Contents

5. Active Control of Spacecraft Charging on ATS-5 and ATS-6

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Abstract

Effects on spacecraft ground potential of active emission of charged particles are being investigated through experiments using the ATS-5 and ATS-6 spacecraft. Each of these spacecraft is equipped with ion engine neutralizers which emit low energy charged particles, and with the University of California at San Diego (UCSD) Auroral Particles experiments which are capable of determining the spacecraft potentials. Despite great differences in design between the two spacecraft, they attain similar potentials in similar environments. Therefore, effects on spacecraft potential of neutralizer operations can be used to compare the effects of operating the two different neutralizers (hot wire filament and plasma bridge). The neutralizers on both spacecraft have now been operated in eclipse. Results of these operations are presented and spacecraft responses compared.

1. INTRODUCTION

One of the objectives of the joint NASA/AF Charging Investigation is to determine the feasibility of active control of spacecraft charging. An investigation is currently underway to study the possibility of active control by charged particle emission using the ATS-5 and ATS-6 spacecraft. This effort is an extension of studies previously reported by Bartlett et al[1] and by Goldstein and DeForest.[2] The present paper reports results of operating the ion engine neutralizers on the two spacecraft during eclipses. The intent is to compare the effectiveness of the two neutralizers in maintaining the spacecraft potentials near ground during eclipse and substorm conditions.

Experiments have been conducted using the ATS-5 hot wire filament electron emitter, the ATS-6 plasma bridge neutralizer, and the UCSD plasma detectors. The particle data were then studied to determine the charge state of the spacecraft before, during, and after neutralizer operations, in order to compare the effects of neutralizer operations. Such experiments have been performed with the ATS-5 spacecraft during several eclipse seasons, so that a relatively large data base exists, and some general trends in spacecraft response can be identified. Due to mission constraints, operation of the ATS-6 neutralizer during eclipse was not possible until the fall 1976 eclipse period. Thus, the data points for ATS-6 neutralizer operations in eclipse are few; however, the available results do provide a basis for some preliminary comparisons.

2. ATS-5 SPACECRAFT AND ION ENGINE EXPERIMENT

The ATS-5 spacecraft was launched in August 1969. It is in a geosynchronous orbit stationed at 105°W longitude. The spacecraft has a cylindrical geometry, 1.3 m in diameter and 2 m in length. It is divided into three cylindrical sections of approximately equal length. Most experiments and spacecraft systems are contained in the center section, while the two outer most sections are open-ended shells to which solar cells have been mounted. These latter two sections have an outer surface primarily of quartz glass covering the solar cells. The center section is covered with a fiberglass skin to which a nonconductive thermal control paint has been applied. Therefore, the outermost surface of ATS-5 is generally an electrical insulator.

Two contact ion engine systems are aboard ATS-5. All engine operations described here involve the No. 2 system. Its location relative to the ATS-5 UCSD Auroral Particles experiment is shown in Figure 1. Due to a design fault in the ATS-5, the spacecraft could not be despun and hence was never gravity gradient

