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N79-24006

SUMMARY OF THE TWO YEAR NASA PROGRAM FOR ACTIVE CONTROL OF ATS-5/6 ENVIRONMENTAL CHARGING

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SUMMARY

Over the past several years numerous experiments have been conducted on the ATS-5 and ATS-6 which have demonstrated the feasibility of modifying or clamping the environmentally induced potential of these spacecraft. This has been accomplished utilizing the ion engine experiments and monitoring their effects with the University of California, San Diego, Auroral Particles instruments on each spacecraft.

The results of these experiments have shown that a thermionic electron source is capable of replacing photo-emitted electrons during eclipse. However, the utility of this type of device is limited if its emission is suppressed by local electric fields. On the other hand, it has been shown that a plasma source will not only serve as a substitute for photo-emitted electrons but will also suppress differential charging of isolated elements of the spacecraft which would tend to suppress electron emission. This later device is therefore capable of clamping the potential of a spacecraft without special consideration of its coupling to the ambient plasma.

An overview of the experiments and a summary of their results are presented in this paper. Therefore, this paper serves as a "road map" to the spacecraft charging experiments conducted on ATS-5 and ATS-6.

INTRODUCTION

In May of 1976, the National Aeronautics and Space Administration (NASA) awarded a contract to the University of California, San Diego (UCSD) with the objective of studying active control of environmental charging on the Applications Technology Satellites (ATS) 5 and 6. This study was an element in the joint NASA/Air Force investigation of geosynchrc ıous satellite charging (Lovell et al., 1976). The in-orbit experimental phase of this study has now been concluded. The contract report of the first year's activities is now available, and the final report will be available in the near future. Initial results of this effort will be summarized here; however, further analysis is warranted, and it is the hope of the authors that this paper will provide sufficient stimulus to encourage additional investigation of these data.

The results of these experiments have provided 213 data sets from ATS-5 and 36 data sets from ATS-6. Several of these experiments were conducted simultaneously on the two satellites. During the course of these measurements, 111 instances of environmental charging to potentials in excess of 1000 volts have been observed. No anomalous effect has been associated with any of these charging events on either satellite.

The ATS-5 and the ATS-6 satellites each carried an Auroral Particles Experiment and a Cesium Ion Engine Experiment. These instruments were jointly utilized to conduct this investigation of actively controlling satellite charging. While neither instrument was developed with this application as an objective, the experimental results demonstrated the achievement of altered or clamped satellite potential. There are features of these experiments which raise questions which have not been conclusively answered. Instruments specifically designed to study active control of satellite charging will clearly yield more definitive results. However, it is felt that the experiments described here have added to the understanding of the environmental charging phenomenon and should complement the results of future experiments such as the USAF Space Test Program, P78-2 (Durrett et al., 1978).

DESCRIPTION OF ATS-5 AND ATS-6 INSTRUMENTATION

The details of the ATS-5 and ATS-6 spacecraft and their respective instruments have been previously presented (Bartlett et al., 1975; Purvis et al., 1976). In summary, Figures 1 and 2 depict the key features of each of these satellites including the relative locations of the Auroral Particles Experiment and the Cesium Ion Engine Experiment. The Auroral Particles Experiment on ATS-5 provided measurement of ion and electron flux in the 50 eV to 50 keV energy range at fixed instrument apertures. The ATS-6 Auroral Particles Experiment extended this range from 0.1 eV to 80 keV and incorporated a scanning aperture to provide angular resolution. The ATS-5 ion engines are of the contact ionization type utilizing a thermionic electron source (neutralizer). Alternately the ATS-6 ion engines are of the bombardment type utilizing a low energy cesium plasma as its neutralizer. When the cesium ion source is operated, the neutralizer serves as a ready source of electrons to maintain a net charge neutrality. The neutralizer can also be operated without the ion source. The ion sources and the neutralizers were utilized to alter the current balance of each spacecraft and thus actively control the spacecraft's potential. The Auroral Particles Experiments were utilized to measure this effect.

TEST CONDITIONS

Since geosynchronous spacecraft charging was first measured (DeForest, 1972), it was clear that the spacecraft normally dominates ambient plasma perturbation with a ready source of photo-emitted electrons. The obvious exception occurs during the vernal and autumnal eclipse of the Sun. The most recent study of ATS-5 and ATS-6 potentials during eclipse is reported by Rubin et al., 1978.

