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Plasma Generator for Space Vehicle Neutralization

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An experiment was conducted in which pulses of high velocity electrons were ejected from a space probe flying a ballistic trajectory. To maintain the electrical neutrality of the vehicle during the experiment, a plasma generator of the MPD arc type was used to create a trail of charged particles which, in turn, provided a conductive path between the vehicle and the ambient space plasma. The plasma generator system consists of a modified Penning type discharge, power conditioning system, argon reservoir, and valve. The total package, 12 in. × 6 in. diam, weighs 9.6 lb and is capable of generating a net positive ion current of greater than 1 A with a power input of less than 200 w.

I. Introduction

THE basic function of the plasma generator is to maintain vehicle electrical neutrality during periods when the onboard experiment emits 50 kv, 0.1 A electron pulses. If neutrality were not maintained during such pulses, the vehicle would charge rapidly to a high positive potential and the electron beam would be either degraded in energy or returned to the vehicle.

The system requirements are that the plasma generator emit a minimum of 0.1 A positive ion current at a positive bias voltage of less than 50 v with respect to the vehicle. The flight duration is less than 10 min.

II. Basic Operation

The device, which resembles the low power MPD arc thruster,[1] consists of a cylindrical anode with a coaxial cathode immersed in an axial magnetic field, as shown in Fig. 1. In operation, the majority of the electrons emitted thermionically from the cathode are confined by the magnetic field to axial cycloidal motion; thus they can reach the anode only by collisions with neutral atoms, ions, or other electrons. The theory of this ionization and conduction mechanism has been discussed in detail by Bowditch,[1] Domitz,[2] and Meyerand.[3]

The basic concept which emerges from these descriptions is that a plasma is formed in the discharge chamber and the plasma potential is approximately equal to anode potential. Downstream of the source the plasma potential falls rapidly as a result of the divergent magnetic field and the decrease in neutral density shown in Fig. 1. The electrons are thus contained electrostatically at the ends of the discharge chamber and oscillate axially back and forth in a manner similar to that of a low-voltage Penning discharge. Ions are accelerated by an axial electric field caused by the electric pressure gradient which exists in the region of diverging magnetic field.[1] The downstream voltage is self-adjusting to permit just enough high-energy electrons to escape to equal the ion current and hence maintain charge neutrality if the source is electrically isolated from its surroundings. If the source is electrically biased with respect to the surroundings, the net current flow may be controlled. In this way the specification that the source must emit 0.1 A at a maximum bias of 50 v can be met. As will be shown below, the source readily emits this quantity of current at zero bias.

The relatively short time available between the start of the program and the freezing of a flight design limited the experimental investigations to those parameters necessary to assure that the basic specifications could be met and that a satisfactory control system could be implemented. Argon was used successfully as the expellant in all tests, although other gases or vapors would undoubtedly serve as well.

III. Laboratory Performance Tests

The experimental circuit is shown in Fig. 1. With this arrangement the beam current (the positive ion current leaving the engine) was recorded by an ammeter in the bias line as a function of the neutral gas flow to the plasma gun for different discharge currents. This was done for engine bias voltage of 0, +6, and +12 v. During these experiments the axial magnetic field was kept constant at 25 *g* (because the performance is relatively insensitive to the magnetic field as long as the field is above a critical value ≈15 *g*). All test data reported here were taken using the breadboarded flight supplies which incorporate a feedback loop to maintain a preset value of discharge current by adjustment of the filament heating power. In addition to the instrumentation shown in Fig. 1, there was a beam scanning Faraday cup which could be moved axially and rotated through 360°.

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Index category: Electric and Advanced Space Propulsion; Sounding Rocket System; and Spacecraft Propulsion System Integration.

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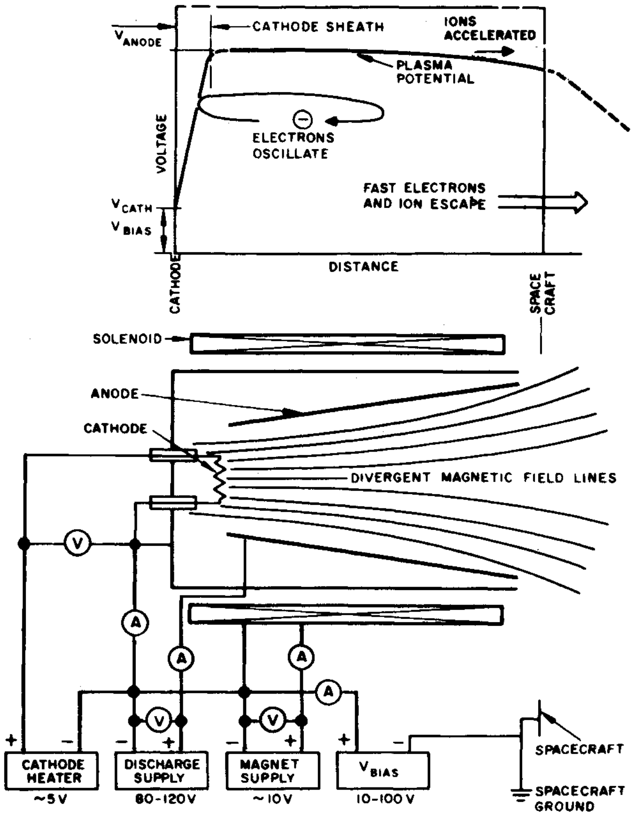