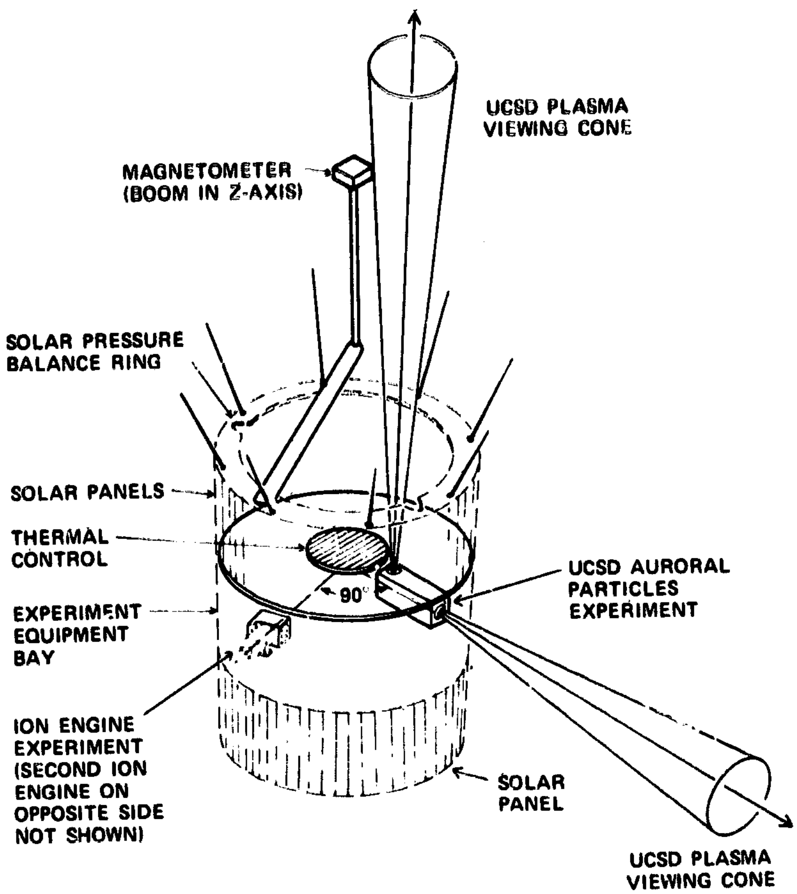

Figure 1

stabilized as planned. As a result of the 76 RPM spin about the spacecraft z-axis, each ion engine is subjected to centripetal force producing an effective gravitational field of 4 G's.

The force on the cesium feed system is sufficient to drive liquid cesium down the vapor feed tube to the ionizer and thus preclude normal thruster operation. The cesium reservoir is sealed by a thermally actuated valve. The ion engine system is designed such that the "Ionizer On" command turns on the ionizer and neutralizer heaters. It has been determined that the heat transferred to the reservoir valve from the ionizer heater when operated continuously is sufficient to open the valve. However, if the ionizer heater is operated for a maximum of 40 min with a 20 percent duty cycle, the valve will remain closed. Therefore, the 20 percent duty cycle was selected for the spacecraft neutralization tests. No ion beam is produced during this type of operation.

The ATS-5 ion engine system has been described in detail by Worlock et al.[3] Its contact ion source was designed to deliver 1 mA of singly charged cesium ions which are neutralized by a hot filament electron source. In studying the control of spacecraft charging, this electron source has been utilized. The ion engine exhaust aperture in the spacecraft skin is 5 cm in diameter. The neutralizing filament is recessed 2.5 cm within the spacecraft and operates at spacecraft potential. The resistively heated filament is powered by a 2 Vac power supply. Thus, the energy of emitted electrons is $\lesssim 2$ volts. The filament of yttrium doped tantalum is 0.18 mm in diameter and operates at a temperature of 1700°C. At this temperature, the neutralizer is emission limited at about 3 mA. The minimum resolvable neutralizer emission current telemetry signal represents 6 μa. No descernible neutralizer emission current has been observed during any of the experimentation described here.

3. ATS-6 SPACECRAFT AND ION ENGINE EXPERIMENT

The ATS-6 spacecraft was launched in May 1974, and is in a geosynchronous orbit. The first year's operational station was at a longitude of 94°W. For its second year of service, ATS-6 was moved to a longitude of 35°E. The spacecraft has now been relocated to its permanent station at 140°W. The configuration of the ATS-6 spacecraft is shown in Figure 2. The end-to-end dimension between the two solar arrays is 16.5 m. The near cubical module at the focus of the 9.1 m parabolic reflector is about 1.6 m on a side. The outer surface of most of the structure is covered with kapton thermal insulation. However, all conductive elements of the structure and the vapor deposited aluminum surfaces of the thermal blankets are bonded to the common spacecraft ground. The parabolic reflector is formed utilizing a dacron mesh with a copper coating. The copper is covered with a noncontinuous coating of silicon rubber. While the copper mesh of the reflector is grounded to the structure, the reflector's outer surface characteristic is dominated by the silicon rubber insulator. The solar cells are covered by quartz glass. Thus, the majority of the outer surface of ATS-6 is nonconducting.