Neither ATS ion engine was designed to provide a bias of the neutralizer or ion source relative to spacecraft ground. Therefore, most of the potential control experiments have been conducted during eclipse when natural spacecraft charging events were likely. All of these eclipse tests have utilized only the neutralizers on the spacecraft. A few operations of the ATS-5 and ATS-6 ion sources have occurred during full Sun periods of the orbit. The design of each ion engine required that the neutralizer be operated when the ion source was operated.[1] This restriction has been eliminated and other features, such as biasing, have been incorporated into the ion/electron source to be flown on USAF Space Test Program mission P78-2 (Cohen et al., 1978).

A summary of the measurements relating to active control of the ATS-5 and ATS-6 potential is shown in Table 1. Various restrictions and problems precluded all combinations of instruments and test conditions. It is felt that the results of these measurements provide a basis for predicting the behavior of electron and ion sources as spacecraft potential control devices. The missing data sets therefore represent desirable but not essential experiments relative to the ATS-5 and ATS-6 spacecraft charging study.

ATS-5 EXPERIMENTAL RESULTS

While the ATS-5 ion engine was operated briefly as a thruster (DeForest et al., 1973), the far more interesting results were obtained from the operation of its thermionic neutralizer during eclipse. This is primarily due to the large spacecraft potentials encountered during eclipse which well exceeded the 50-eV minimum energy resolution of the UCSD Auroral Particles Experiment. Recent spectrogram data from day 87 of 1978 are presented in Figure 3 as typical of a spacecraft charging event which is modified by the operation of the thermionic neutralizer. The spectrogram is a time plot showing energy of arriving electron and ion fluxes. The density of the particle flux

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[1]A special operation of the ATS-5 ion engine was conducted in 1973 commanding it off in an abnormal manner. This briefly produced an ion beam while the neutralizer was off. Limited data indicate that the spacecraft charged to a potential of about -3000 V (DeForest et al., 1973).

is indicated by the gray scale moving from dark (minimum) to light (maximum). At the onset of eclipse, denoted on Figure 3, the spacecraft charged to a potential of about -2000 volts. This can be seen in Figure 3 as the dense (light) band of ions rising in energy. As the spacecraft potential goes negative, low energy ions from the ambient are attracted to the spacecraft and their energy upon arrival would be that of the spacecraft's potential. It follows that no ions can have energy less than the spacecraft's potential. The apparent ion flux at energies less than the spacecraft potential is therefore instrument noise. Considering the nearly 9 years of orbital operation, this instrument remains remarkably sensitive.

The spectrogram primarily finds its utility in qualitative examinations of environmental flux features. By extracting the spacecraft's potential from the environmental data, the effect of the operation of the ion engine's thermionic neutralizer during day 87, 1978, eclipse is shown again in Figure 4. This linear plot more quantitatively demonstrates the effect of the neutralizer's operation. When the hot filament is first turned on, the spacecraft initially discharges to a potential below -130 volts. The time between the energy scans showing the spacecraft at -1500 volts and -130 volts is about 14 seconds. Subsequently, the spacecraft is charged to a potential of about 1000 volts. Following the turn-off of the neutralizer, the spacecraft charged to about -2500 volts.

The slow charging of the spacecraft while the neutralizer is on is believed to have resulted from the suppression of electron emission by differential charging between the spacecraft structure at neutralizer potential and the insulated thermal cover around the neutralizer. The hot neutralizer filament is mounted approximately 3 cm inboard of the spacecraft skin. The suppression of electron emission from the ion engine neutralizer in this geometry has been measured in the laboratory (Goldstein, 1976). Additionally, laboratory measurement of differential charging between conductive and nonconductive materials immersed in a high energy electron beam has been performed by Purvis (1978) which simulated the emission of electrons from the conductive element of the spacecraft. A charging of the insulated materials with a similar time constant to that measured in orbit was observed. The potential overshoot observed at the turn-off of the neutralizer (Figure 4) is also typical of numerous active charge control experiments. This phenomenon can also be explained as an effect of differential charging of the insulated spacecraft surfaces associated with the operation of the neutralizer. The artificially higher negative potential on these surfaces at neutralizer turn-off would alter the natural current balance with the ambience until all surfaces reached their equilibrium potentials.

An additional series of orbital tests was structured to further examine the effect of the neutralizer's operation on spacecraft potential. Simultaneous operation of both the ion engine neutralizers on ATS-5 was performed. Typical results of these experiments are presented in Figure 5. Three such data sets were obtained. The turn-on of the second neutralizer did not have a marked effect. However, when the first neutralizer was turned off, a slight decrease in the spacecraft potential was observed during all three tests. This phenomenon is not understood. When the second neutralizer was turned off, the spacecraft potential rose in a fashion typical of single neutralizer operations.

