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A TECHNIQUE FOR SIMULATING THE IONOSPHERIC PLASMA

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A TECHNIQUE FOR SIMULATING THE IONOSPHERE PLASMA

Test and Evaluation Division
Systems Reliability Directorate

May 1968

A dissertation submitted to the faculty of the School of Engineering and Architecture of the Catholic University of America in partial fulfillment of the requirements for the Degree of Master of Science in Engineering.

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

A TECHNIQUE FOR SIMULATING
THE IONOSPHERIC PLASMA

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PROJECT STATUS

This report describes the initial design and development of hardware and techniques for the simulation of the plasma of the ionosphere.

AUTHORIZATION

Test and Evaluation Charge No. 325-831-32-25-01

A TECHNIQUE FOR SIMULATING THE IONOSPHERIC PLASMA

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SUMMARY

Techniques and hardware are described by which an environment simulating the plasma of the ionosphere can be produced. This environment was developed to determine the operating characteristics of spacecraft systems and experiments in the presence of charged particles, and to determine the effectiveness of electrostatic shields against the charged particles.

The plasma is produced by a low energy electron beam ionizing the residual gas or introduced gas in a vacuum chamber. The relative motion between an orbiting spacecraft and the ionized media is included by accelerating the ions through a screen into the test volume. Ion beams 40 inches in diameter have been produced to simulate the electron and ion densities of the F-region. Tests to date have shown open cathode photomultiplier tubes particularly vulnerable to charged particles as indicated by noise and transients in the signal circuits of the tubes. Plasma energies and densities are determined by retarding potential analysers and Langmuir probes.

A directed ion beam with variable energy from 2 ev to 30 ev is obtained in the test volume.

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A TECHNIQUE FOR SIMULATION THE IONOSPHERIC PLASMA

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INTRODUCTION

Failures within some recently orbited spacecraft demonstrate that space environment simulation techniques currently in use are incomplete. Rigors associated with the launch and space environment that appear to cause the most trouble are vibration, thermal heating, vacuum, solar radiation, and the plasma encountered in the ionosphere.

Although the plasma has been blamed for at least one failure, its simulation is not part of present standard test procedures. Arcing in exposed high-voltage circuits and false counts in open cathode photomultipliers are two of the recent problems born of inadequate safeguards against the ionospheric plasma. Failure of the Harvard Spectroheliograph on the OSO-II flight (Orbiting Solar Observatory) can be traced to the disrupting effects of the plasma (Street, 1966).

In recognition of the problem, a program was initiated to recreate as closely as possible the plasma environment encountered by spacecraft in orbit. Since the F-region of the ionosphere contains the plasma density maximum, and since a large number of satellites operate in this region, it was decided to reproduce the F-region plasma and in a manner that takes into account the relative motion of the spacecraft and the ions. Ion energies from 2 ev to 30 ev can be simulated. Previous plasma simulations have required scaling because of high densities or much higher energies (Hall, Kemp and Sellen, 1964; Kasha and Johnston, 1967).

Some Case Histories

A simulated ionospheric plasma has been used in functional tests of several spacecraft systems. A majority of the tests have been on experiments for the Orbiting Astronomical Observatory (OAO). These include the Wisconsin, Smithsonian, Princeton and Goddard experiments as well as the star tracker for the OAO spacecraft. Let us consider some of the results of those tests; some of which underlined the need for plasma protection.

The Wisconsin plasma exposure was made on the prototype 8" Stellar Photometer Module No. 1 to determine the plasma susceptibility of its components, consisting in part of a phototube, high voltage power supply and leads, amplifier and electrometer. No anomalies were recorded in the simulated plasma test of this experiment. A similar test on the star tracker which contained almost duplicate electrical components yielded the same results. The functional test of the Princeton experiment in a plasma environment was made on the OAO-PEP Spectrometer/Fine Guidance Subassembly, which included regular and open cathode phototubes with their associated electronics. Orbital motion was not simulated; magnetic fields were cancelled to enhance plasma diffusion. The open cathode photomultiplier tubes were saturated by the ions from the plasma. As a result of this test, electrostatic screens will be installed to protect the tubes. A sequence of tests was performed on mock-ups of the Goddard Experiment Package (GEP) to determine the most effective ion trap for the experiment. These exposures were all made on full scale models and it was found that the ions from the plasma could be attenuated three orders of magnitude by the optimum ion trap.

To date, the most significant test has been made on the Harvard College Observatory Spectroheliograph for the Orbiting Solar Observatory. This instrument failed in orbit on OSO-II and the probable cause of the failure was arcing induced by the plasma environment at the orbital altitude. Many changes were made in the design of a similar Harvard experiment for OSO-D. These included rerouting the cable harness, using shielded leads on all high voltage circuits and increasing the venting of the experiment interior, thereby greatly reducing the likelihood of high voltage breakdown in the ionospheric plasma. In addition to the hardware improvements, the test program of the OSO-D experiment was expanded to include a functional test in the simulated orbital plasma. This test showed that the OSO-D instrument in its flight configuration was not susceptible to the charged particles. However, with no protective devices inhibiting their passage (dust covers and electrostatic shields were removed) the charged particles could be monitored on the instrument sensor, an open cathode photomultiplier. It was found that the signal generated by the ions was identical to the signal generated by incident photons on the photomultiplier tube, thus confusing the desired data reception and rendering the instrument useless.