There are two cesium bombardment ion engine systems on ATS-6. They are located on the north and south faces of the earth viewing module as shown in Figure 2. The thrust axis of each engine is in the Y-Z plane and exhausts outward from the spacecraft at an angle of 38° to the +Z axis. The orbital operations of the ion engine experiment have been reported by Worlock et al.[4] Each of the two ion engine systems has been operated. The initial operation of each thruster was nominal. However, subsequent attempts to restart either system have not been successful. It is believed that the restart problem is due to a design error in the

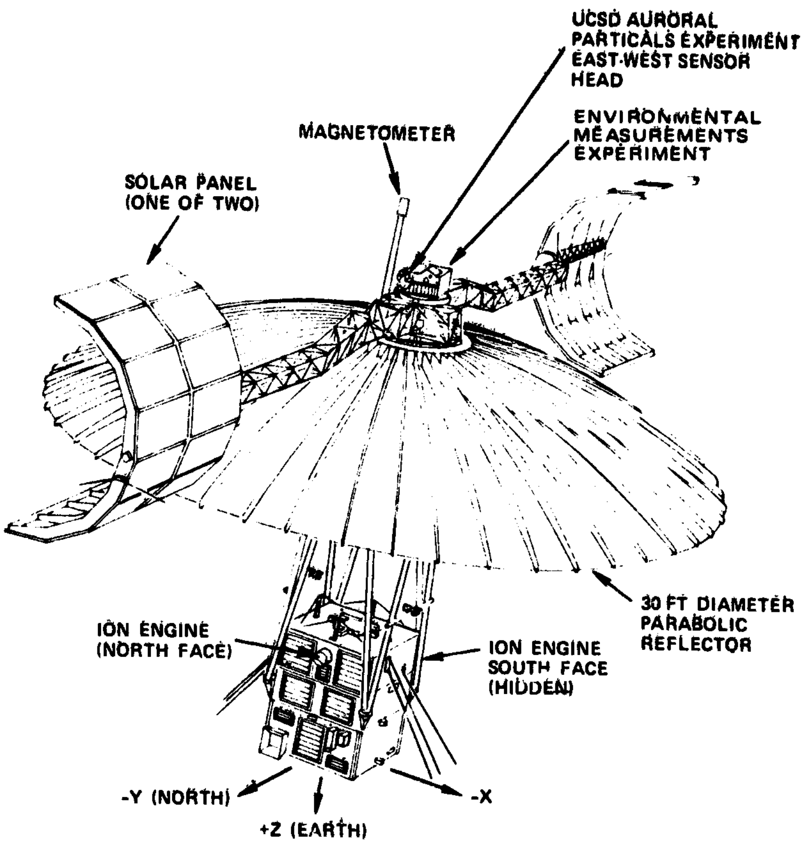

Figure 2. ATS -6 Spacecraft Configuration

main propellent feed system. This design problem has not precluded the operation of the ion engine's neutralizer and its cesium feed system. Operation of the neutralizer of each ion engine has been demonstrated subsequent to its initial operation.

The ATS-6 ion engine system has been described in detail by James et al.[5] Basically, each system produces a 115 mA beam of singly charged cesium ions which are extracted from a primary plasma. This beam is then neutralized by electrons which are extracted from a second cesium plasma. This electron source, or neutralizer, is of interest when studying the control of the interaction of a geosynchronous spacecraft with its ambient plasma since it can serve as a source of both electrons and ions.

The neutralizer consists of a feed system which supplies cesium vapor to a hollow cathode electron source. The hollow cathode consists of a heated tantalum emitter which is placed at the end of the cesium vapor feed tube. The feed tube is than capped with a plug containing a 0.15 mm diameter orifice. An electrode, or plasma probe, is mounted 3.2 mm outboard from the cathode aperture. To initiate operation, this electrode is biased 150 Vdc positive with respect to the tantalum emitter and serves as an anode. The emitter operates at spacecraft ground potential. Cesium vapor is introduced into the hollow cathode and a plasma discharge occurs. This process requires about 35 min from initiation of the operations. After the neutralizer discharge starts, the probe is operated from a high impedance +15 Vdc power supply. In this mode, 50 mA of electrons are extracted from the neutralizer's plasma by the probe. The probe also serves as a plasma potential sensing element for control purposes. For normal ion engine operations, the ion beam would become the hollow cathode's anode with the neutralizer's plasma providing a low impedance bridge to the beam. However, when the ion beam is not present, the plasma probe will continue to function as an anode. During operation, the power supply is typically loaded down to 6 or 7 volts. Thus the energy of emitted electrons is <15 volts, typically 6 or 7 volts. The aperture for the ion engine's exhaust beam is approximately 12 cm outboard from the spacecraft's skin with the neutralizer located an additional 5 cm outboard.