In summary, the hot filament neutralizer has been shown to have a significant effect on the potential of ATS-5 during a spacecraft charging event. However, due to suppression of electron emission, the spacecraft was not clamped at plasma potential. Laboratory data support the likelihood that differential charging of insulated spacecraft surfaces is suppressing electron emission. This hypothesis is consistent with the transient behavior observed at the turn-on and turn-off of the neutralizer in orbit. Alternately, the suppression of electron emission by a plasma sheath around the spacecraft can not be ruled out. Measurements suggesting the presence of such a barrier around ATS-6 have been presented (Whipple, 1975). Additional consideration of these data seems well justified.

ATS-6 EXPERIMENT RESULTS

The results of the ATS-6 experiments complement those of ATS-5. Since the ATS-6 ion engine neutralizer utilized a low energy plasma as an electron source, the effects of a second-type neutralizer could be measured. Additionally, the ATS-6 Auroral Particles Experiment provided significantly enhanced energy resolution.

The effect of the operation of the ATS-6 ion engine as a thruster has been studied by Goldstein et al., (1976) and more recently by Olsen (1978). In this configuration the ion source and neutralizer are simultaneously operated. To summarize these tests, Figure 6 is presented. The data demonstrate that the potential of ATS-6 was clamped at about -4 volts throughout the 4-day operation of the Ion Engine Experiment.

The cesium vapor flow to the plasma neutralizer is regulated to control the potential of an anode probe in its discharge. The potential of the probe during the four-day operation of the ion engine was about +4.5 V relative to spacecraft ground as measured by telemetry. Since the neutralizer cathode potential is that of spacecraft ground, the potential of the anode probe is at or very near the potential of the ambient plasma. If the probe were operated at spacecraft potential and the cathode of the plasma neutralizer were operated with a negative bias, the spacecraft might well have been held at plasma potential. The ATS-6 Ion Engine Experiment had no such bias capability. It remains for this concept to be demonstrated.

Several other interesting features of the UCSD data were observed while the ion thruster and neutralizer were jointly operated. There are indications that differential charging on ATS-6 was suppressed during this operation and that the measurement of environmental data was enhanced by a constant spacecraft potential (Olsen, 1978). Although the UCSD particle detectors cannot distinguish between protons and other ions, further analysis of the data may yield additional insight into the nature of particle flux to the ATS-6 while the Ion Engine Experiment was operating. Present indications are that variation in low energy ion flux appears to more nearly follow natural variations of the plasma rather than an ion flux originating from the ion engine itself (Olsen, 1978).

Of equal interest were the ATS-6 ion engine neutralizer tests that were conducted during eclipse. A spectrogram of such a test on day 97, 1977, is presented in Figure 7. The spacecraft potential from the same data is linearly plotted in Figure 8. These data demonstrate that the low energy plasma neutralizer is sufficient to discharge the spacecraft. Due to the absence of natural low energy ions during this test, the exact potential to which the spacecraft was clamped can not be measured with precision. Other experiments of this type have shown that the spacecraft potential is clamped to approximately -5 V by the neutralizer's operation. The operation of the plasma neutralizer has also been shown to reduce differential charging of the spacecraft, but not to the same extent as the operation of the ion thruster. This is most likely due to the larger density of free low energy ions associated with the ion thruster's operation.

Closer examination of the data presented in Figures 7 and 8 provides several interesting observations. The operation of the plasma neutralizer differs significantly from that of the thermionic neutralizer. To operate the thermionic neutralizer on ATS-5, power is simply applied to a tantalum filament by command, and the filament reaches its operating temperature in a fraction of a second. When the plasma neutralizer is commanded on, power is applied to a heater which warms a supply of cesium in order to deliver cesium vapor to the plasma neutralizer. When the density of the cesium vapor and the cesium surface coverage of the neutralizer cathode are sufficient, a plasma discharge strikes. Initially, this discharge operates from a relatively low cesium vapor flow rate and is referred to as the plume mode of operation because of its physical appearance. As the cesium supply continues to heat, the cesium vapor flow rate increases and the plasma transitions to a point discharge described as the spot mode of operation. As seen in Figure 8, the occurrence of neutralizer spot mode operation, which is telemetered, had no measurable effect on the spacecraft's potential. The occurrence of plume mode, which is not telemetered, seems to have provided an ample source of electrons to discharge the spacecraft with a time constant too short to be measured with the 16-second energy range scan of the UCSD instrument. As shown in Figures 7 and 8, the discharge of the spacecraft occurred toward the end of the predicted time when the neutralizer would strike based on ground test data. Due to a malfunction of the ion engine, the neutralizer vaporizer heater was operating at a slightly reduced power, so a longer start-up time for the neutralizer would be expected. To turn off the neutralizer, all power was removed from the experiment. This effectively meant that the neutralizer would instantaneously cease providing electrons and ions. Figures 7 and 8 indicate that the time constant associated with the spacecraft naturally recharging was significantly longer than that required to discharge the spacecraft with the neutralizer. Also note that natural charging and discharging time constants associated with the onset and exit from eclipse are similar to that associated with the recharging of the spacecraft following the neutralizer operation. The conclusion drawn from these facts is that the ambient plasma currents on this day were overwhelmingly dominated by the operation of the neutralizer. This same conclusion was supported by all other ATS-6 active charge control experiments.