To confirm that the OSO-D Harvard experiment was protected from the plasma and at the same time to verify that the simulated plasma is a valid test environment, a test was performed on a prototype of the OSO-II Harvard experiment. The objective of this exposure was to determine whether the simulated plasma environment could induce anomalous behavior in the same instrument that had failed in orbit. The results of the exposure on the OSO-II instrument in flight configuration showed the same anomalous signal that was observed in the unprotected OSO-D instrument. The OSO-II instrument also showed a tendency to arc occasionally at turn on and at elevated particle flux levels, indicating that it was susceptible to the simulated plasma environment. These tests demonstrated the value of plasma simulation in assuring the correct operation of high voltage experiments in the orbital environment. OSO-D, now renamed OSO-IV, was launched October 18, 1967, and the Harvard Spectroheliograph worked perfectly at turn on. Subsequently, a non-plasma malfunction has occurred.

SIMULATION DEVELOPMENT AND CHARACTERISTICS

Nature of the Natural Plasma Environment

The electron density in the F-region ranges from 10^4 to 10^6 electrons per cubic centimeter, depending on the time of day and the solar activity as shown in Figure 1. Electrons in the F-region have a thermal energy of a few tenths of an electron volt (ev) which is equivalent to a mean velocity of 3×10^7 cm/sec. On the other hand, ions in orbit (a combination of 0^+ and H^+) have the same density and a temperature equal to or lower than the electrons (Bourdeau, 1965). Due to a greater ionic mass, the mean velocity of the ions is much less, i.e. 10^5 cm/sec. A spacecraft in a 400 nm orbit has a velocity of about 8×10^5 cm/sec. Therefore, the orbital velocity is negligible when compared to the electron's random velocity, but is comparable to the ion's random velocity. Relative to the spacecraft, the ions have a directed velocity of 8×10^5 cm/sec corresponding to an ion energy of 5 ev. The number of ions bombarding the spacecraft is 10^{10} to 10^{12} /cm-sec. Now that the properties of the environment have been outlined, the steps undertaken in executing the simulation of the ionospheric plasma will be described.

Plasma Simulation Methods

The plasma in the ionosphere is the result of the ionization of the neutral gases by solar radiation and the diffusion of these ions and

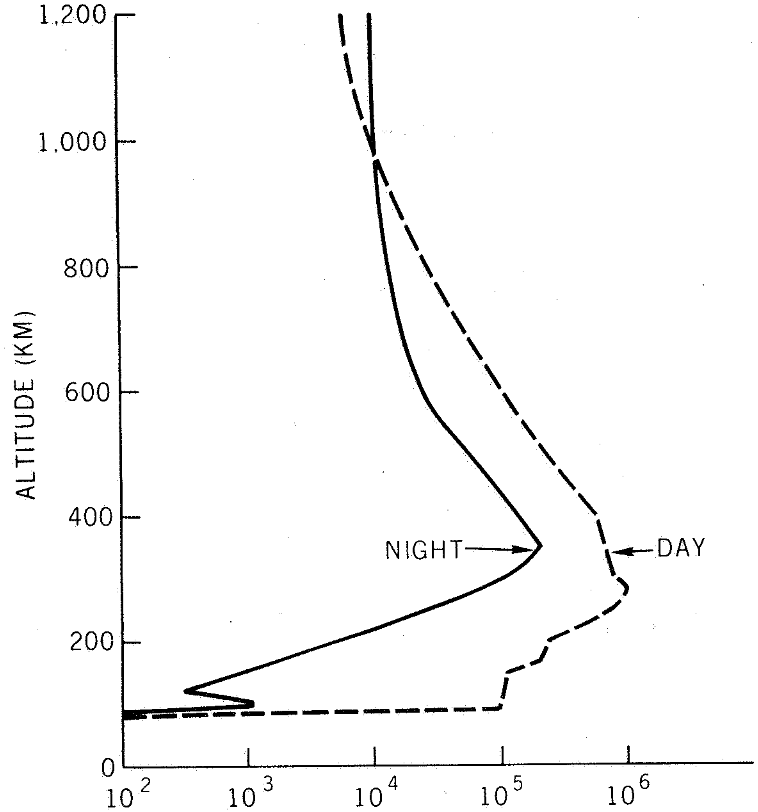

Figure 1–Ionospheric Density Variation

electrons. To generate a plasma in this manner in the laboratory would require a strong ultraviolet source and a high optical density of gas. The latter would necessitate a large volume chamber or high gas pressure. These two restrictions can be eliminated if a more efficient ionization source is available. Several other ionization techniques for the plasma generation have been investigated.