The emission characteristics of the neutralizer vary with its cesium flow and the temperature of the tantalum emitter. Neutralizer control is accomplished by presetting the emitter temperature and regulating the pressure of the cesium vapor in the hollow cathode in response to the potential of the plasma probe. For normal operations, the neutralizer is emission limited at about 3A of electrons and a few milliamperes of ions. Since the experiment's telemetry scale was sized for operations as an ion thruster, the minimum resolvable neutralizer emission current is 1 mA of electrons only. No measurable neutralizer emission current has been observed during any of the experiments described here.

4. ATS-5 AND ATS-6 PLASMA DETECTORS

The UCSD Auroral Particles experiment on ATS-5 consists of two pairs of plasma detectors. These are mounted to the body of the spacecraft (see Figure 1) so that one pair looks parallel to the spacecraft spin axis and the other pair looks perpendicular to it. Each pair of detectors is comprised of an electron detector and an ion detector which cover the energy range from 50 eV to 50 keV. These detectors have been described in more detail by DeForest and McIlwain.[6]

The ATS-6 instrument is an outgrowth of the ATS-5 detector. The main detectors are arranged in two electron-ion pairs. These are mounted on the Environmental Monitor Experiment (see Figure 2), one pair in the north-south plane and one pair in the east-west plane. They can be mechanically swept in their respective planes to obtain angular information. The energy range covered by these detectors is 1 eV to 80 keV. The ATS-6 detectors are described in more detail by Bartlett et al[1] and by McIlwain.[7]

The voltages to which the spacecraft grounds are charged can be estimated by observing shifts in the particle flux-energy distributions measured by the plasma detectors. Such shifts are most evident in the ion spectra. Examples of spectrograms showing this type of spectral shift are given by Goldstein and DeForest.[2]

5. CHARGING RESPONSE OF ATS-5 AND ATS-6

In order to make meaningful predictions about the possibility of active control of spacecraft potentials, it is necessary to be able to predict the potential that a spacecraft will assume when immersed in a natural plasma. In particular, this task is made much more difficult if there are first-order differences due to the details of a given configuration. Table 1 gives the comparison of spacecraft and systems for ATS-5 and 6. Clearly, these two spacecraft are very different in size, construction, orientation, and outer surface composition. Therefore, if these two space vehicles change to approximately the same potential when exposed to the same environment, then perhaps a detailed study of either one will have some general validity. During two eclipse seasons (fall 1974 and spring 1975) when ATS-5 and 6 were separated by only 1.2 earth radii, and when the on-board plasma

Table 1. Comparison of Spacecraft and Systems

	ATS-5	ATS-6
Characteristic Size	2 m	10 m
Stabilization	Spin (Axis Parallel to Earth's)	3-Axis
Outer Surface	Mostly Quartz (Good Insulator)	Quartz, Kapton, Paint, Aluminum (Mixed Insulator and Conductor)
Ion Engine Neutralizer	Thermal Emission (Electrons Only)	Discharge Plasma
Neutralizer Placement	Recessed: 2.5 cm	Outboard: 17 cm
UCSD Detectors	Body Mounted (50 eV - 50 keV)	Rotating (1 eV - 80 keV)

instruments on both indicated similar plasmas, the simultaneous potentials were calculated and are plotted in Figure 3. The line in this figure is the line of equal potentials and was drawn before the points were added. Considering the differences shown in the table and the fact that there is variability in the plasma, the agreement is remarkable. (Note: The earth's umbra at this distance is approximately 2 earth radii across, allowing ample opportunity for the two spacecraft to be simultaneously eclipsed.)

