of the double probes is connected directly to ground. In this case ground potential is anode potential and plasma space potential. Thus this probe remains at anode potential, and the analysis becomes a single probe technique. The resulting effective circuit is shown in Fig. 19.

Point by point measurements were taken during the data runs using the recorder. When plotted, these were interpreted as single probe characteristics. Recorder curves were still erratic and point by point measurements were hard to obtain. The input impedance of the recorder is 100,000 ohms. This results in a current to ground several orders of magnitude larger than probe current. The effect of the recorder then was to greatly distort probe current.



ACTUAL CIRCUIT



SCHEMATIC

Fig. 18. DOUBLE PROBE CIRCUIT

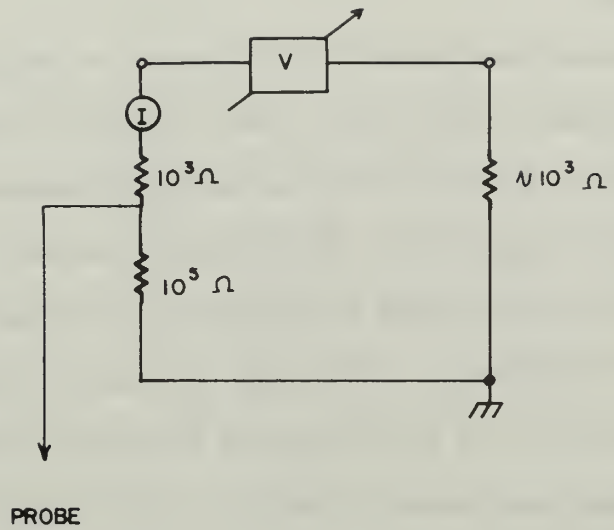


Fig. 19. EFFECTIVE PROBE CIRCUIT

CONCLUSION

The loss of communications during space vehicle reentry continues to be a major problem in the space exploration program. The technical community is expending considerable effort in an attempt to find a satisfactory alleviation technique for this problem. Accurate methods for the acquisition of data from the plasma sheath during flight is difficult and the known methods for generating a plasma are not representative. Thus, a critical drawback in this study is the laboratory simulation of the reentry plasma.

The discharge described in this report is thought to simulate the reentry plasma more closely than others studied to date. The necessity to plot radiation patterns required far field measurements of an antenna imbedded in the plasma slab. This dictated the use of X band and K band frequencies in order to have the capability of studying cutoff and transmitted modes of operation. The range of electron densities is then defined to be 10^{12} to 7×10^{12} electrons per cubic centimeter.

Preliminary measurements indicate that electron density is 4×10^{12} electrons per cubic centimeter for the conditions used. Further measurements will be required to confirm this. Recommendations for future studies are discussed in the next section of this report.

RECOMMENDATION FOR FUTURE STUDY

Applications for future study fall into two general categories: those requiring a Physics background - the analysis of the discharge, and those requiring an Electrical Engineering background - the study of how the plasma effects electromagnetic radiation. As will be shown below, however, there are a number of potential problems which require a background in both fields. These problems could be studied by an individual or jointly, but in any case, interdepartmental effort between the Physics Department and the Electrical Engineering Department is indicated.

The very brief description of discharge operation presented in this paper was based on an observation of the plasma and a comparison to known facts about ionized gases. This, however, is a new type of discharge and very little is known about it. A detailed experimental and theoretical study would be required to analyze the electric field pattern, current and space charge density, the spatial distribution of dark and luminous zones and loss mechanisms such as recombination and diffusion.

A determination of plasma parameters by the various measurement techniques - probes, cavity, radiometer, microwave interferometer, spectral and optical - are all topics for future study. Density profiles, particle temperatures and collision frequencies are of interest academically and in the analysis of plasma effects on incident of energy. Since this is thought to be a new type of discharge, a study of the many phenomena observed in plasmas would be relevant. Instabilities, waves, resonances and magnetic field effects are but a few of the more obvious effects requiring analysis.

At present, a study is being conducted to determine the magnitude of scattering matrix elements, treating the plasma as a two-port network.

The facility has been instrumented for measurements at X band and K band microwave frequencies. Radiation patterns will also be plotted. No attempt will be made to determine phase relationships. A complete analysis of plasma effects on incident electromagnetic radiation will have to include phase shift and polarization measurements. The effect on the plasma of incident high power rf energy should be studied. The channel capacity and information carrying capability of various types of signals would be of interest. Recent studies [25] indicate that excitation of a plasma column induces oscillations which effectively make the plasma an antenna. This effect may be applicable and could possibly be a solution to the blackout problem.