Ionization by radio frequency excitation was investigated as a possible means of generating a plasma for the simulation. This method provided a discharge over a large pressure range. However, it was accompanied by an unacceptable level of electrical noise and large electron losses to the walls.

The high energy of the primary ion beam from an ion engine was the cause for its being eliminated from consideration as a source for the plasma simulation. The primary ion energy can not be reduced below 160 ev if any appreciable ion flux is to be extracted from the engine. In addition, a second ion component with energies of 20 ev was produced by charge exchange with the primary beam. These high ion energies are too great for the F-region ionospheric plasmas, but have been used for solar wind simulation (Sellen, Bernstein, and Kemp, 1965).

A brush cathode (Persson, 1965) was tried as a possible ionization source, and while it was very good at pressures in the range of 1 torr, it was not acceptable at lower pressures. Very high potentials (3000 v) were unable to produce a usable discharge.

To date, the hot filament has proved most successful as an ionization source. A nude ionization gage filament can produce an electron beam of several miliamperes which is accelerated to ionize the chamber gas. A schematic drawing of the source is shown in Figure 2. The energy of the electrons is adjusted to maximize their collision cross section with the chamber gas (Tate and Smith, 1932).

The following simple considerations may be made to estimate the energy and magnitude of the electron beam and the chamber pressure. The ion-electron pair generation rate, which is needed to maintain a uniform plasma, can be determined from the ion continuity equation

$$\frac{\partial n_i}{\partial t} + \mathrm{div}\, n_i V_i = 0 \tag{1}$$

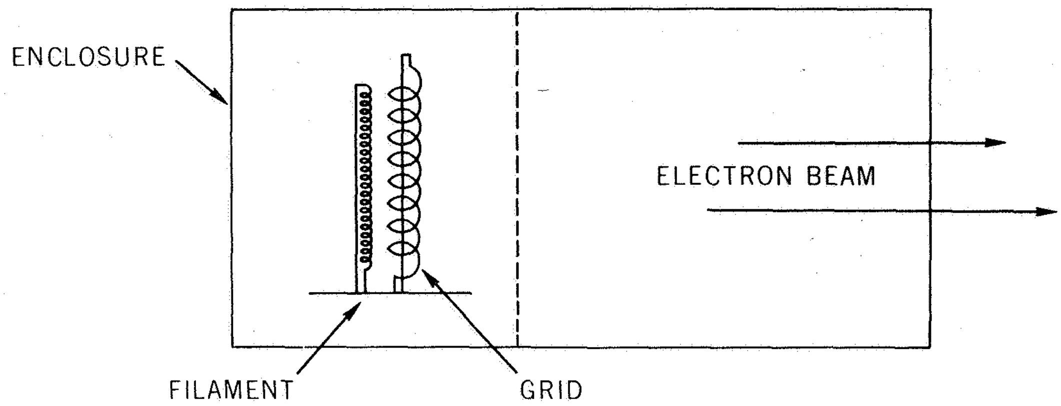

Figure 2–Electron Source

where n_i is the ion number density and V_i the ion velocity. If the only loss mechanism is the ions striking the walls, the loss from a volume can be written

(2A) $$\frac{\partial}{\partial t}\left(\int_V n_i dv\right) = -\int_V \mathrm{div}\, n_i V_i dv$$

(2B) $$\text{or } \frac{\partial N_i}{\partial t} = -\int_V \mathrm{div}\, n_i\, V_i\, dv$$

where N_i is the number of particles in the volume under consideration, and by the divergence theorem and assuming collisions normal to the walls.

(3) $$\frac{\partial N_i}{\partial t} = -n_i\, V_i A$$

where A is the area enclosing the volume under consideration. This is the rate at which ions are being lost and is also the rate at which they must be generated. The arithmetical average velocity, V_a is related to temperature by the equation

(4) $$V_a = \sqrt{\frac{8kT}{m\pi}}$$

where m is the particle mass, k is Boltzmann's constant and T is temperature in degrees Kelvin. The generation rate, G, for an electron beam in nitrogen or oxygen is given by

$$G = \frac{I}{e} d P s \qquad (5)$$

where I is the beam current in amperes, e is the electronic charge, d is the beam length in meters, P is the pressure in microns, and s is the differential ionization coefficient. s has the units ion-electron pairs per meter per micron of Hg, and is unity for a 100 ev beam (Tate and Smith, 1932).

For the ionospheric simulation, the plasma is generated by an electron beam between a plate and parallel screens as shown in Figure 3. For a density of 5×10^5/cc and temperature of 2000°K characteristic of the F-region, at the walls of a volume of 2×10^5cc and a confining area of $2 \times 10^4 cm^2$, a 5 ma 100 ev electron beam 1 meter long is needed at a chamber pressure of 3×10^{-5} torr. The ions are then accelerated by a potential between the plate and screen until they attain an energy which simulates the spacecraft motion. Electrons in the test volume are the result of diffusion and scatter from the initial electron beam and ionized volume. The primary purpose of the screens is to retard the entrance of electrons into the test volume. Some focusing of the ions may occur by the screens acting like an Einzel lens (Grivet, 1965).