Since the two vehicles behave similarly in the natural plasma, it is possible to compare their responses to active control using the assumption that differences in response are due to differences in the characteristics of the neutralizers rather than to differences in spacecraft charging response.

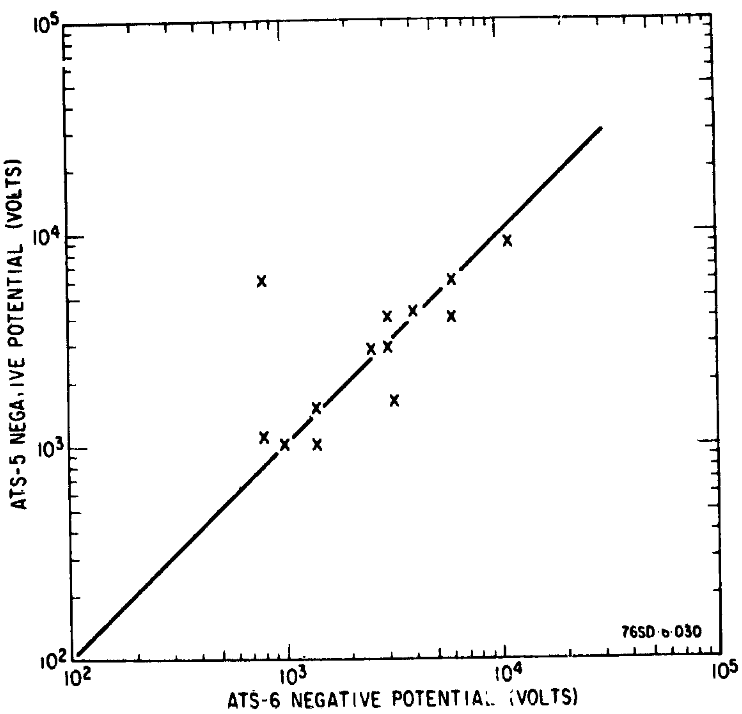

Figure 3. Simultaneous ATS-5 and ATS-6 Potentials

6. RESPONSE TO ACTIVE CONTROL

As was previously noted in Section 1, the data on ATS-5 response to neutralizer operations are far more extensive than those for ATS-6. In addition, because of differences inherent in the two neutralizers and operational constraints, the operations themselves are somewhat different.

The ATS-5 hot wire filament can be turned on and off in very short times, that is, it requires no "warm up" period. The experiment sequence used for the tests reported here was to allow the spacecraft to enter eclipse with the neutralizer off, to command the neutralizer on 10 min later, and to command the neutralizer off again 5 min later. Particle data were taken for at least 15 min before and after the neutralizer operations. Some experiments are also being run using a 10 min "neutralizer on" period. Results of these will be reported as data become available.

In contrast to the fast response time of the hot filament, the ATS-6 plasma bridge neutralizer requires about 35 min after the "on" command is given to come into full on operation (see Section 3). Because of concern for the spacecraft's power system, the neutralizer was brought into full operation before entry into eclipse during the fall 1976 eclipse period. The neutralizer remained on for 10 min after entry into eclipse and was then commanded off. Particle data were taken 24 hr per day during these neutralizer operations. Additional experiments are being conducted using these ATS-6 instruments, and results will be reported as the data become available.

The operating conditions for the experiments reported here are summarized in Table 2.

Table 2. Comparison of Test Operations

	ATS-5	ATS-6
Turn-On Time	<1 min	35 min
Turn-Off Time	<1 min	~2 min
Full-On Operation Time in Eclipse	5 min	10 min
Emission Current	<6 μA	<1 mA
Energy of Emitted Particles	~2 V	~7 V

Figure 4 shows the response of the ATS-5 spacecraft to activation of the neutralizer. The potential with and without the electron emitter energized is shown here. The potential determinations were made within minutes of each other and under conditions where the potential was not changing rapidly. The dashed line here is the line along which the two potentials are equal; the solid line is fit to the data.