Fig. 1 Electrical schematic.

Figure 2 shows the beam current as a function of gas flow with discharge current as a parameter at a discharge voltage of 100 v and engine bias voltage of 0 v. The variation with gas flow becomes more rapid as the discharge current is increased. The discharge current chosen for the final operating point is nominally 0.4 A. Reference to Fig. 2 shows that for the zero bias condition and a gas flow of ~11.4 cm³-atm/min (~815 eq. *m*A),‡ a 0.4 A discharge current results in a beam current of 100 mA. To insure that the gas flow was adequate at the end of flight, initial gas flow was adjusted to be 12 cm³-atm/min.

Measurements of the floating potential of the plasma gun are shown in Fig. 3. The measurements were taken by adjusting the gas flow to produce a given beam current; the ground return line was then broken and the floating potential was measured with a high impedance voltmeter. The 10–25 *V* potentials measured are believed to approximate the potential to which the space vehicle will charge between electron pulses.

The Faraday cup used for diagnostic studies of the emergent plasma beam permits measurement of the ion beam profile. The screen in front of the cup is biased to exclude electrons and the ion arrival rate is monitored as a function of operating conditions or cup position. It is more difficult to measure the electron current accurately because the measured current is very strongly dependent on the magnitude and sign of the relative voltage between the screen in front of the cup and the (unknown) plasma potential in the emergent beam at the point where the measurement is being made.

The resultant measurements indicate a beam spreading with a half angle of approximately 16°. With 100 v discharge the ion energy spectrum as obtained by retarding potential measurements showed a sharp peak between 20 and 30 v with a high energy tail extending to 70 v. This is consistent with the above model which indicates that ions may be formed with any value of energy up to the potential at which the plasma floats above ground (approximately anode potential).

‡ Equivalent MA is the current which would result if each argon atom were singly charged.

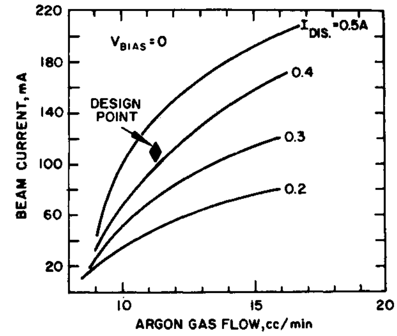

Fig. 2 Beam current as a function of expellant flow.

IV. Flight Hardware Design

The flight package consists of three subsystems: the expellant storage system and valve, the power conditioning and control systems, and the discharge chamber, as shown in Fig. 4. All three are integrally packaged in a cylinder nominally 6 in. in diam and 12 in. long. The beam emerges from one end along the axis of the cylinder. The weight of the complete package is less than 10 lb. Primary power input and telemetry output signals are all transmitted through a single connector located as shown in Fig. 4. The complete system mounts to the vehicle with eight bolts, as shown in the figure. Good thermal contact with the vehicle structure is required at the mounting points to permit heat rejection into the structure.

A. Discharge Chamber

Details of discharge chamber construction are shown in the layout of the complete flight package shown in Fig. 4. The chamber is $3\frac{1}{4}$ in. long and 2 in. in diam. The filament is closely patterned after that successfully used on the SERT-I flight test of an ion rocket.[4] The filament is mounted in the discharge chamber by pairs of stainless steel blocks which, when screwed together, clamp the filament to mounting studs. Nominal power for the filament chosen for the final design (0.002 in. × 0.125 in.) is 80 w (i.e., 20 A at 4.0 v). As part of the prototype verification program, nine filaments were vibrated over the frequency and amplitude spectrum specified for the Aerobee 350 vehicle. The spectrum was modified to include the most severe conditions specified for the thrust and the lateral axes. The mounting is such that the symmetry axis of the filaments lies in three mutually orthogonal directions. One vibration test thus subjects a particular design to vibration in all three axes. No failures were observed during this test, which included both unused and fired filaments 0.002 in. thick. One fired filament was placed in each of two lateral axes.