The ultimate goal for which the Reentry Plasma Facility was designed was a study of alleviation techniques to the reentry blackout problem. Some of the current proposals appropriate for study using the Facility are:

a) communications system design - considering increased power, reduced bandwidth and antenna construction as possible solutions;

b) magnetic windows - requiring further theoretical analysis, determination of aperture size in relation to radiator efficiency, investigation of rf breakdown level in the presence of a magnetic field, and a study of the possible use of superconductors to reduce magnet size and weight;

c) coolant injection - to include type of coolant, injection technique and minimum requirements regarding weight;

d) other injection techniques - dust, chemicals and electro-negative gases;

e) high frequency communications.

A discussion of each of these alleviation techniques can be found in [2].

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APPENDIX A

OPERATING INSTRUCTIONS FOR THE REENTRY PLASMA FACILITY

Obtaining a Vacuum

1. Ensure that all system components are clean prior to assembly.

2. Check adequate cooling water flow to pumps and baffle as follows:

   a) 2/3 gpm to ten inch diffusion pump cooling walls.

   b) 1/2 gpm to four inch diffusion pump cooling walls.

   c) 1/3 gpm to the baffle.

3. Have on hand gaseous dry nitrogen for purging, liquid introgen for baffle and fore line trap, and argon for the discharge.

4. Close the three 1/8 inch vent valves, the gas leak, and the leak detector connector valve.

5. Open fore line valve, four inch high-vacuum valve, and throttle valve in the feedthrough collar.

6. Turn on thermocouple gage controller and ion gage controller (do not turn on ion gage filament).

7. Turn on forepump. The system is of sufficient volume (about seven cubic feet) so that the ballast valve on the fore pump may have to be opened slightly to keep the pump from overloading and tripping the over-current relay.

8. Within five minutes pressure throughout the system should be fifty microns or less. This will be indicated on the thermocouple gage. Purge the system at one hundred microns for five minutes by bleeding in dry, gaseous nitrogen through the gas leak in the feed through collar. This removes much of the condensable vapor from the system, reducing pump down time, increasing cold trap efficiency and reducing contamination of pump fluids.

9. With pressure stabilized at one hundred microns and while purging, turn on both diffusion pumps. The flow of gas through the system reduces back diffusion of oil vapors as the diffusion pumps begin to operate.

10. In about five minutes pressure will begin to fluctuate and rise to 200-300 microns. Then pressure will drop rapidly. Close the gas leak valve, securing the nitrogen purge.

11. Select thermocouple No. 4 on the controller, monitoring pressure in the belljar. The pressure will be off scale on the indicator (less than one micron) in approximately fifteen minutes. Turn on the ion gage filament and adjust in accordance with the instructions found in the RG3A gage control operating manual.

12. Within forty minutes pressure will be in the 10^{-6} torr range. Fill fore line trap with liquid nitrogen and turn the LN level control to automatic. The ten inch LN baffle will begin to fill An "on" time of three minutes has proven satisfactory for the LN timer.

13. In five minutes the pressure should drop to about 10^{-7} torr. Degas the ion gage in accordance with the instructions in the operating manual.

14. The discharge can be turned on at this time. However, a cleaner chamber will result if the system is allowed to pump for a few hours. When a stable ultimate pressure (usually about 3×10^{-8} torr) is attained, the system is as clean as it will be without baking.

Leak Detection

If the times or pressures outlined in the above steps are not obtainable, the system has probably developed a leak. In the past the following places have been prone to leaks:

1. All welds in the feed through collar, particularly at the spot

welds on the outside of the collar. These can usually be sealed using GEVAC, a General Electric vacuum leak sealer which can be applied directly to the leak while the system is evacuated.

2. The double O-ring seal around the ion gage. Extreme care in assembly and disassembly, thorough cleaning, and a light coat of silicone grease on the O-rings are necessary for a vacuum tight seal. The seal nut should be hand tight only.

3. The double O-ring seals around the probe carrier shafts. The same instructions outlined in 2. above apply.

If a leak is apparent, the following steps should be taken:

1. Read the instruction manual for the Veeco MS-9AB Mass Spectrometer Leak Detector to become familiar with its operation.