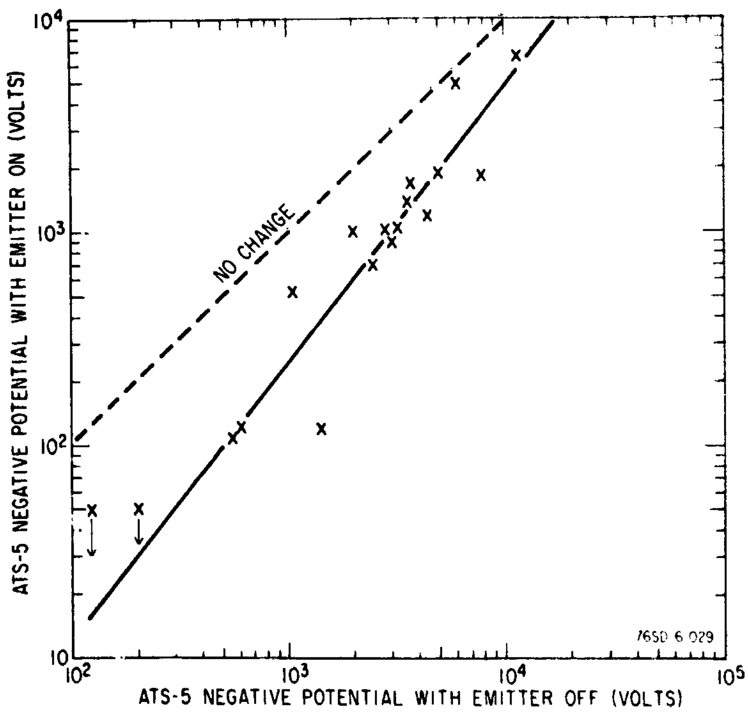

Figure 4. Effect of ATS-5 Electron Emitter on Spacecraft Potentials

The first conclusion that one reaches from Figure 4 is that the electron emitter does lower the potential, but it has the unfortunate characteristic of being less effective in maintaining the spacecraft potential near ground at larger magnitude initial potentials and very effective in doing this at potentials which are already sufficiently low in magnitude that they do not pose much of a problem. This result is supported by laboratory simulations reported elsewhere in this conference by Goldstein.[8] Since the emitter filament on ATS-5 is located within a cavity, perhaps its effectiveness is decreased by the shielding action of the spacecraft body. In addition, there is evidence that a potential barrier may exist around spacecraft.[9] Thus, it is possible that the electrons leaving the filament cannot escape from the spacecraft because they lack sufficient energy to penetrate such a barrier. An emitter that was both exposed and biased with respect to spacecraft ground might be more effective in coupling to the plasma.

There are insufficient data to make a similar plot for ATS-6. Figure 5 shows the spacecraft response to the neutralizer activation. This figure shows the spacecraft response on the most "active" day for which data are available. ("Active" here refers to magnetospheric substorm activity.) The plasma environment remained relatively constant from about 2350 until after 0130 on this day so that the changes in the spacecraft's potential can be attributed to the neutralizer's operation and to entry into and exit from eclipse. The figure shows that the spacecraft potential was maintained within 10 volts of ground during the entire neutralizer