The optimum source that has been developed to date consists of screens with a 1/4 inch mesh serving to retard the electrons and another screen of 1/8 inch mesh substituting for the plate. Several electron sources may be necessary to obtain required fluxes, depending on the transparency of the screens to the ions.

Ideally, the electrons in the test volume would have only thermal energy. To assure this, care must be taken to align the electron beam with the existing magnetic field in order to prevent the electrons of the beam from being deflected into the test volume. The worst case for this exists when the electron beam is perpendicular to the magnetic field. Since the Larmor radius is given by

$$R = \sqrt{2\, eVm}/eB \sin\theta \qquad (6)$$

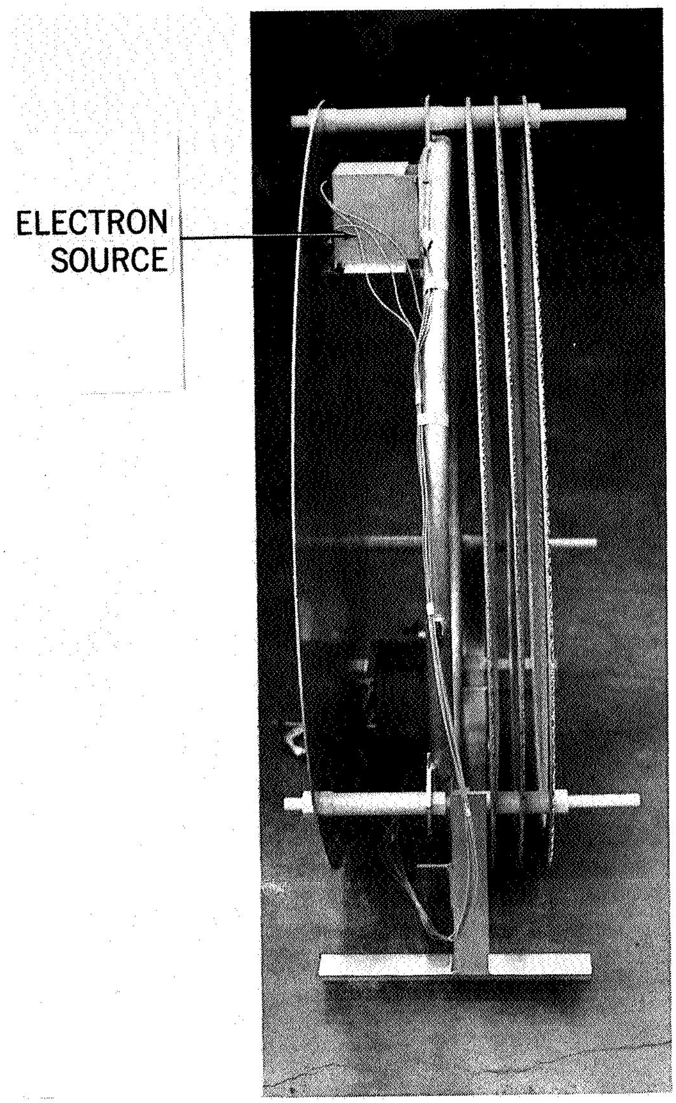

Figure 3—Plasma Source

where eV is the electron energy, m is the mass, B is the magnetic field and θ is the angle between the particle velocity vector and the magnetic field vector. An undesirable orientation of the vectors forming θ for a 100 ev electron in the earth's magnetic field can produce a radius as small as 60 cm, in which case the electron beam could be bent into the test volume.

Plasma fluxes and densities are determined with a retarding potential analyzer, RPA (Hinteregger, 1960). A schematic drawing of the analyzer is shown in Figure 4. This sensor can be used to determine an integral energy spectrum by plotting collector current versus the retarding potential on the third grid while the front grid is held at ground potential and the second at a potential to exclude the particle species not being measured. A bias on the collector may be necessary to eliminate an initial current rise in the I vs. V plot. The device can also be used as a planar Langmuir probe by grounding the grids and measuring the collector current as a function of its bias (Francis 1956, Bourdeau, et al, 1961).