The electromagnet, shown in Fig. 4, consists of six multiturn coils of aluminum strip mounted coaxially with the dis-

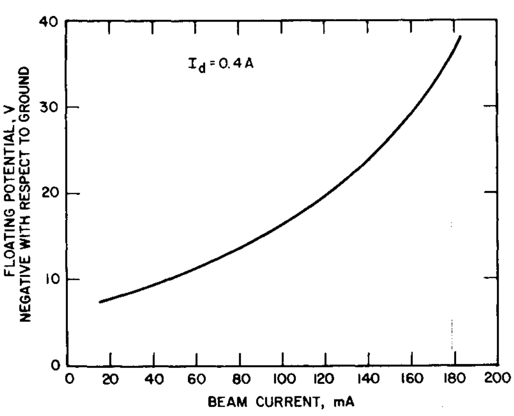

Fig. 3 Floating potential of plasma generator.

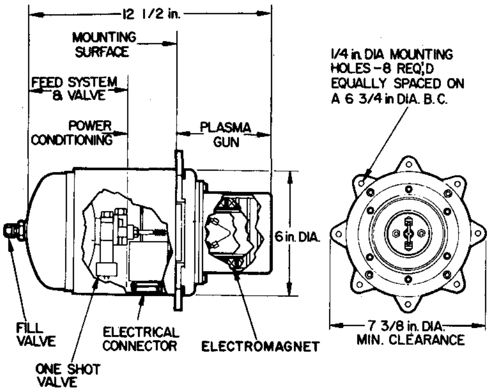

Fig. 4 Plasma generator layout.

charge chamber. The aluminum is anodized to a depth of 0.0003 in. to provide electrical insulation both between layers and between the coils and the magnet holder. The holder itself is also anodized aluminum. The coils are wound in place in the holder from a continuous aluminum strip. A 0.002 in. H-Film strip is placed between the coil holder and the first turn and also between the first and second turn. After winding, a layer of H-Film is placed over the last turn and a taut stainless steel band is spot welded over each individual coil to provide structural integrity. The coils are electrically connected in series to provide relatively high-voltage, low-current operation (3 v at 0.6 A for 25 G). The downstream end of the strip is spot welded to the magnet holder, which serves as the electrical return for the magnet current.

Argon is fed into the cathode end of the discharge chamber on-axis through a series of diffusion baffles. A nickel bellows in the feed line provides both mechanical and thermal isolation between the plasma generator and the expellant storage reservoir. The feed tube connection is both sealed and insulated by a nylon gasket and a split sleeve under the retaining screw.

The magnet, anode, filament, and expellant inlet are mounted individually to a common bulkhead. A number of high purity alumina parts are used to provide the necessary electrical insulation. The alumina parts are precision flat ground plates. The isolated gun structure is mounted against and indexed to the plates; dimensional integrity of the gun structure is maintained in this manner. When operating temperatures permit, the major structural parts are made of aluminum alloys. Thus, the reservoir, valving, outer housing, gun mounting ring, and power conditioning mounting rings are all aluminum alloys.

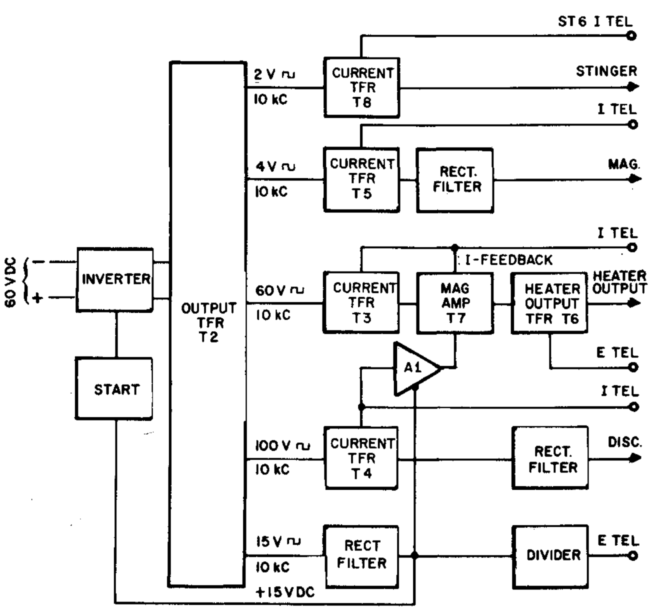

Fig. 5 Block diagram of power conditioning and controls.