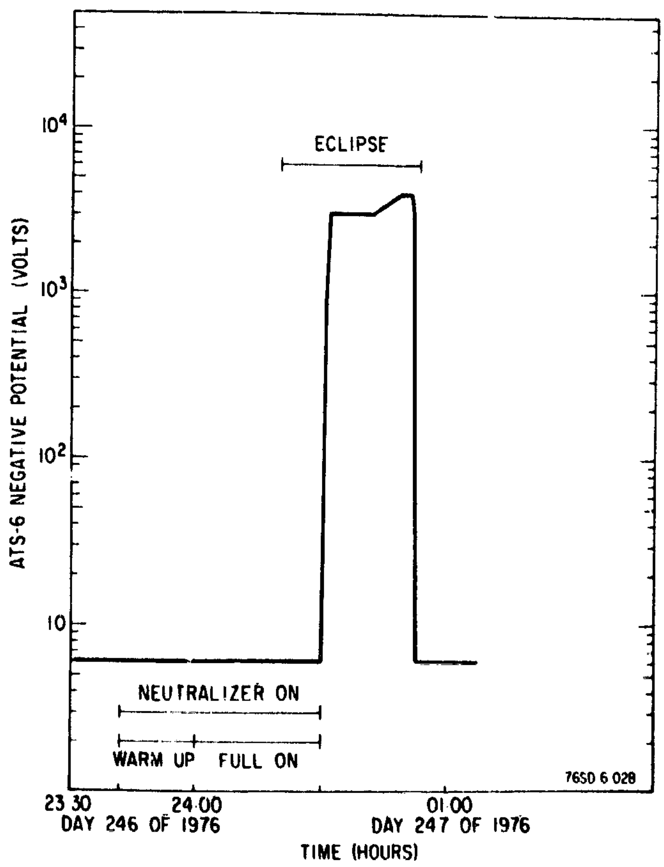

Figure 5. Effect of ATS-6 Neutralizer on Spacecraft Potential

operation, both in sunlight and in eclipse. The fact that the spacecraft potential changes rapidly to several thousand volts negative when the neutralizer is turned off implies that very large potentials can be discharged by this neutralizer.

The low energy electron spectrum is also affected by neutralizer operation. While this has not been studied in detail, such effects have been interpreted as representing changes in the potential barrier surrounding the ATS-6 spacecraft caused in this case by neutralizer operation.[2]

Comparison of this event with the ATS-5 results leads one to believe that the plasma discharge may be the more effective method of control.

One other difference between the two systems can be noticed. ATS-6 seems to have been held to a steady potential during neutralizer operation, but this is not always the case for operation of the electron emitter on ATS-5. Figure 6 gives the time history of discharge for three events on ATS-5. The changes in potential

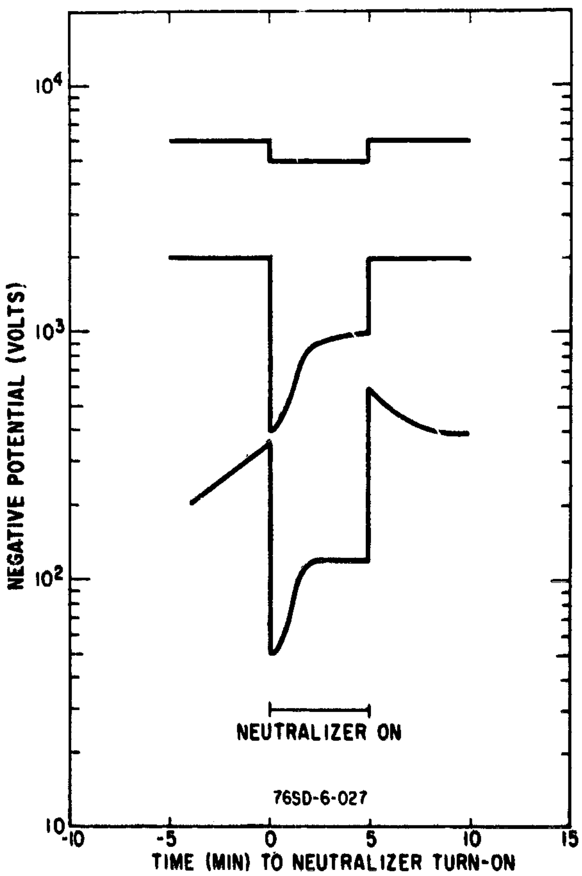

Figure 6. Effect of Electron Emitter on ATS-5 Ground Potentials

during neutralizer operation shown in this figure do not seem to have been produced by changing environmental conditions. The reason for this strange behavior is not known.