2. Attach the Leak Detector to the Vacuum system at the 1½ inch leak detector connector valve in the foreline. Any one of the MS-9 test inlets will suffice; however the one on the right side of the detector has been used in the past.

3. Once the Leak Detector is operating and the test valve has been opened, evacuating the test manifold, the system connector valve can be opened, mating the vacuum system and the test manifold. As a precautionary measure, close the four inch high vacuum valve prior to joining the vacuum system to the test manifold.

4. Open the four inch high vacuum valve. Test for leaks as outlined in the MS-9AB instruction manual.

5. Upon completion of the test close the 1½ inch connector valve, vent the test manifold and disconnect the leak detector.

Discharge Operation

1. Turn on the General Radio 1217C Pulse Generator. Set pulse

repetition frequency to 300 pps, Δf to mid scale, pulse duration to one microsecond, and amplitude to 450 units. The trigger generator requires a positive timing pulse out of the GR 1217C.

2. Turn on the Pulse Forming Network (PFN) and the Trigger Generator. Both have a one minute time delay. The PFN has a lapsed time indicator on the front panel and a high voltage ready light.

3. Set the Trigger Generator to the Automatic Pulse in mode.

4. Close the throttle valve in the feed through collar. Select thermocouple No. 4 on the controller.

5. Set the ion gage controller to the 10^{-4} torr range.

6. Attach the argon supply to the gas leak connection. Slowly bleed argon into the belljar. Thermocouple No. 4 will indicate belljar or discharge pressure. The ion gage monitors system pressure.

7. The discharge operates most satisfactorily over a pressure range between 50 and 300 microns. System pressure will range from 4 to 8 x 10^{-4} torr for these discharge pressures. The gas leak valve is hard to adjust.

8. Turn the high voltage switch on the PFN to On.

9. Adjust the high voltage in the trigger generator to 1700 volts.

10. Slowly apply the pulse to the discharge with the main rheostat on the PFN. The discharge will operate satisfactorily from 3000 to 6000 volts.

11. Monitor the discharge pulse from the pulse viewing circuit. Adjust pulse shape by varying pressure (argon leak rate), discharge voltage and pulse repetition rate, pulse duration, and amplitude of the timing pulse.

12. To turn off the discharge, turn discharge voltage to zero, high voltage on trigger generator to zero and high voltage on PFN to off.

13. Close the gas leak valve. Belljar pressure will slowly drop to about ten microns, and after two or three minutes system pressure will be less than 1 x 10^{-4} torr. The throttle valve in the feed-through collar may then be opened. System pressure may rise sharply for a second or two, but it will immediately drop to the 10^{-7} torr range. It should reach 3 x 10^{-8} torr in ten to twelve minutes after the throttle valve is opened.

Bringing the Vacuum System up to Atmospheric Pressure

1. Let both LN traps go dry and continue to pump, preferably for twelve hours or more.

2. Attach dry gaseous nitrogen to the gas leak and purge at 5 x 10^{-4} torr for two minutes. This establishes a flow of gas through the system reducing back diffusion of oil vapors.