CONCLUSION

The generalized conclusions presented here are based on the results of all active spacecraft charge control experiments conducted on ATS-5 and ATS-6 rather than the limited data presented in this paper. In summary, these experiments have provided the first known measurements of the interaction of the natural plasma and an artificially produced plasma at geosynchronous altitude. The effects of these experiments on the potentials of ATS-5 and ATS-6 have been examined with the following observations:

- The thermionic electron source on ATS-5 provided electrons to replace photoemitted electrons in eclipse; however, charging of the insulated surface around this emitter suppressed electron current and prevented the spacecraft from being driven to plasma potential for all plasma conditions.

- The neutralizer plasma source on ATS-6 maintained the spacecraft potential within a few volts of the ambient potential for both positive and negative charging events for all observed plasma conditions.

- Based on these measurements, it seems likely that a spacecraft could be clamped at plasma potential by a low-energy plasma discharge which could be biased to compensate for the coupling to the ambient. This has not been demonstrated however.

- Operation of the ion engine on ATS-6 was shown to suppress differential charging and clamp the spacecraft potential at a fixed voltage relative to the ambient plasma.

- Active spacecraft potential control has not hindered, but has enhanced the ability to make environmental measurements at energies less than a few volts.

It has previously been shown that the environmental charging of ATS-5 and ATS-6 has produced nearly identical potentials when the two satellites were at similar longitudes (Purvis, 1976). This seems quite astonishing considering the marked difference between the two satellites as summarized in Table 2.

Based on this observation, it follows that the dominant factor controlling the equilibrium potential of a satellite is not the satellites' characteristics but the constituency of the ambient plasma. It is therefore felt that the above observations are generally valid and do not apply solely to the satellites upon which the measurements were made.

Lastly, the time constants associated with all observed natural charging and discharging events well exceeded the time constant associated with the discharging of the satellite by either of the two active control devices. It is therefore clear that these active control devices completely dominate all natural current sources during these experiments. Since no spacecraft anomaly on ATS-5 or ATS-6 has been associated with a natural charging event or an active control experiment, it follows that the task of insuring that a satellite is not sensitive to the electromagnetic interference (EMI) potentially associated with environmental charging is feasible. There is no question, however, that unique satellite design constraints may make the task of EMI sensitivity quite severe.

ACKNOWLEDGMENT

The two instruments utilized to conduct this study were independently conceived with individual experiment objectives. The authors wished to express their appreciation for the support and guidance in conducting these experiments from the principal investigators of the Auroral Particles Experiment, Dr. Carl E. McIlwain, UCSD, and of the Cesium Bombardment Ion Engine Experiment, Dr. Robert E. Hunter, GSFC, retired.

This investigation was conceived after launch, and both scheduling and operations support had to be arranged. The authors therefore wish to additionally acknowledge the contributions of the Orbiting Satellite Project staff and their contractors, GSFC, Dr. James E. Kupperian, Project Manager.

The authors finally wish to acknowledge the contributions of Dr. E. C. Whipple, Dr. S. E. DeForest, and Mr. R. C. Olsen of UCSD and Dr. R. Goldstein of JPL, all of whom have served as co-experimenters during this investigation.

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Table 1. - Summary of Test Conditions

Configuration	Satellite	
	ATS-5	ATS-6
Ion Source w/Neutralizer	Sunlite - 2 Eclipse - None	Sunlite - 2 Eclipse - None
Neutralizer Only*	Sunlite - 24 Eclipse - 217	Sunlite - 22 Eclipse - 14

*The ATS-5 neutralizer produces electrons only while the ATS-6 neutralizer produces both electrons and ions.