7. SUMMARY AND CONCLUSIONS

Active control of spacecraft potential has been demonstrated using both an unbiased electron emitter and a plasma discharge. Activation of either of these devices resulted in reductions in the magnitude of the spacecraft potential. Of the two devices studied here, the plasma bridge neutralizer was more successful in maintaining the spacecraft potential near ground. Its operation held the spacecraft potential steady and less than 10 volts from ground. In contrast to this behavior, the ATS-5 potential during electron emitter operation is more variable. Also, although operating this neutralizer results in reduction of the magnitude of the spacecraft potential, it does not, in general, hold the potential near ground. In fact, while the absolute magnitude of the change in potential increases with increasing magnitude of the "neutralizer off" potential, the percent change decreases with increasing magnitude of the "off" potential. Thus, this device is considered less effective than the ATS-6 plasma device.

This result does not imply that no electron emitter could hold the spacecraft ground potential near plasma ground. The particular device being used is both unbiased and recessed into the spacecraft body. As noted earlier, this recessed location may result in suppression of the emission, particularly since the spacecraft surface near the emitter is an insulator and thus would remain charged negatively even when the frame is discharged. The fact that the filament is unbiased further means that the electrons leaving it will have energies determined by the 2 Vac filament power supply, that is, 2 volts. These may not have sufficient energy to overcome a potential barrier surrounding the spacecraft. It appears that a biased emitter extended some distance from the spacecraft surface would be preferable for active control purposes.

The plasma device on ATS-6 has the inherent advantage that ions from the discharge can be attracted to nearby negative surfaces, so that this device has a mechanism for discharging insulator surfaces as well as the spacecraft frame. An electron emitter has no such mechanism available to it. In addition, the location of the ATS-6 device, about 17 cm outboard of the spacecraft body, and the fact that the emitted electrons have energies on the order of 7 volts seem advantageous compared to the location and electron energies characteristic of the ATS-5 device. The fact that the spacecraft is maintained within 10 volts of plasma ground throughout neutralizer operation implies that electrons are escaping from the spacecraft. This could be because the electrons are emitted with sufficient energy to overcome the potential barrier or because neutralizer operation alters the barrier in some advantageous way.

The ATS-6 device, then, looks promising as an active control device. However, additional experiments using this device under a variety of natural environmental conditions are needed. Such experiments, as well as experiments utilizing both ATS-5 and ATS-6 in conjunction with one another, are being conducted as a part of the Spacecraft Charging Investigation.

References

1. Bartlett, R.O., DeForest, S.E., and Goldstein, R. (1975) Spacecraft charging control demonstration at geosynchronous altitude, AIAA Paper 75-359, AIAA 11th Electric Propulsion Conference, New Orleans, La.

2. Goldstein, R., and DeForest, S.E. (1976) Active control of spacecraft potentials at geosynchronous orbit in Progress in Astronautics and Aeronautics 47:169, A. Rosen, Editor, MIT Press, Cambridge, Mass.

3. Worlock, R., Davis, J.J., James, E.L., Ramirez, P. and Wood, O. (1968) An advanced contact ion microthruster system, AIAA Paper 68-552, AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio.

4. Worlock, R.M., James, E.L., Hunter, R.E., and Bartlett, R.O. (1975) The cesium bombardment engine north-south station-keeping experiment on ATS-6, AIAA Paper 76-363, AIAA 11th Electric Propulsion Conference, New Orleans, La.

5. James, E.L., Worlock, R.M., Dillon, T., Gant, G., Jan, L., and Trump, G. (1970) A one millipound cesium ion thruster system, AIAA Paper 70-1149, AIAA 8th Electric Propulsion Conference, Stanford, Calif.

6. DeForest, S.E., and McIlwain, C.E. (1971) Plasma clouds in the magnetosphere, J.Geophys.Res. 76:3587.

7. McIlwain, C.E. (1975) Auroral electron beams near the magnetic equator in Physics of the Hot Plasma in the Magnetosphere, B. Hultquist and L. Stenflo, Editors, Plenum Publishing Co., New York.

8. Goldstein, R. (1976) Active control of potential of the geosynchronous satellite ATS-6, Paper I-6, Spacecraft Charging Technology Conference, Colorado Springs, Colo.

9. Whipple, E.C., Jr. (1976) Observation of photoelectrons and secondary electrons reflected from a potential barrier in the vicinity of ATS-6, J.Geophys. Res. 81:715.