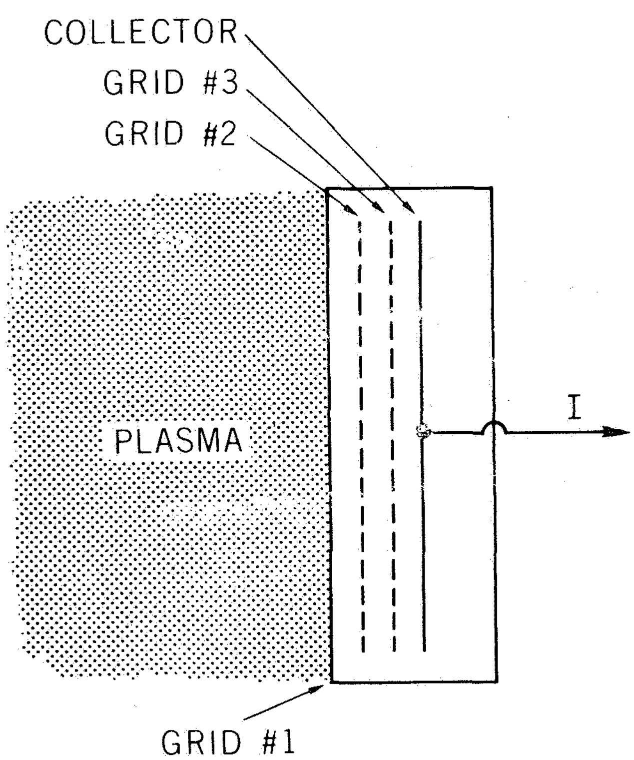

Figure 4—Retarding Potential Analyzer

The plasma simulation was undertaken primarily to determine the effects of ions on photocathodes. This objective is apparent in the characteristics of the plasma produced to simulate that occurring in the ionosphere. The characteristics of a natural plasma found in a 400 nm orbit and a simulated plasma generated in a ground test chamber are compared in Table I.

Table I
Comparison of Simulated and Orbital Characteristics

	Orbital	Simulated
Pressure	5×10^{-8} torr	3×10^{-5} torr
Electron Density	$1 \times 10^{5}/cm^{3}$	$1 \times 10^{5}/cm^{3}$
Electron Temp.	0.5 ev	6 ev
Ion Flux	$8 \times 10^{10}\ /cm^{2}\,sec$	$8 \times 10^{10}\ /cm^{2}\,sec$
Ion Energy	5 ev	2 - 30 ev. avg.

Quality of Simulated Plasma

Measurements in a cylindrical volume twenty-six inches in diameter by twenty inches long indicate the ion flux to be uniform to within 50% of the maximum in the circular plane nearest the source, thirteen inches away, and to fall off another 50% in the circular plane farthest from the source. In other words, there is a 4 to 1 variation in the ion flux in this volume. Floating potential measurements with the RPA's facing the source gave a floating potential of -4 ± 2 volts to the plasma volume. Whereas, measurements with an RPA facing the wall indicated a floating potential of -15 ± 2 volts, but also measured less than 5% of the ion flux received by the other RPA's.

The electron energy of the simulation as put forth in Table I is one order of magnitude higher than in orbit. As stated previously, the electrons in the test volume are the result of diffusion and scatter from the primary electron beam and ionized volume. The electrons are omnidirectional and their total flux as measured by the RPA varies only 50% in the test volume. Figures 5 and 6 show the RPA energy spectra for the ions and electrons under typical operating conditions.