Table 2. - Spacecraft Characteristics Summary

Launch (technology)	ATS-5 1969	ATS-6 1974
Attitude control	Spin stabilized	3 axis stabilized
Exterior surface	Quartz, paint	Kapton, aluminum, quartz, silicon, paint
Characteristic dimension	2 m	10 m

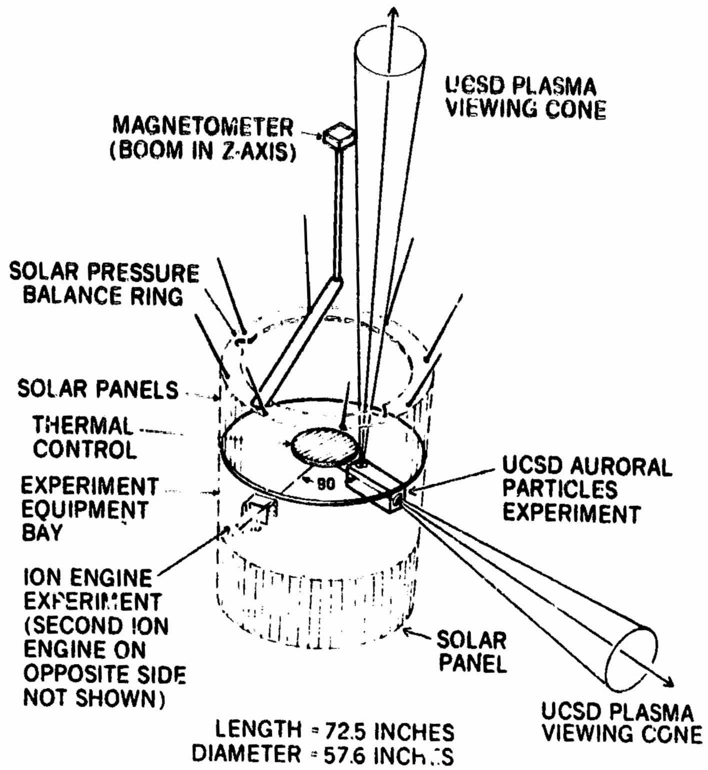

Figure 1. - ATS-5 Orbital Configuration