3. Turn off both diffusion pumps.

4. Turn on quench water to both diffusion pumps. Continue to let cooling water flow.

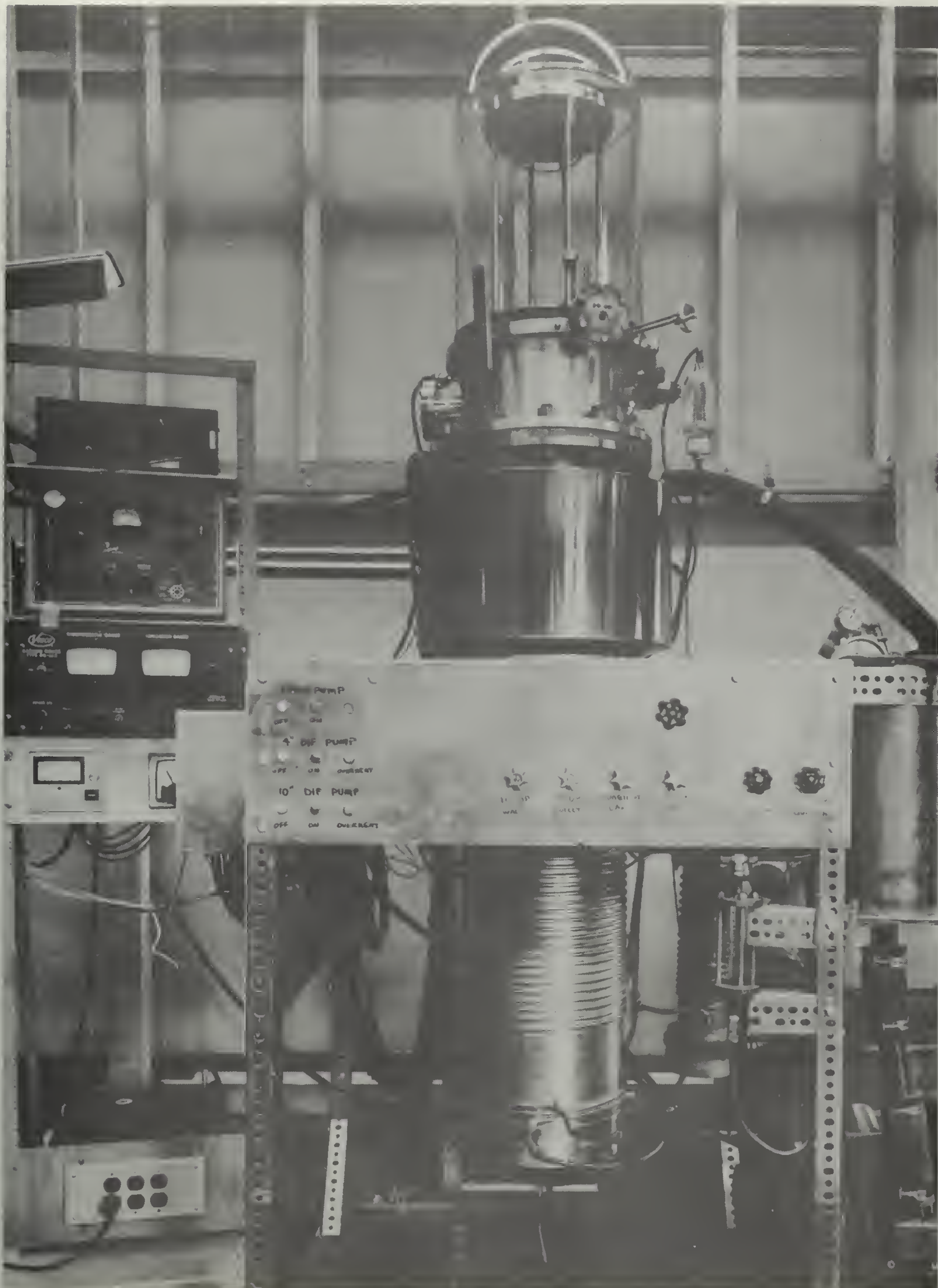
5. Monitor system pressure. In about five minutes, the oil jets in the diffusion pumps will break. Pressure will rise rapidly to 50-100 microns. Turn off the ion gage filament.

6. Adjust nitrogen flow to maintain 200-300 microns with fore pump running.

7. When the bases of both diffusion pumps are cool to the touch, turn off the fore pump.

8. Allow the system to come up to atmospheric pressure slowly. Do not bleed in nitrogen at an excessive rate or the belljar will be unseated.

9. When system is at atmospheric pressure as indicated on the manometer in the foreline, turn off nitrogen, water, ion gage, and thermocouple gage controllers.



The Reentry Plasma Facility - Front View

The Reentry Plasma Facility - Top View Showing Ground Plane

The Discharge

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Naval Postgraduate School
Monterey, California

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

Design, Construction, and Operation of a Laboratory Simulation of the Reentry Plasma

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Thesis, M.S., June 1967

5. AUTHOR(S) *(Last name, first name, initial)*

HANLE, Ray L.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1967	69	26

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

[redacted]

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

A Reentry Plasma Facility has been constructed which simulates the plane plasma slab that develops in front of a reentering blunt body. The Facility will be used to study planar plasma effects on incident electromegnetic radiation. Design, details of construction, and operating procedures are presented.

The pulsed discharge is developed above a ground plane in which is imbedded a slot antenna. Preliminary measurements, made with Langmuir probes, indicate that electron density is $4 \times 10^{12}/cm^3$ and electron temperature is 2 eV, placing the plasma cutoff frequency between X and K band frequencies.

DD FORM 1 JAN 64 1473

UNCLASSIFIED

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Blackout						
Communications						
Discharge						
Plasma						
Reentry						
Sheath						
Simulation						

[redacted]