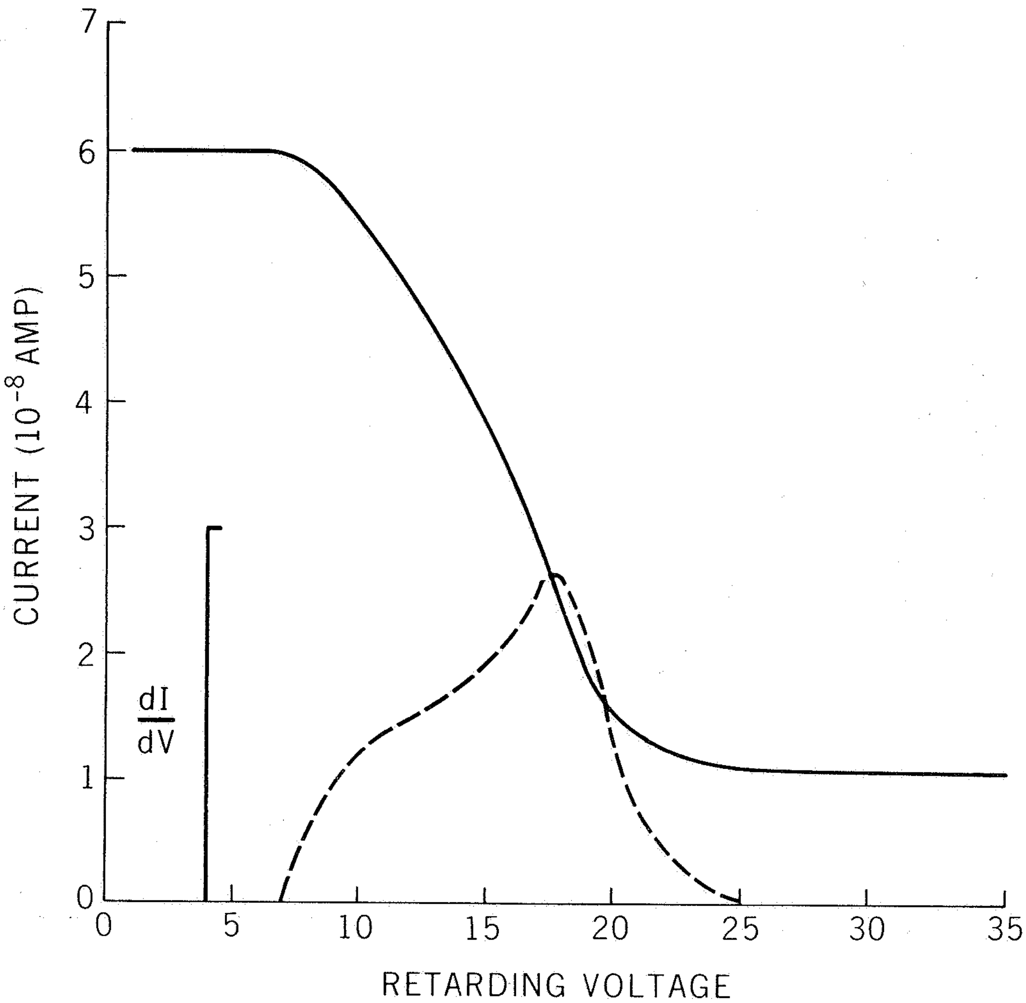

Figure 5–Ion Energy Distribution

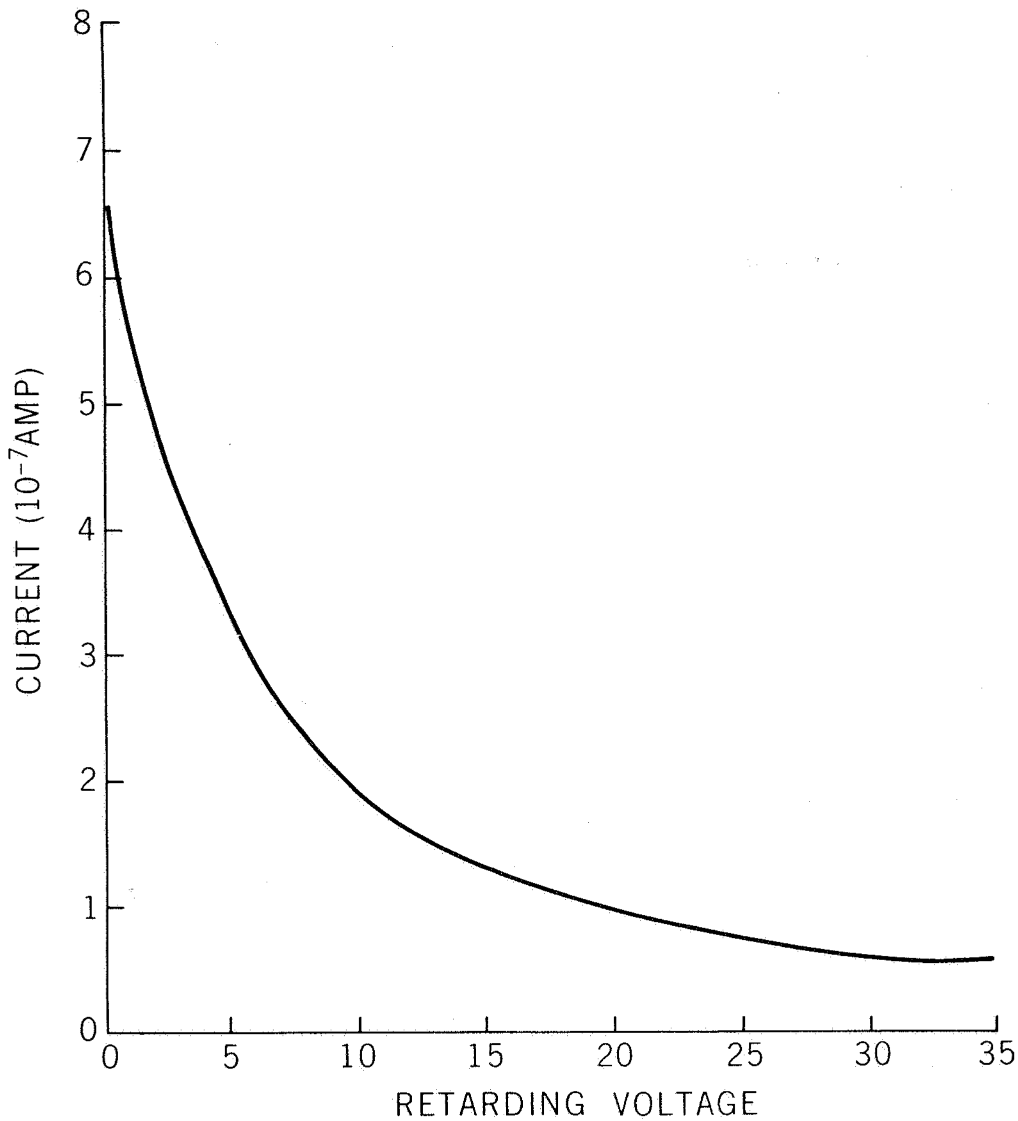

Figure 6–Electron Energy Distribution

An estimate of the maximum ion flux versus pressure can be obtained from an empirical relationship, $\phi = 10^{10}$ P where ϕ is the ion flux in particles/cm^2-sec and P is the pressure in terms of 10^{-5} torr, e.g. P = 1 for a pressure of 1×10^{-5} torr. This expression is valid to ±50% in the pressure range 2×10^{-6} torr to 1×10^{-4} torr at a distance of 13 inches from the source. The source operating conditions were optimized at each pressure setting with the restriction that the second screen voltage was held at -160 volts and the filament emission current did not exceed 50 ma. The constant 10^{10} ions/(cm^2sec torr), can be as large as 10^{11} four inches from the source. In calculating the above fluxes, an average ion energy of 10 ev was used. In most operational cases, the maximum current density measured by the RPA stays constant when the ion energy is varied so that the fluxes will vary inversely with the square root of the mean ion energy.

SIMULATION CAPABILITIES AND RESTRICTIONS AND TESTING TECHNIQUES

Simulation Capabilities and Restrictions

The present simulation is capable of reproducing the plasma ion and electron densities over much of the range shown in Figure 1. The simulated electron temperature is approximately one order of magnitude higher than those in the natural environment. The ion flux can be duplicated over a range of 10^8 to 10^{12} /cm^2 sec, and the ion energy is variable from an average of 2 ev up to 30 or 40 ev. Such an energy range can be used to simulate a spacecraft potential which increases the ion energy. For example, a large spacecraft such as the OAO with large solar paddles can have a spacecraft potential as much as 15 volts below the plasma potential, thereby giving the ions an additional 15 ev of energy as they are accelerated through the sheath.

The present simulation has several limitations. Nitrogen gas is used in the test chamber, therefore proper ion species are not simulated. The electron energy in the test volume is an order of magnitude too great. Radiation is produced by the luminous filament of the electron source and by ionic recombination. The operating pressure during flight simulation is several decades higher than the pressure in orbit. Safety restrictions prevent the introduction into the vacuum chambers of large concentrations of oxygen; for this reason, those ions cannot be generated in the test plasma. The high electron energies probably result from primary electron scattering and electric fields created by large electron density gradients. Neutralizing the ion beam by thermal electrons from other filaments reduces such gradients but increases the visible radiation in the chamber.