B. Expellant Storage and Regulation

The expellant feed and storage system consists of a 1000 cm^3 reservoir pressurized to approximately 90 psig with argon. A 75% dense porous tungsten plus provides flow control. It was originally planned to provide vernier control with a needle valve built into the valve assembly. During testing it was found that control was more easily effected by adjusting the initial reservoir pressure. The one shot valve fires when power is initially supplied to the system. This design sacrifices a regulated flow rate for over-all simplicity; it is considered to be both the simplest and most reliable design for short ballistic flights. With the tank volume and flow rate of this system, flow regulation of 5% is possible over the full-flight duration.

The reservoir is constructed by welding together two ellipsoidal weld caps. The fill valve and one shot valve are located on the centerline, as shown in Fig. 4. The two ends are machined to accept the outlet and fill valve fittings. The fittings are welded to the ends before the two ends are joined so that radiographic and dye penetrant inspection of the weld areas can be accomplished more readily. The final assembly is hydrostatically proof tested.

The flow impedance, which is cut from a billet of porous tungsten material, is mounted inside the reservoir. The material is filled with copper and machined to size, and the copper is evaporated out of the material in a vacuum furnace. Finally, the outer cylindrical surface of the resultant slug is locally melted in an electron beam welder so that gas must flow down the full length of the slug. The slug is then electron beam welded to a refractory metal tube which is O-ring sealed into the valve body.

The valve consists essentially of a spring loaded stinger which pierces a thin stainless steel tube to permit gas to escape from the storage reservoir. The stinger is released under spring pressure when a fuse link is melted upon initial application of power to the system.

C. Structure

The structure was designed to provide a firm base for mounting the gun, the power conditioning, and reservoir to the vehicle; it also provides a heat-transfer path from the gun and power conditioning to the structure of the vehicle. The second requirement places the mounting interface surface between the plasma generator package and the flight vehicle near the plasma generator gun. In addition, since the operating temperature of some of the electronic components in the power conditioning must be limited, the power conditioning section should be mounted as closely as possible to the vehicle mounting interface. The plasma generator and the power conditioning must be isolated thermally because the plasma generator operates at a higher temperature level. This was accomplished by the eight lobe mounting design shown in Fig. 4. Four of the mounting lobes are part of the discharge chamber mount, and the remaining four are part of the power conditioning mount. The two subsystems are held together by four stainless steel screws and spacers which have relatively low-thermal conductivity. The only other thermal connection between the two are the electrical leads from the power conditioner to the plasma generator.

D. Power Conditioning and Control System

The power conditioning and control circuitry is shown in Fig. 5. The inverter has as an integral part a start circuit which is activated by application of the +60 v bus. Once oscillation is initiated, the start circuit is deactivated. The heater supply is regulated by two independent feedback loops. The first feedback loop limits the maximum current before the heater reaches temperature and the discharge occurs. The second feedback loop is operative when discharge current is sensed by the discharge current transformer (T4). Its output is rectified and filtered, providing discharge current telemetry and a signal to the summing point of the voltage regulating amplifier. This, in turn, increases the current through a magnetic amplifier bias winding and maintains a constant discharge current by raising and lowering the heater temperature, as required.

Beam current telemetry is accomplished by isolating the discharge supply and heater output transformer from vehicle ground. A resistor is connected from the center tap of the heater and the negative return of the discharge supply to vehicle ground. The voltage developed across this resistor is used for beam telemetry. All telemetry outputs are 10,000 Ω output impedance and provide a 0–5 V positive output voltage. The outputs are individually protected from over voltage by use of a 5.1 v zener diode. The internal impedance of the telemetry is high enough to prevent damage to the power conditioning unit from an external short circuit.

V. System Testing

Two units of the above design were constructed and tested. The procedure used was to first check the individual subsystems and then operate the complete system in vacuum using both the telemetry and, where possible, external metering to check the performance. Both units were then subjected to a complete launch vibration simulation§ and retested in vacuum. No failures were encountered, and the units were considered flightworthy.

§ Appropriate for the Aerobee 350 vehicle.

VI. Conclusion

A plasma generator system has been designed to provide electrical neutralization for a space vehicle which may either collect or emit charged particles. The device described here was successfully launched and operated on Aug. 13, 1970. The results of this test have been reported separately.[6–8] The particular device described here was specifically designed for that ballistic flight. Relatively simple modifications of the expellant feed system, and possibly the type of expellant would make the system useful for continued or pulsed operation on long duration flights.

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