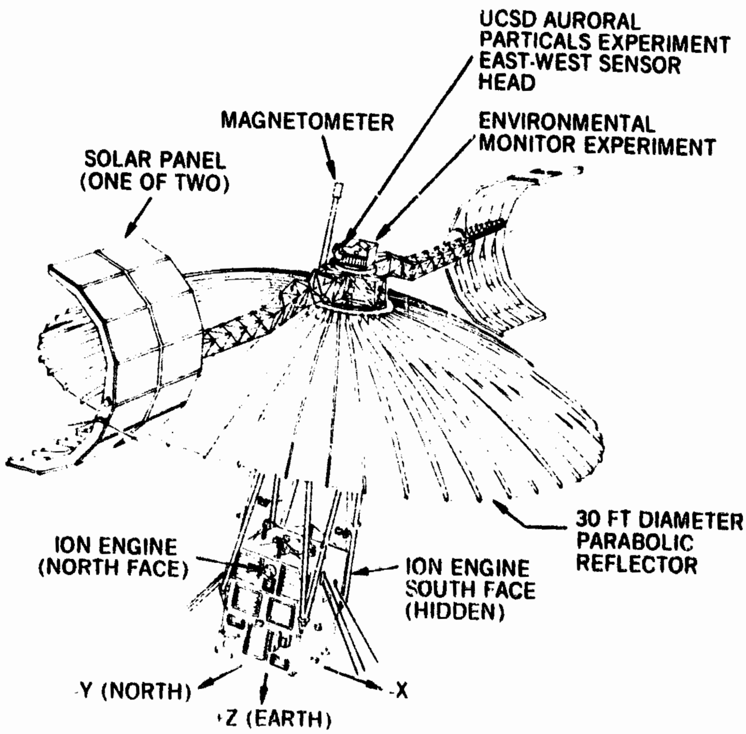

Figure 2. - ATS-6 Orbital Configuration

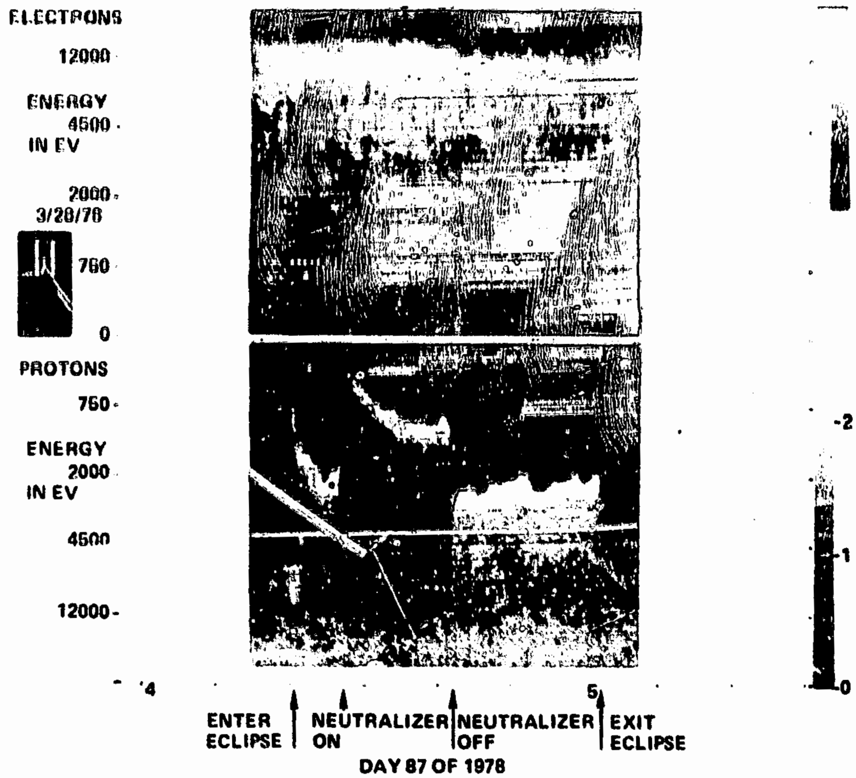

Figure 3. -ATS-5 Spectrogram (March 28, 1978 - Day 87)

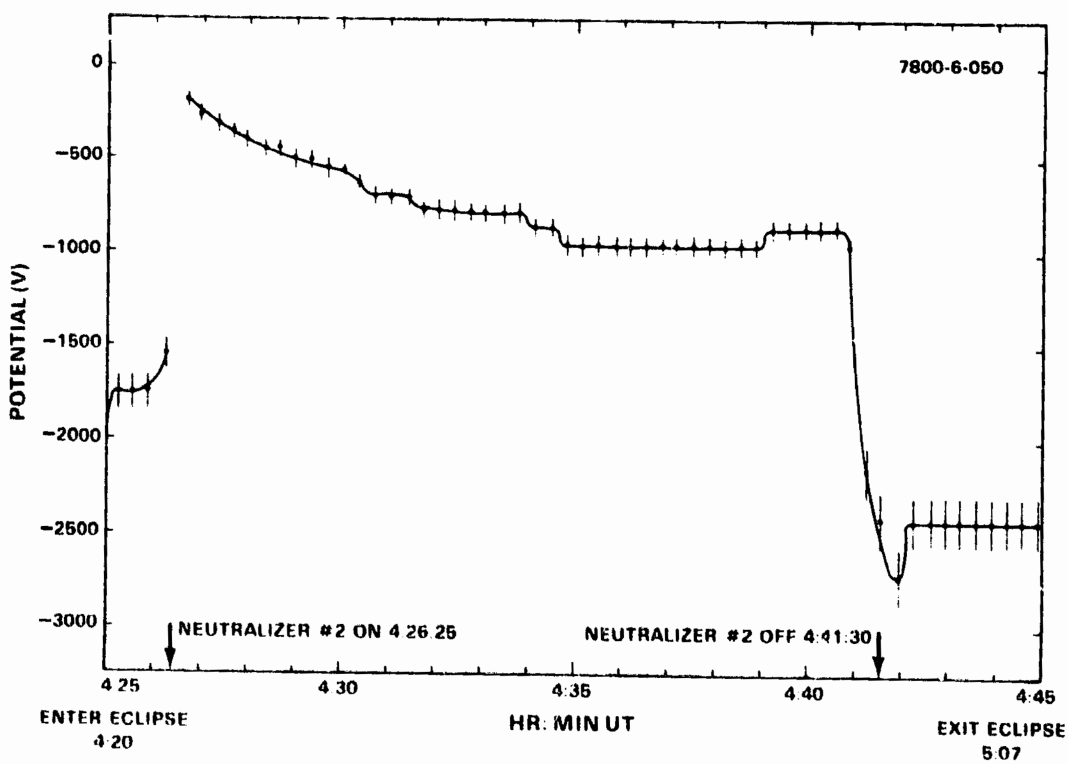

Figure 4. - ATS-5 Neutralizer/Eclipse Operation (March 28, 1978 - Day 87)