Filament radiation from the electron gun is sufficient to saturate most phototubes sensitive to visible radiation. The filament output is of the same order as a 40-watt light bulb. The recombination radiation is in the vacuum ultraviolet region between 1500 and 1800Å, and its intensity under normal operating conditions is about 1000 photons/cm^2/sec. Recombination problems would be reduced by operating at pressures less than 10^{-5} torr, the pressure which is presently needed for the desired ion fluxes. Further, 10^{-5} torr is near the maximum operating pressure allowable for many spacecraft high voltage systems. Operation at this pressure increases the voltage breakdown risk in functional testing.

Testing Techniques

Tests involving plasma simulation have been carried out in existing vacuum facilities obviating the need for large capital outlays for new facilities. A typical test setup starts with the installation of the plasma source shown in Figure 3 in the vacuum chamber with RPA's. A determination of the source's output and operating characteristics is made by varying the accelerating potential and chamber gas pressure. The chamber pressure is controlled by a variable leak of nitrogen gas, which increases the pressure several decades above the 10^{-7} torr ultimate vacuum that the chamber is capable of attaining. The gas is normally introduced in the vicinity of the electron beam to enhance the ionization process by any local pressure gradients. The upper limit for the chamber operating pressure is restricted by the item under test and is normally 5×10^{-5} torr. To prevent filament damage, the electron source is not operated above 5×10^{-4} torr. Desired plasma fluxes and characteristics determine the low pressure limit.

In the usual instrument examination procedure, once the plasma input is established, a functional test of the instrument is made in flight configuration with and without the plasma in order to determine whether the plasma induces anomalous operation or results. If a model or mock-up is under test, an RPA or Langmuir Probe is installed to establish the plasma flux or charged particle density within the model. This technique has been used to evaluate the effectiveness of electrostatic ion traps and optical baffling. A setup with a model of the Goddard Experiment Package is shown in Figure 7. The most desirable technique is

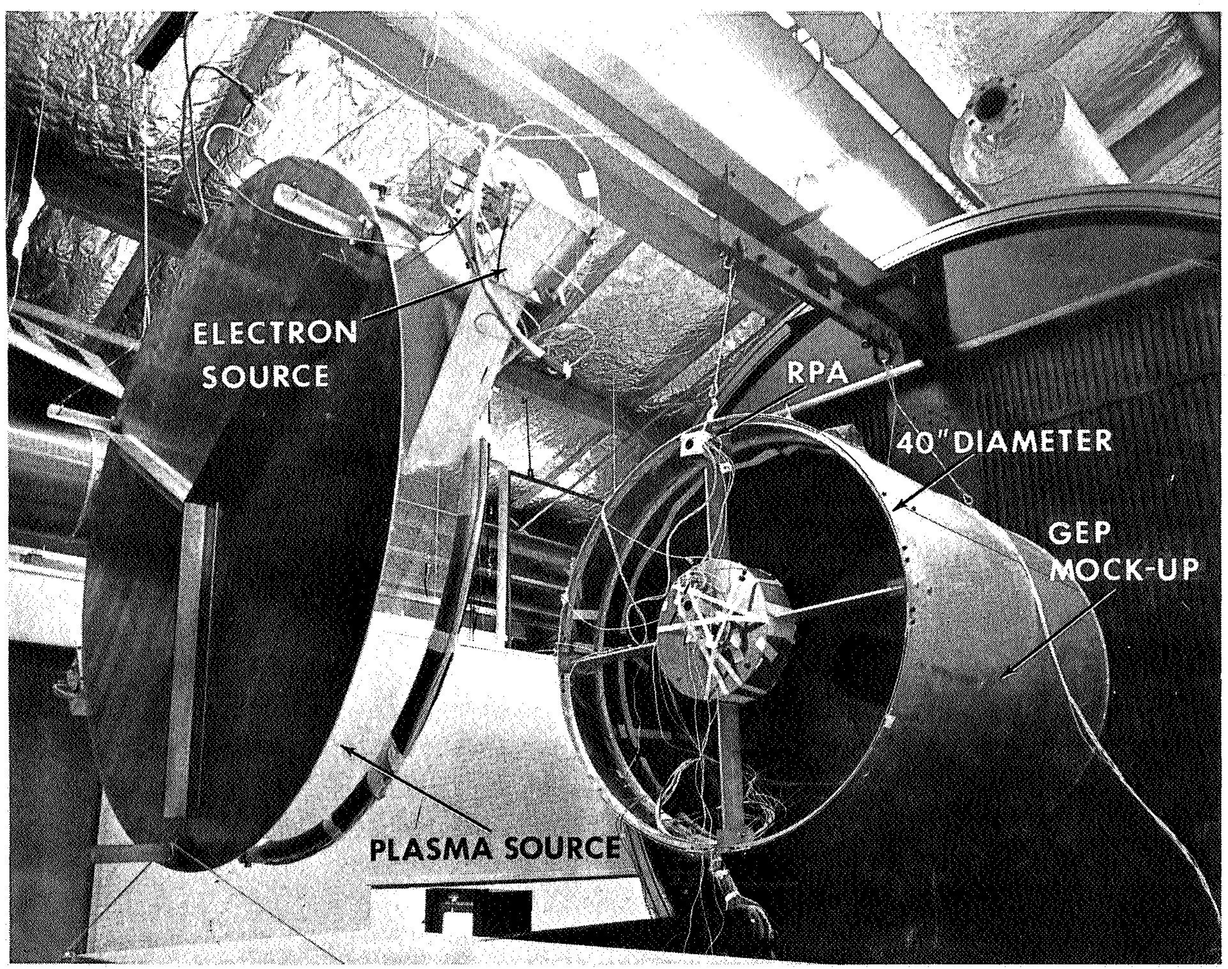

Figure 7—Test Setup for GEP

to test prototype space hardware so that the actual plasma susceptibility of the instrument can be established, whereas, the mock-up technique is limited because the susceptibility of the actual hardware cannot be established.

CONCLUSIONS

The ideal total test environment would combine and duplicate every aspect of the expected space environment. This generally is not feasible in greater or lesser degree, and a simulation is found which will fulfill the test requirements. A duplicate ionosphere should contain correct ion species and particle energy spectra, along with penetrating radiation, photoionization effects, and very low pressures. To date, this has not been accomplished, but it does constitute a goal for further work.

An artificial ionospheric plasma is generated inside existing vacuum facilities by means of an electron beam which creates the desired ion species. These ions are then accelerated through a screen into the test volume. The ion beam energy is equivalent to the energy of ions striking a spacecraft moving through the ionosphere at orbital velocity.

A test environment and a test technique have been developed which for the first time permits the simulation of the ionospheric plasma for spacecraft performance evaluation. The effect of this plasma on ion traps and high voltage instrumentation can now be determined by functional testing in the simulated environment. An evaluation was performed on the Harvard College Observatory Experiment of OSO-IV and verified by a test of a prototype of the Harvard OSO-II instrument which failed in orbit. The OSO-II instrument showed a plasma sensitivity in the newly developed test. Subsystems and experiments of the OAO have also been tested. These tests have shown that open cathode photomultiplier tubes are particularly sensitive to the presence of charged particles, a condition which can lead to false signals or arcing.

With the development of simulated space plasma and the accompanying test techniques, it is now possible to evaluate the behavior of a spacecraft and its systems in an ionospheric, charged particle environment. A void in the test environment has been filled and an increase in system reliability can be expected.

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