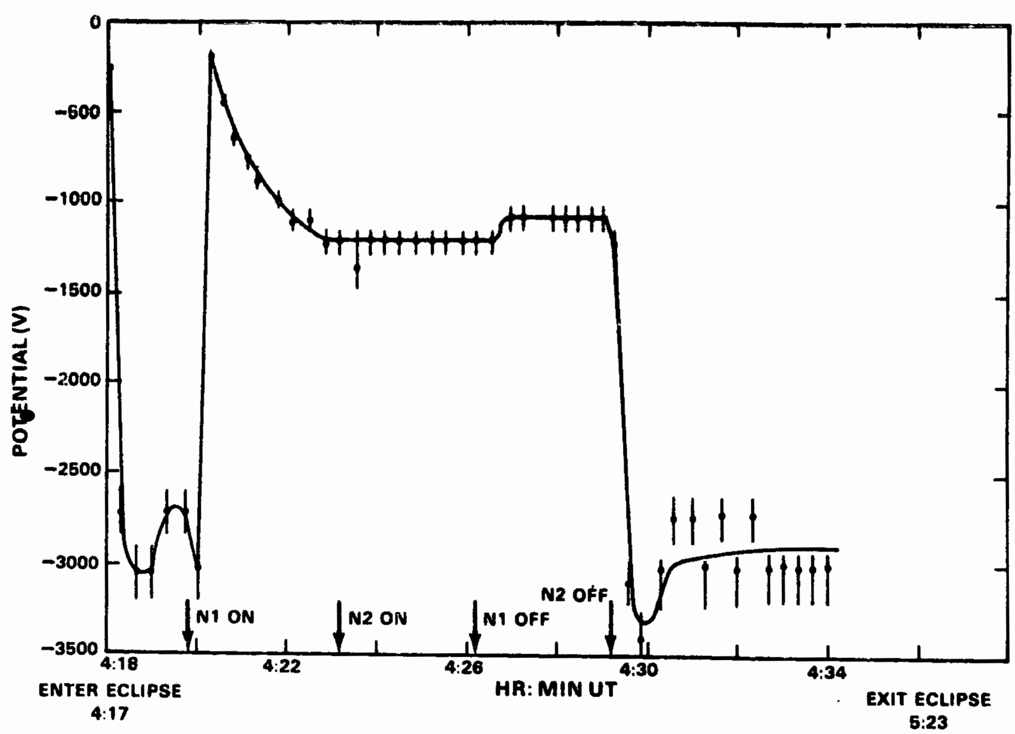

Figure 5. - ATS-5 Neutralizer/Eclipse Operation (February 28, 1978 - Day 59)

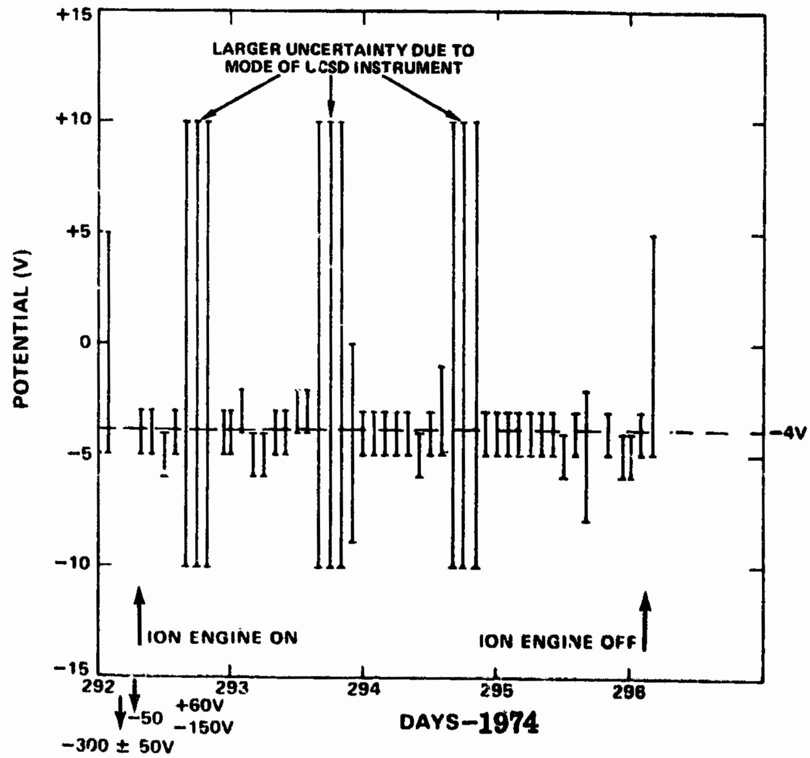

Figure 6. - ATS-6 Ion Engine Operation (No Eclipse)

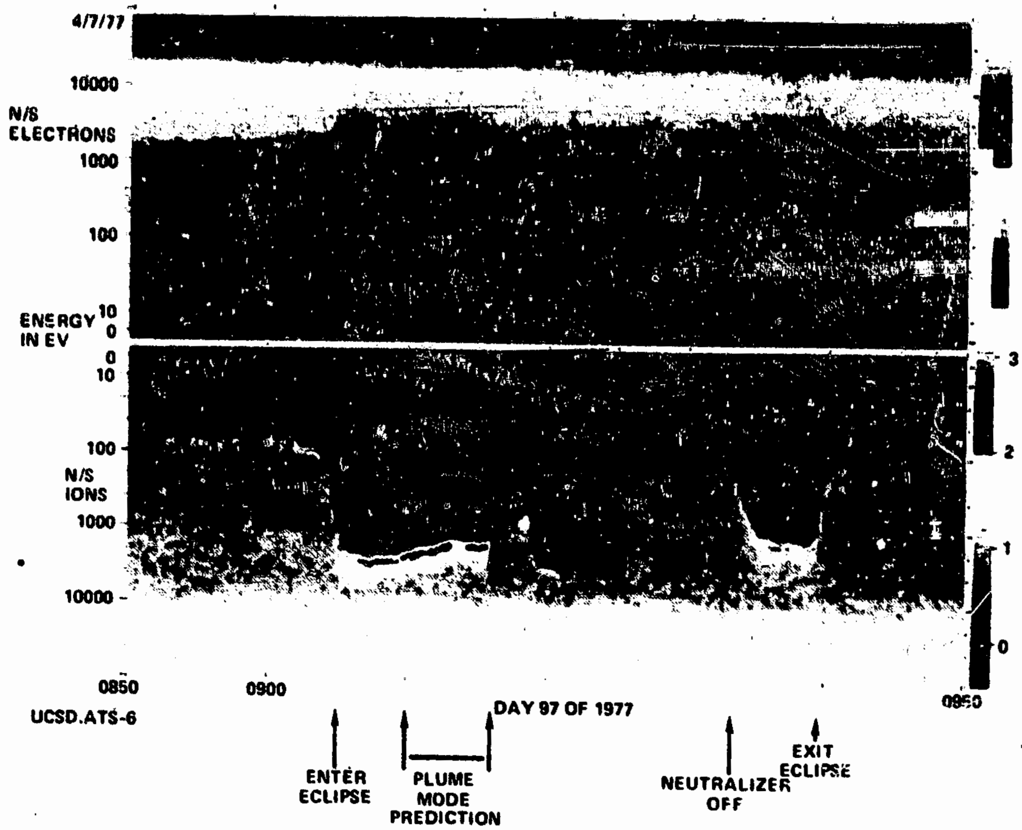

Figure 7.-ATS-6 Spectrogram (Day 97 of 1977)

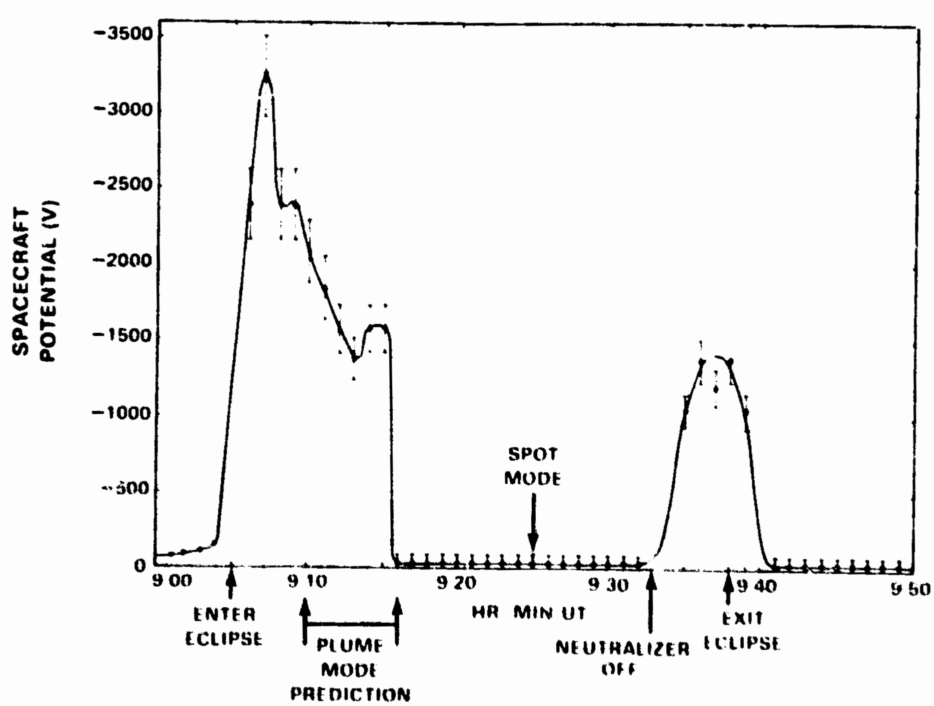

Figure 8.-ATS-6 Neutralizer/Eclipse Operation (Day 97 of 1977)